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State of the Art of Earthquake Early Warning Research
in California; Future Implementation and Consequences
for Geoethics

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Author's Declaration

Unless otherwise indicated in the text or references, or acknowledged above, this thesis is entirely the product of my own scholarly work. Any inaccuracies of fact or faults in reasoning are my own and accordingly I take full responsibility. This thesis, with the title, 'State of the Art of Earthquake Early Warning Research in California; Future Implementation and Consequences for Geoethics' has not been submitted either in whole or part, for a degree at this or any other university or institution.

Vienna, 05.02.2014

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Wien, 05.02.2014

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List of Abbreviations

2-D – two dimensional

BDSN – Berkeley digital seismic network

CalMagNet - California Magnetometer Network

CISN - California Integrated Seismic Network

CPU – Central Processing Unit

EGU – European Geoscience Union

ELF – Extremely Low Frequency

EM - Electromagnetic

EWS – Early Warning System

GDS – Geomagnetic Depth Sounding

GPS – Global Positioning System

GMPE's – Ground Motion Prediction Equations

GSHAP – Global Seismic Hazard Assessment Program

Hz - Hertz

IAPG - International Association for Promoting Geoethics

IR – Infrared

Kg - Kilograms

M – Magnitude

m - meter

MMI – Modified Mercalli Intensity

µm - micrometer

NASA – National Aeronautics and Space Administration

NCSN – northern California seismic network

NEIC – National Earthquake Information Center

Pc1 – continuous pulsations in the 0.2-5Hz frequency band.

P_d – peak displacement

PDF – Portable Document Format

PDPC – Phase Dynamic Probability Change

$P_{d/v}$ - peak displacement or velocity amplitude

PGA – Peak Ground Acceleration

PGV – Peak Ground Velocity

P_v – peak velocity

RH – Relative Humidity

s- seconds

SFBA – San Francisco Bay Area

SNR – signal-to-noise ratio

TEC – Total Electron Content

T_p^{max} – *maximum predominant period*

ULF – Ultra-low Frequency

UN – United Nations

USGS – U.S. Geological Survey

Abstract

Current research fields in seismology and geophysics are in the process of developing warning systems that may, given time and further critical testing, be able to predict earthquakes. The goal of this thesis is to compare two state of the art early warning system research projects in California (namely ElarmS and QuakeFinder), and consider the impact that such warning systems would likely have upon full implementation.

Research questions focus on how and how well these systems can be used to predict earthquakes, whether the systems could potentially be deployed in earthquake prone regions worldwide and what time span for a warning the two methods would allow. The two systems are subsequently compared to each other. In a further step, questions concerning geoethical implications that the implementation of such warning systems would have should be answered. In order to answer these research questions, a literature analysis was conducted.

The analysis of Elarms concluded that this system is robust, yields low estimation errors on earthquake location and magnitude and is at the stage where online testing is feasible. Improvements in the algorithms to reduce errors through site effects, and instrument type can still be made and denser instrument coverage should equally be considered.

The analysis of QuakeFinder concluded that this system is still in an earlier testing phase, as data on ULF-EM activity prior to and during earthquake events are still limited and rare. The results of this method, particularly from more recent papers are very promising and an effort should be made to improve instrument coverage and enhance noise discrimination.

Relating to which system may be best for implementation, an interesting notion would be implementing both systems as they have the potential to complement each other well. This may also improve some of the problems concerning geoethics (particularly the range of issues that need to be considered with the implementation of the QuakeFinder system), allowing for long-term planning ahead of an earthquake and last minute mitigation measures.

Kurzfassung

Aktuelle Forschungsfelder der Seismologie und Geophysik beschäftigen sich aktuell mit der Entwicklung von Frühwarnsystemen, die mit Zeit und weiteren Tests, voraussichtlich in der Lage sein werden Erdbeben vorherzusagen. Ziel dieser Arbeit ist es, zwei der modernsten Frühwarnsystem-Forschungsprojekte in Kalifornien (ElarmS und QuakeFinder) zu analysieren, zu vergleichen und mögliche Auswirkungen dieser Systeme in Hinblick auf die Geoethik zu analysieren.

Die Forschungsfragen konzentrieren sich auf die Fähigkeit dieser Systeme Erdbeben vorherzusagen, ob diese Systeme auch weltweit eingesetzt werden könnten, sowie welche Zeitspanne für eine Warnung bei einem bevorstehenden Erdbeben möglich wäre. Die beiden Systeme werden auch miteinander verglichen. Anschließend sollten die Fragen hinsichtlich der Geoethik in Betracht gezogen werden, um die möglichen Auswirkungen einer Umsetzung solcher Warnsysteme zu analysieren. Um diese Forschungsfragen zu beantworten, wurde eine Literaturanalyse durchgeführt.

Die Analyse des ElarmS-Systems hat ergeben, dass dieses System sehr robust ist, niedrige Schätzfehler hinsichtlich Erdbeben Lage und Größe ergibt und bereit ist für eine Implementierung in einer Interaktiven Umgebung. Verbesserungen wären im Bereich der Algorithmen möglich (um Standort- oder Gerätetyp bezogene Fehler zu reduzieren). Eine dichtere und größere Flächenabdeckung mit Instrumenten könnte sich ebenso vorteilhaft auswirken.

Die Analyse des QuakeFinder-Systems hat ergeben, dass dieses System noch in einer früheren Testphase zu sein scheint, da nur wenig Daten von ULF-EM-Aktivität in der prä- und co-seismischen Phase vorhanden sind. Die Ergebnisse der neueren wissenschaftlichen Artikel sind sehr vielversprechend. Auch hier sollte sich eine dichtere und größere Flächenabdeckung mit Instrumenten vorteilhaft auswirken, weitere Verbesserungsmaßnahmen liegen in der besseren Differenzierung von Störungen. Hinsichtlich einer Wertung, wäre eine Umsetzung beider Systeme interessant und vielversprechend, denn beide Systeme haben das Potenzial sich sehr gut zu ergänzen. Eine Implementierung von beiden Systemen könnte eine Lösung für einige geoethische Probleme bieten, die ansonsten(vorrangig bei QuakeFinder) auftreten würden.

1. Introduction

Providing ample warning to local residents in an area prior to an earthquake seems like an impossible task. Earthquakes aren't predictable, or are they? Current research fields in seismology and geophysics are in the process of developing warning systems that may, given time and further critical testing, give from a few seconds to possibly a few weeks warning prior to earthquake events.

Much work has been focussed on analysing data from previous earthquake events. While this does provide a good basis for vulnerability analyses, a probabilistic hazard assessment will never be able to predict the exact timing of a future earthquake event. Few organisations also focus on analysing real-time data as soon as an earthquake happens, so that information becomes available minutes after the earthquake for emergency response. Very few organisations or research groups however, try to focus on optimizing data inputs in order to predict earthquakes before or as they happen. The goal of this thesis will be to look into current research projects in California, to see which signals can be used to monitor seismic hazards and in particular, to see which of these signals may appear as earthquake precursors and could therefore be incorporated into an effective earthquake early warning system which would allow for hazard mitigation prior to an event or at least prior to the severest ground shaking.

Furthermore, what implications will this have on geoethics? Questions such as 'When should a population be warned?', 'When should the population be given the all-clear that no further event will take place?', 'How well does the warning system need to work in order to be taken seriously by the at-risk population?' should be answered in this thesis.

After introducing the subject, motivation and goals, the second chapter will be devoted to defining Earthquake hazards, earthquake types (Chapter 2.1) and will deal with defining EWS (Early Warning Systems) in chapter 2.2. Chapter 2.3 I will focus on defining geoethics in the context of early warning systems.

Earthquakes can broadly occur along three tectonic boundary types, this is solid scientific knowledge. Earthquake hazard research has an equally long history in literature, although early warning for earthquakes still is, even after decades of research,

in its baby steps. Geoethics however, seems to be more of an emerging topic, which make sense as it only gains importance with rising efficiency of all kinds of early warning systems.

In chapter three describing the methods used, the search methods and data (scientific paper pool) found will be elaborated on and briefly assessed. Chapter four will focus on a short description of the study area.

The analysis of two of the most promising early warning research projects in California will be based mainly on the literature found, with information supporting the various projects coming from each of the projects main literature pool (as indicated on their websites). Criticism on the projects will be based both on the information gained through the analysis of these articles as well as through own thoughts and ideas. Chapter five will focus on the early warning research done by ElarmS and QuakeFinder.

The sixth chapter will assess both early warning research projects with their potential implications on geoethics, thus covering the human aspect of risk mitigation, warning and the responsibility for informing the affected population.

In the last chapter the findings of the previous chapters will be summarised in a conclusion. A re-evaluation of the methods used will also be done to see how successful the research was in producing a valuable overview of two current earthquake early warning research projects, possibilities for future implementations and possible consequences for geoethics.

1.1. Motivation

The main motivation for this thesis topic lies in the fact that there are few in depth comparative studies on possible earthquake early warning systems. Earthquakes as such are already an interesting topic and cover various fields of study ranging from seismology, geology to geography. Although the main focus of my geography degree lies in several areas of geomorphology and also in human geography, the importance of combining both areas of study with such a fascinating topic that corresponds closely with risk research in geomorphology seemed close at hand.

Furthermore a research related trip to California in 2012 was very informative and helped clarify the research interests for this thesis. Experiencing the incredible motivation of the people at NASA Ames Research Center, QuakeFinder and Stanford University in facilitating progress in this area of research was inspiring.

1.2. Goals and Research Questions

The main goal of this thesis is to successfully compare two earthquake early warning research projects in California and to analyse the possible implications that the implementation of such warning systems could have on geoethics.

Following research questions should be answered:

- **How well can the P-wave/S-wave modelling (ElarmS) be used to predict earthquakes?**
- **Can this method (as used by ElarmS) be applied to all fault types?**
- **What time-span prior to an earthquake would this method allow?**

These three questions will be answered by analysing the papers published by ElarmS directly (from www.elarms.org), as well as critically reviewing this monitoring method.

- **How well can electromagnetic- and air ion precursors be used to predict earthquakes?**
- **Can this method (as used by QuakeFinder) be applied to all fault types?**
- **What time-span prior to an earthquake would this method allow?**

These three questions will be answered by analysing the papers published by QuakeFinder directly (from www.quakefinder.com), as well as critically reviewing this monitoring method.

- **Which of these two systems would work best in a comprehensive early warning system?**

This question will be answered in chapter 5.3, where a direct comparison between both methods/organisations will be undertaken.

- **What problems concerning geoethics would be raised through these prediction methods?**
- **Is it thinkable that earthquakes will become predictable in the near future (50 years)?**

After answering the previous research questions, it may be possible to give a brief insight in what the future in earthquake early warning research may bring.

2. Background

This chapter will give in depth background information which will serve as a basis for the analysis chapter. The subchapter Earthquakes and Earthquake hazards will explain how and where earthquakes happen through several geophysical theories, as well as discussing various tectonic boundary types and ground wave types. A basic understanding of the minimum requirements for a successful warning system is equally important. Chapter 2.3 on Geoethics should then give a brief background on this recently emerging topic.

2.1. Earthquakes and Earthquake Hazards

To understand earthquakes we must first understand the processes that cause this movement of the earth's crust. In 1915 a first theory was developed by A. Wegener that went towards explaining why earthquakes might happen. In his continental drift theory, Alfred Wegener had formed the idea that the continents had once been joined together and had drifted apart over time. For example, if you were to align the South American continent with the borders of Africa, you would see that they fit together (like puzzle pieces). He enforced this idea by comparing geology, geography, biology and paleoclimatology on the continental borders. (MATHEZ and WEBSTER 2004: 84-93)

It was only in the several decades later that the continental drift theory could be confirmed through the theory of seafloor spreading. In 1960 Harry Hess suggested oceanic crust forms along submarine mountain zones and spread out laterally. This theory was easily proven with the measurement of magnetic anomalies and marine sediments. Robert Dietz, a slightly younger geophysicist also came up with a very similar theory for seafloor spreading in 1961. (KIOUS and TILLING 1996: online on 06.11.13)

It thus becomes obvious, that if the Earth's crust is drifting apart in some places, it should be pushed together in other places. The reason for this movement is that within the mantle, radioactive decay causes an immense release of heat, in turn causing the convection of magma. (MATHEZ and WEBSTER 2004: 84-93)

This movement causes the movement of plates, the subsequent build-up of stress along some plate margins, which, when released, cause earthquakes. These tectonic plate margins can be broadly split into three types, convergent, divergent and transform plate boundaries.

At convergent plate boundaries, two plates move towards each other, usually resulting in the subduction of the denser plate beneath the lighter one. Convergent plate boundaries usually mean that the part of the crust that is subducted is 'destroyed' because it heats up and melts to become magma again. There are three subcategories to convergent plate boundaries: oceanic-continental convergence, oceanic-oceanic convergence and continental-continental convergence. These are illustrated in figures 1 to 3. (KIOUS and TILLING 1996: online on 06.11.13)

Figure 1 shows an oceanic-continental convergence zone. Here, the oceanic plate is subducted underneath the continental plate as it is much denser and heavier. The continental plate is then lifted creating a mountain range due to the lateral pressure of the subducting plate. This type of convergent boundary can cause large earthquakes usually originating from the subduction trench. (KIOUS and TILLING 1996: online on 06.11.13)

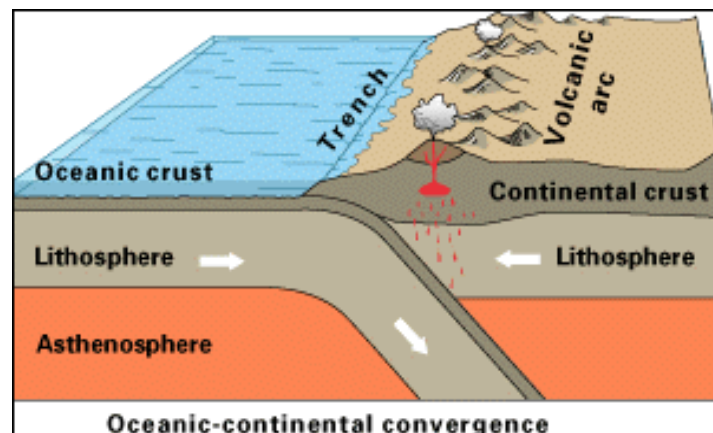


Figure 1: oceanic-continental convergence (Source: KIOUS and TILLING 1996: online on 06.11.13)

At the convergence zone of two oceanic plates (Figure 2), the heavier/denser one is usually subducted under the lighter/less dense oceanic plate, forming a deep ocean trench. At such convergence zones, volcanoes are frequently formed. Earthquakes tend to be less intense than at other convergent or transform boundaries. (KIOUS and TILLING 1996: online on 06.11.13)

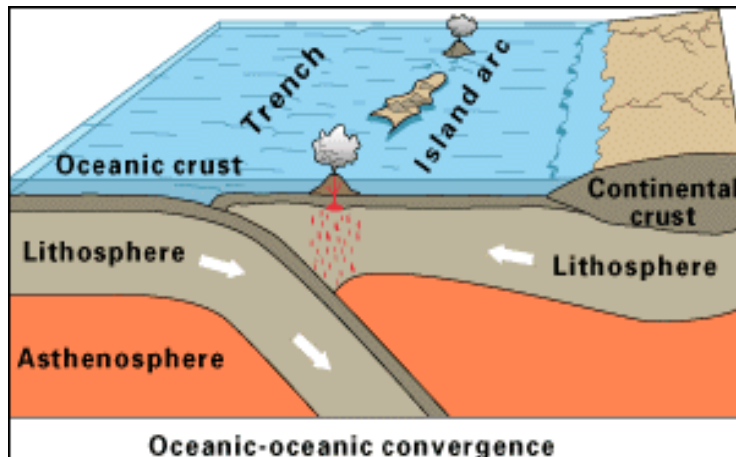


Figure 2: oceanic-oceanic convergence (Source: KIOUS and TILLING 1996: online on 06.11.13)

Figure 3 shows a plate boundary where two continental plates are moving toward each other. At the convergence zone of two continental plates it is less likely for subduction to occur as both plates are relatively light and tend to buckle into each other forming large mountain ranges. As the plates continue moving toward each other, the mountain range can continue to grow taller. Earthquakes are frequent at such plate boundaries. (KIOUS and TILLING 1996: online on 06.11.13)

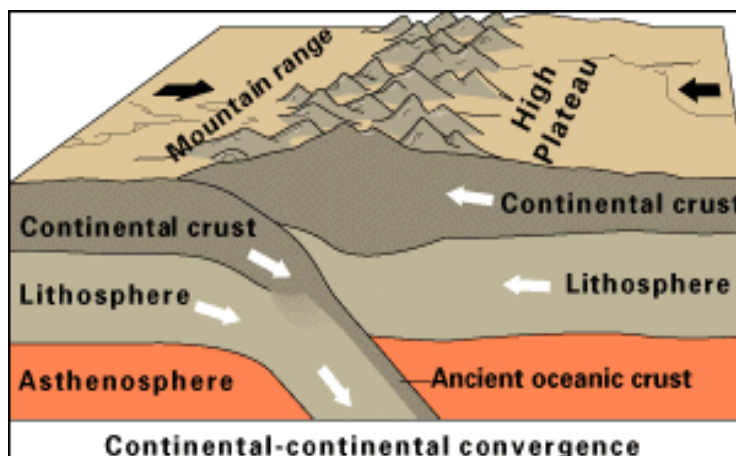


Figure 3: continental-continental convergence (Source: KIOUS and TILLING 1996: online on 06.11.13)

At divergent plate boundaries, the plates move away from each, creating a space in between in which magma rises and forms a new crust. Such divergence can occur on continental and on oceanic plate. On a continental plate, such a divergence will eventually create a rift, over time even a new sea can form between the divergent plate masses. (KIOUS and TILLING 1996: online on 06.11.13)

Figure 4 shows this process well:

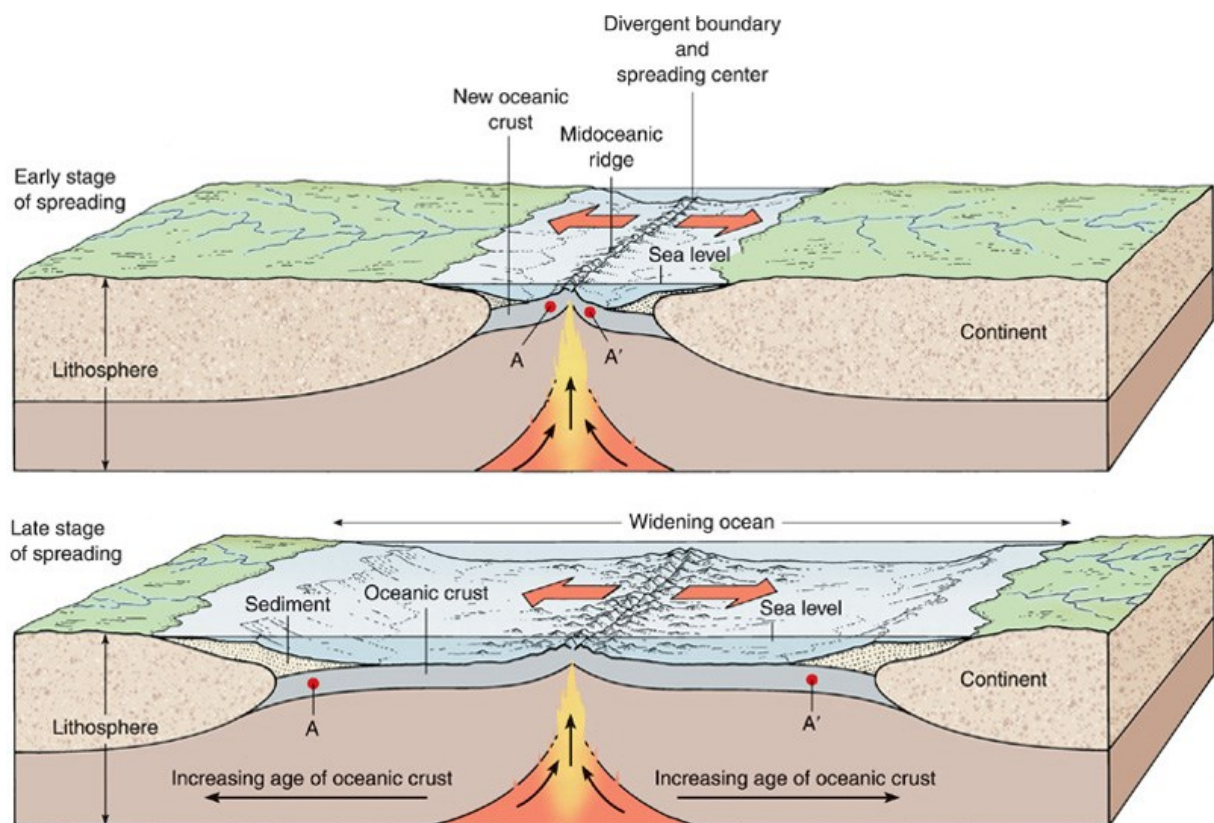


Figure 4: divergent plate boundaries (Source: LEVIN 2010: 190)

We can see in figure 4 how, as magma starts rising from the earth's core, the mid-oceanic ridge starts to lift and spread apart. This is the divergent boundary. As magma continues to rise up and form new oceanic crust, the seafloor starts to spread apart, widening the ocean.

At transform plate boundaries the plates slide past each other either in opposite directions or at different speeds. Due to these movements and the friction along the plate margin, there is a build-up of stress (also due to the formation of transcurrent faults) until the rocks slip and the pressure is released in a (usually) shallow earthquake. Such plate margins can also be called faults. (KIOUS and TILLING 1996: online on 06.11.13; BRYANT 2005: 185)

The most well-known fault is the San Andreas Fault in California, shown in figure 5 where the movement at transform plate boundaries is shown:



Figure 5: Transform plate boundaries (Source: KIOUS and TILLING 1996: online on 06.11.13)

There are 5 specific types of faults or transform plate boundaries associated with strong earthquake activity. These can be seen in the figure below:

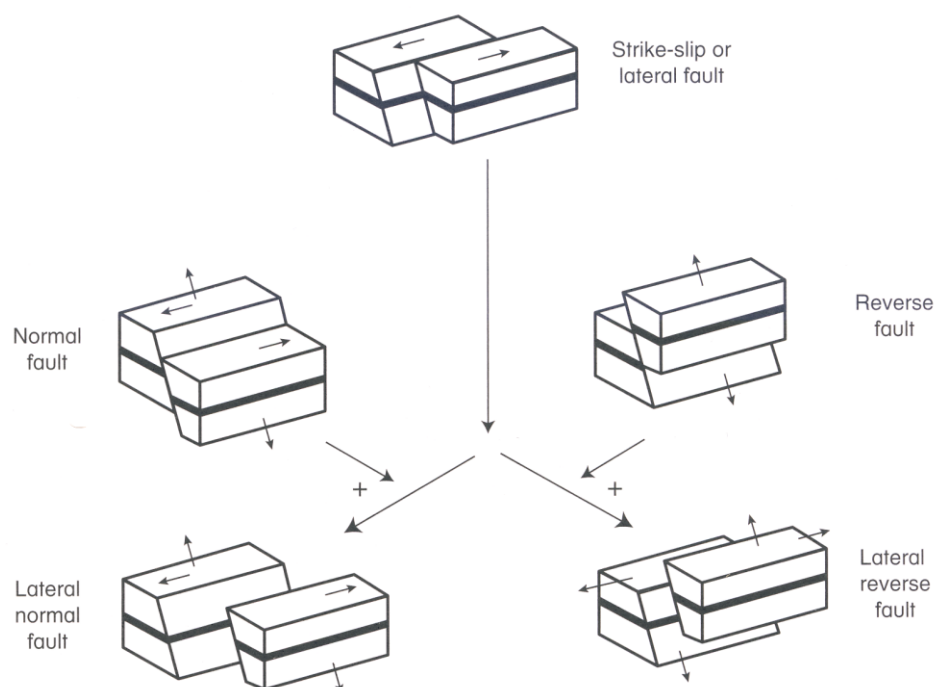


Figure 6: Fault types associated with earthquakes (Source: BRYANT 2005: 188)

Strike-slip or lateral faults usually show only lateral movement processes, whereas normal or reverse faults show mainly vertical movement. Lateral normal and lateral reverse faults move both laterally and vertically. The extent of damage or influence depends much more however, on the angle of the fault zones: the shallower the angle of the fault zone, the more extensive the area of shaking will be. (BRYANT 2005: 188)

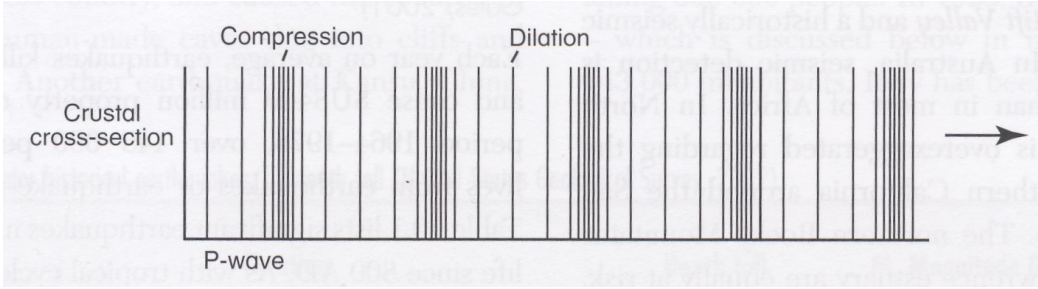
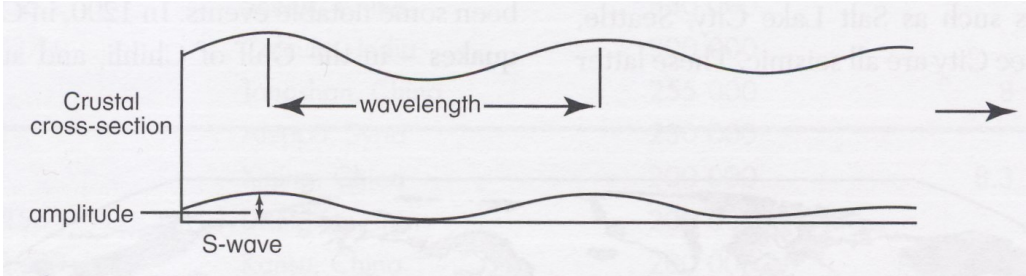
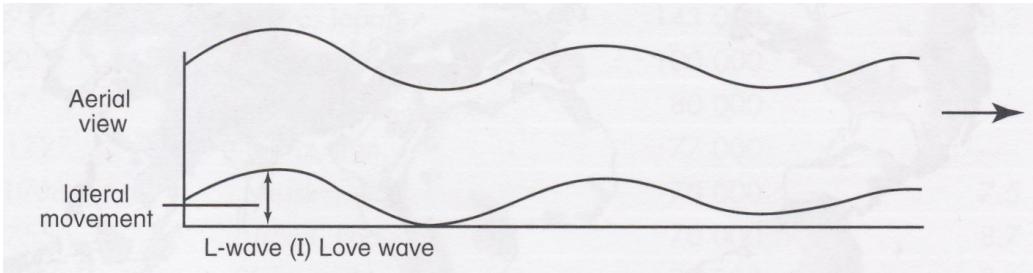
Earthquakes can also be grouped by the depth in which they occur. BRYANT (2005: 183) defines two groups – shallow and deep, whereby *'about 75% of earthquake energy is released in the upper 60km of the crust along plate boundaries. These are termed shallow-focus events compared to earthquakes that occur up to 700km below the crust beneath subduction zones'*.

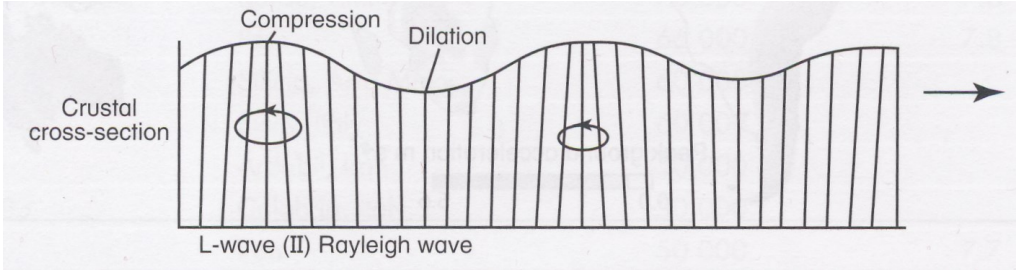
It should however, also be mentioned that not all earthquakes occur around plate margins. There have been a few earthquakes with intra-plate origin, for example the 1556 earthquake near Shensi, China (BRYANT 2005: 182). Even a probabilistic hazards assessment must be difficult for such 'freak' earthquakes.

In this next section, all hazards associated with earthquakes will be explained. First of all, *'Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth.'* (U.S. Geological Survey (ed.) N.D.a: online on 21.10.13).

Prior to an earthquake it is possible for pre-shocks to occur. These are usually smaller than the main earthquake event, but can only be defined as such after the main earthquake event has happened. Similarly, after a main earthquake event, smaller aftershocks can frequently occur, these are most frequently smaller in size than the main event. Pre-shocks, earthquakes and aftershocks happen in the same way due to the same physical mechanisms. When stress is released at a fault zone, energy is also released in form of heat and movement. From the epicenter of the quake, waves of motion begin to emanate. These can be classified in 4 types: the two most well-known are P- and S-waves, there are also two L-waves that transfer the energy from the epicenter, they are called Love waves and Rayleigh waves. (BRYANT 2005: 202)

Table 1: Description of seismic wave types (data basis: BRYANT 2005: 202-203; own visualisation)

Wave Type	Description and Visualisation
P-Wave	P-waves are characterized by the compression and dilation they form in the ground as they are longitudinal waves. They can pass through all material phases and can be refracted at solid/liquid boundaries. 
S-Wave	S-Waves are shear waves and propagate (about 0.6 times) slower than P-waves, the speed depends much on the geology. These are the most damaging waves when an earthquake occurs as the ground is physically displaced the most through both the horizontal and the vertical shaking. 
Love Waves	Love Waves are a type of L- (Long-) Wave that spread slowly between the Earth's surface and the lower crustal layers. The Love-Wave <i>'literally slithers back and forth through the crust'</i> and is equally responsible as the S-wave for severe damages to infrastructure and houses. 

Rayleigh Waves	Rayleigh Waves (also a type of L-Wave) behave somewhat like ocean waves. Both types of L-Waves (Rayleigh and Love waves) travel much slower than the P- and S-Waves. 
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There are however other processes or hazards related to or a direct consequence of earthquakes, these could be considered ‘secondary earthquake hazards’. Some of the most well-known are processes of mass movement, fires, flooding and tsunamis. A further process that should be briefly explained that can also occur during earthquakes is liquefaction. Table 2 lists and explains these hazards:

Table 2: Secondary Earthquake Hazards

Earthquake Hazards	Description and Explanation
Mass movement processes	Earthquakes can set off many mass movement processes through the sudden release of energy. This can include almost all kinds of mass movement processes including falls, slides and flows.
Liquefaction	Liquefaction is a process whereby the kinetic energy from the earthquake can cause (mainly clay-free) sands and silts to ‘liquefy’, in turn causing supporting structures to become unstable and sink. This has much to do with how the compressional waves affect or increase the pore water pressure in the ground. (BRYANT 2005: 202)
Fires	Particularly in populated areas, Earthquakes can set off fires usually due to disruptions in electric circuits (power lines), damage to industrial machinery, gas/oil pipelines or storage tanks and similar infrastructures. Due to damage in water pipelines, such a fire induced by ground shaking may end up being more hazardous than one might think. (Michigan

	Technological University (ed.) 2007a: online on 24.10.13)
Flooding	Flooding can also occur as a direct consequence of an earthquake, for example when liquefaction occurs, when dams, reservoirs or levees are damaged through ground shaking (Michigan Technological University (ed.) 2007a: online on 24.10.13). Seiches can also occur on closed bodies of water and can be described as standing waves that oscillate in response to a disturbing force (University of California (ed.) 2006: online on 24.10.13).
Tsunamis	<i>‘Tsunami [...] are water wave phenomena generated by the shock waves associated with seismic activity, explosive volcanism or submarine landslides. These shock waves can be transmitted through oceans, lakes or reservoirs’</i> (BRYANT 2005: 214).

We can now understand that there are many equally potentially hazardous events that can be set off by an earthquake. The next question that needs to be answered in this chapter is how earthquakes can be measured.

There are two well-known scales of measuring earthquake magnitude or intensity. The Richter scale focuses on the amplitude of the largest seismic wave recorded during an earthquake event, thus, on the surface magnitude of an earthquake. The scale goes from 1 to 10 and is logarithmic, meaning that with the increase of the magnitude by 1, the intensity of ground motion multiplies by about ten and the energy released by about 32. A major setback of the Richter scale for earthquake magnitude is that it requires instruments to be able to measure and then calculate the size of the earthquake. (Michigan Technological University (ed.) 2007b: online on 26.10.13; BRYANT 2005: 180)

The Mercalli Scale on the other hand relies on a qualitative assessment of the size of an earthquake. The assessment of size can be made through a description of the extent of detection (how strongly it is felt by humans) and the extent of damage (from small objects rattling to total destruction). For accurate results, descriptions of damage or detection should be collected as close to the epicenter of the quake as possible. Table 3 illustrates all intensities on the Mercalli scale, including a reference to the corresponding Richter scale: (BRYANT 2005: 180)

Table 3: The Mercalli Scale of Earthquake intensity. (Source: BRYANT 2005: 181)

Scale	Intensity	Description of effect	Maximum Acceleration (mm s²)	Corresponding Richter scale
I	Instrumental	Detected only on seismographs	<10	
II	Feeble	Some people feel it	<25	
III	Slight	Felt by people resting; like a large truck rumbling by	<50	<4.2
IV	Moderate	Felt by people walking; loose objects rattle on shelves	<100	
V	Slightly Strong	Sleepers awake; church bells ring	<250	<4.8
VI	Strong	Trees sway; suspended objects swing; objects fall off shelves	<500	<5.4
VII	Very Strong	Mild alarm; walls crack; plaster falls	<1000	<6.1
VIII	Destructive	Moving cars uncontrollable; chimneys fall and masonry fractures	<2500	
IX	Ruinous	Some houses collapse; ground cracks; pipes break open	<5000	<6.9
X	Disastrous	Ground cracks profusely; many buildings destroyed; liquefaction and landslides widespread	<7500	<7.3
XI	Very Disastrous	Most buildings and bridges collapse; roads, railways, pipes and cables destroyed; general triggering of other hazards	<9800	<8.1
XII	Catastrophic	Total destruction: trees driven from ground; ground rises and falls in waves	>9800	>8.1

2.2. Early Warning Systems (EWS)

An early warning system is complex and consists of several components. The UN, in their 2006 global survey of early warning systems defines the following components (or steps) as being vital to an early warning system (UN (ed.) 2006: v):

- Knowledge of the risks faced.
- Technical monitoring and warning service.
- Dissemination of meaningful warnings to those at risk.
- Public awareness and preparedness to act.

Concerning Earthquakes the knowledge of the risks faced is not an issue. People in earthquake prone areas tend to have a heightened knowledge about how to act during an earthquake in order to minimize risk of injury or death. Equally, the scientific community has profound knowledge of all the risks associated with earthquakes.

Technical monitoring is equally in place in all regions of the earth in the form of seismometers. However, the large range of associated phenomena prior to and during earthquakes is so large that a complete monitoring of all possible parameters is unthinkable. Equally, warning services are rare and rarely successful as earthquakes are relatively unpredictable. Due to this fact, step 3 in the early warning system falls short when dealing with earthquakes. Dissemination of meaningful warnings is rarely possible, accounts of successful warning are few, one example being 1975 Haicheng earthquake were USGS reported:

'Chinese officials ordered the evacuation of Haicheng (population about 1 million) the day before the earthquake. In the preceding months, changes in land elevation and in ground water levels, and widespread reports of peculiar animal behavior had been reported. The increase in foreshock activity triggered the evacuation warning.' (U.S. Geological Survey (ed.) N.D.b: online on 26.10.13)

It thus seems that dissemination of meaningful warnings to those at risk is more a chance of luck at predicting an event correctly, rather than something that can be built upon as a reliable component of an earthquake EWS. Equally then, public awareness in the past decades has been negatively influenced by media and earth-

quake prediction hoaxes. Similarly, the focus in the scientific community lies less on being able to forecast future events and rather more on probabilistic hazard assessments. BRYANT (2005: 195-196) however suggests a multitude of starting points for technical monitoring projects that could lead to worthwhile predictions, warning services and potentially successful earthquake EWS. He mentions following earthquake associated phenomena:

Land deformation – Land deformation can help to predict earthquakes which may occur in a few hours up to a few months. The strain energy in the earth builds up with time due to tectonic activity, causing lateral and/or vertical distortions at the Earth's surface. By surveying the land using benchmarking or triangulation, or by using tiltmeters and strain gauges, these movements can be tracked and measured. Points showing rapid changes in earth movement along faults may be signals for future earthquake events. Steadily increasing strain measurements may signal an event within the following months, whereby a rapid increase in tilting may signal an earthquake in as little as a few hours. (BRYANT 2005: 195)

Seismic activity – According to BRYANT (2005: 195) foreshocks and microseism can also be considered as forewarnings to an impending earthquake. These can occur a few hours up to a few days before the main earthquake event, or may decrease or even cease to occur prior to an earthquake event.

Geo-magnetic and geo-electric activity – Unexplained changes in geomagnetic activity could also be used as an indicator for impending earthquakes, in some cases these can be measured years in advance of an earthquake. Similarly, changes can also be noted in the geo-electric activity of a region through a decrease in resistivity up to a few months prior to an earthquake or a stepped increase in resistivity a few hours prior to an earthquake. (BRYANT 2005: 196)

Ground water – Similarly, it has been noticed that the ground water level in some regions may change between half a day and 10 days prior to an earthquake event with a magnitude of 5 or above on the Richter scale. (BRYANT 2005: 195)

Natural phenomena – alongside the above mentioned, there are several other phenomena that can be linked with earthquake activity. The most controversial of these

phenomena is probably how animals have been seen to react prior to a large earthquake. Examples of such phenomena are (BRYANT 2005: 196):

- Catfish, particularly calmer species, have been known to become restless and very active, even to jump out of water, prior to earthquakes.
- Ground animals have been noticed to leave their tunnels prior to earthquakes, where it can be assumed that they would not have survived the earthquake.
- Other stabled animals or dogs can equally become restless prior to earthquakes.

The problem with these natural phenomena is that the precise cause of the reaction of the animals is unknown. There are however scientists that presume the cause of reaction may be changes in electromagnetism, release or changes in electrostatic particles at the earth's surface or ultrasound.

There is also one main problem with most of these earthquake related phenomena, namely that each earthquake is different, resulting in an extremely difficult task of finding and setting thresholds for each of these possible accompanying phenomena and for when an alarm could be given to the potentially at-risk population. What makes matters worse in terms of earthquake prediction is that earthquakes tend to cluster both in space and in time. For most large earthquakes, there tends to be spatial cluster of (usually smaller) earthquakes either as direct pre-shocks usually days in advance or aftershocks for up to many years after the 'main' earthquake event. (BRYANT 2005: 197)

The main focus of this coursework is thus set in looking at projects that try to overcome exactly these problems in the ‘technical monitoring and warning service’. The UN Global Survey of Early Warning Systems refines the tasks for each of the four components of a people-centered early warning system, as can be seen in Figure 7. The questions set in the UN Survey in the section ‘monitoring and warning service’ thus correspond to the core questions of this thesis.

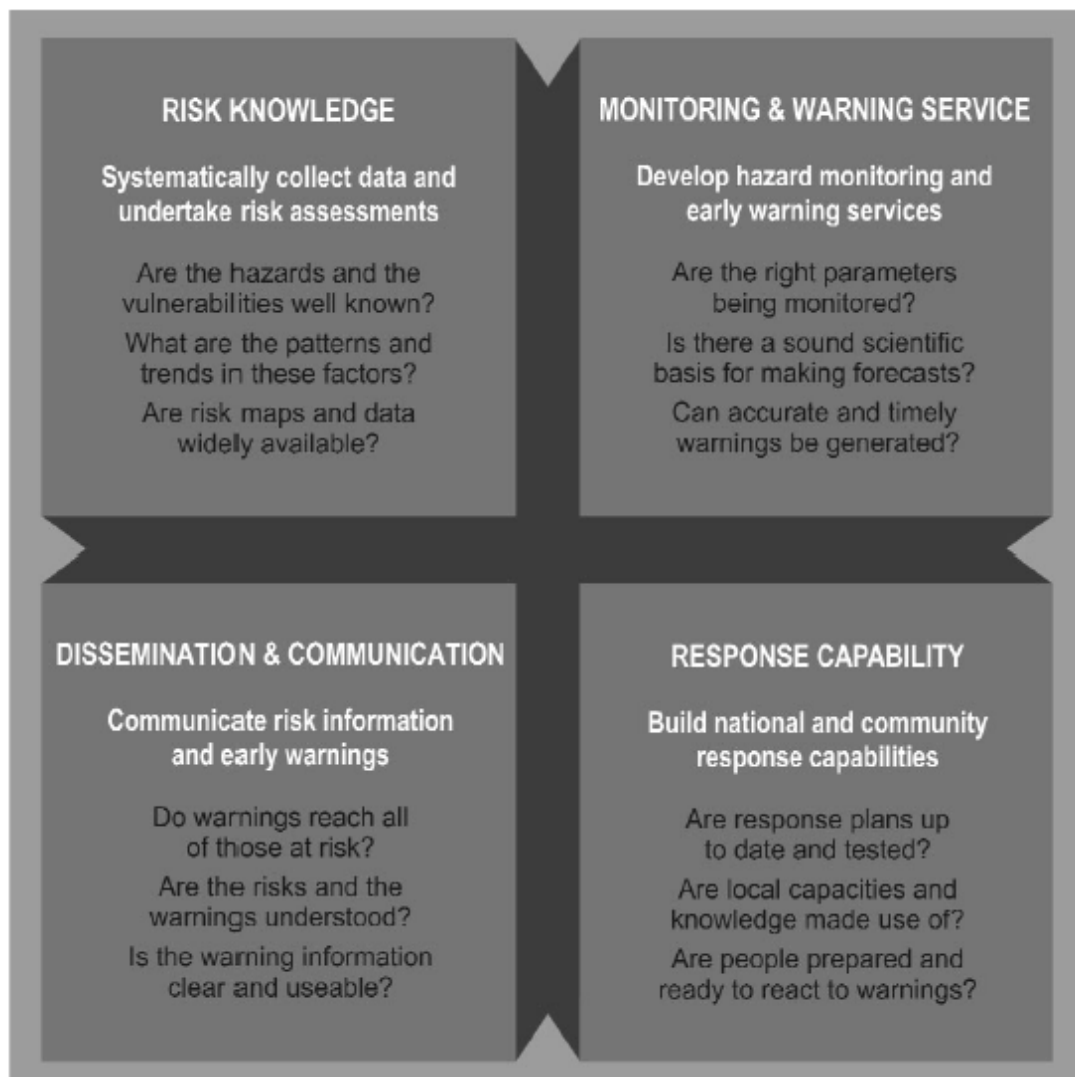


Figure 7: The four fundamental components of people-centered Early Warning Systems (Source: UN (ed.) 2006: online on 28.10.2013)

2.3 Geoethics

Geoethics is a recently emerging topic in earthquake hazards, particularly since the L'Aquila (Italy) earthquake in April 2009 where scientists were made responsible for the failed warning that the recorded shocks represented the main earthquake rather than being foreshocks for a larger event. This topic, the politics involved and trial case was also discussed in depth during the oral presentations on 'Geoethics and natural hazards: the role and responsibility of the geoscientists' at the EGU (European Geoscience Union) 2013.

The International Association for Promoting Geoethics (IAPG) defines geoethics as follows (IAPG (ed.) N.D.: online on 26.10.13):

- *'Geoethics consists of the research and reflection on those values upon which to base appropriate behaviours and practices where human activities intersect the Geosphere.'*
- *Geoethics deals with the ethical, social and cultural implications of geological research and practice, providing a point of intersection for Geosciences, Sociology and Philosophy.*
- *Geoethics represents an opportunity for Geoscientists to become more conscious of their social role and responsibilities in conducting their activity.*
- *Geoethics is a tool to influence the awareness of society regarding problems related to geo-resources and geo-environment.'*

Geoethics in the context of earthquake early warning focusses on the interaction platform between the scientific community and at-risk community. Applying geoethics, scientists should not focus entirely on the scientific and technical aspect of their research, but go a step further as to offer guidance in the translation of information to the politically level and socially relevant media.

In short, geoethics is concerned with responsibility in risk management and where possible, in the mitigation of geohazards at the science/politics/media interface.

3. Methods

In this chapter, the search methods will be outlined in order to guarantee their objectivity. First of all, a fair method for gathering information had to be found. For answering the research questions, following options were found:

- Conducting expert interviews – due to time constraints and availability during the 2012 California visit, this method for gathering information was not further considered.
- Analysing data outputs – would have been an option for directly comparing the success of both research organisations, but would have equally required a much deeper knowledge of geophysical processes more associated with an academic study of said topic.
- Conducting a literature analysis – seemed the most viable option for gathering all the required data as well as building a deeper understanding for seismology and geophysics as scientific papers should in theory be understandable to interdisciplinary peer groups. It furthermore allows a continued focus on geoethics which would not have been possible otherwise.

For the primary literature pool it was important to represent both systems/research projects equally. For comparing the systems and including critical reviews, a different literature pool might have to be drawn upon and finally, for the chapter on geoethics, a different approach would definitely be needed as the requirements for the information needed in this chapter are entirely different.

The two projects/organisations QuakeFinder and ElarmS were chosen specifically, firstly because they represent competitive but potentially complementary earthquake early warning systems, secondly because both projects actively receive funding to push forward in science and optimise processes and techniques. Furthermore, both projects are based in California, where the North American and Pacific plates meet and form one of the most seismic active fault regions in the world. More detail on the study area and why it was chosen will be given in the following chapter.

ElarmS was chosen specifically as it is part of the USGS funded research network CISEN (California Integrated Seismic Network). It represents one of three algorithms

that were put to the test in the initial phase of the CISN project. The reason ElarmS was chosen over the On-site or Virtual Seismologist real-time environment was that ElarmS has much support from Berkeley University, with Richard Allen being probably the most well-known contributor to the project as well as being the director of Berkeley's seismological laboratory. It can thus be said, that the research taking place in the ElarmS project can definitely be considered state of the art. Virtual Seismologist was not considered as the research group is based in Switzerland and very little information could be found online to the On-site environment of the CISN project. (CISN (ed.) N.D.a: online on 31.10.13)

QuakeFinder was chosen specifically as a strongly contrasting research organisation with a strong focus on complex geophysical phenomena rather than seismology. This project equally receives funding from the parent company Stellar Solutions as well as research grants from NASA. Furthermore, QuakeFinder also cooperates with Stanford University, for example with Emeritus Professor Anthony Fraser-Smith, a leading researcher in electrical engineering and geophysics. It can therefore equally be confirmed, that this is a state of the art research organisation.

3.1 Literature (primary pool)

For the representation of what both research projects/organisations - ElarmS and QuakeFinder try to achieve in terms of early warning it seemed appropriate to take the information made available by each of the corresponding websites (www.elarms.org and www.quakefinder.com) as a primary literature pool.

To counter any critique this may provoke, both websites provide a large base of scientific literature in the form of scientific papers which have also been published in various renowned journals (e.g. *Natural Hazards and Earth System Sciences*, *Annals in Geophysics*, *Journal of Geophysical Research*, *Geophysical Research Letters*, *Nature*).

Furthermore, both ElarmS and QuakeFinder should be represented equally in the number of papers chosen for the analysis. After an initial listing of papers published directly by research group members, ElarmS had a total of 16 papers whereas QuakeFinder only had 11.

In the next step, any papers concerning other study areas or previous projects were excluded. This left ElarmS with a total of 15 and QuakeFinder with a total of 11 scientific papers.

The article excluded from ElarmS covers the possible implementation of such an early warning system in Italy and therefore specifically covers another study area which this thesis is not focusing on.

Furthermore, the QuakeFinder website offers a section on 'Papers by Others' with a list of over 50 further articles largely relevant to the research. In order to narrow these articles down (another 4 articles would be appropriate to balance the scales) only articles published from 2005 onwards were considered in order to guarantee state of the art research. Out of these more recent articles, 6 were underlined on the webpage, signifying that they may be particularly relevant.

From these 6, two articles can easily be excluded. The first article excluded is from the Prediction science section as it does not cover QuakeFinder's methods in a relevant way and the article on Infra-red and Heat Emission was excluded as it concerns data from Greece and Turkey only, thus leaving the remaining four scientific papers to be added to the QuakeFinder primary literature pool, balancing the representation of both organisations entirely with 15 articles to be analysed for ElarmS and 15 to be analysed for QuakeFinder.

3.2 Options for Comparison

For comparing the two projects, the focus will lie on comparing the following parameters:

- The methods used to gather data and configure the early warning system
- How well the data can be used to predict future earthquakes (including if there are gaps in the data)
- How successful the early warning system is in terms of correct warnings

- The potential for incorporation into a comprehensive warning system including information dissemination and response capability (including the potential time span where a warning could be given to the potentially affected population)

In order to compare the two organisations, the previously analysed articles from the primary literature pool should suffice in providing enough information for a good comparison. Comparing the two systems is seen as important as they both have their pros and cons and this comparison will help for the analysis in chapter 6 focusing on geoethics.

3.3 Geoethics

For the analysis chapter on implications for geoethics a search for scientific papers on www.Scopus.com will be conducted. This platform was chosen as it contains one of the largest pools of scientific papers and allows for an easy search through the entire database of articles.

The first search conducted on Scopus (www.scopus.com) was using the term 'geoethics', searching in all fields. This search came up with 34 results. In order to compare various search terms, the search was again conducted using the terms 'geoethics' AND 'Earthquake' in all fields, but the search engine returned only two results.

For this reason, only the search term 'geoethics' was used. The 34 results this search returned, the articles were mainly from the Journal the Annals of Geophysics. A complete list of journals can be seen in Table 4:

Table 4: Search results for 'geoethics' from www.scopus.com (own visualisation)

Journal	Number of possibly relevant articles
Annals of Geophysics	10
Episodes	3
Evidence-based Climate Science	2
Energy and Environment	2

Xenotransplantation	2
Revista de obras Publicas	1
Methods in Molecular Biology	1
Annales de Geographie	1
Global and Planetary Change	1
Espace Geographique	1
Journal of Coastal Research	1
City and Society	1
Muslim World Journal of Human Rights	1
Bollettino della Societa Geologica Italiana	1
American Ethnologist	1
Mortality	1
Research Strategies	1
Annals of the Association of American Geographers	1
Worldviews: Environment, Culture, Religion	1
Unknown journal	1

This search shows that the most relevant articles are from the Annals of Geophysics, surprisingly all from Volume 55, no. 3. As many other articles relate more to social sciences and even medicine, the focus will remain entirely on the Annals of Geophysics, Vol. 55, no. 3.

As not all of the relevant articles from the Annals of Geophysics from the Scopus search for 'geoethics' are available for the full PDF-download on scopus.com, the 10 articles will be downloaded (in full) from the Annals of Geophysics homepage.

Only the relevant articles focussing on geohazards will be analysed in the chapter on geoethics. Furthermore, any useful information from the previous sets of articles may be used in order be able to fully apply all acquired knowledge.

4. Study Area

In a first step of the selection process for the study area, we will take a look at the Ring of Fire and the Global Seismic Hazard Map in order to explain which areas may be more or less suitable for conducting such research, before describing the final study area: California.

4.1. Ring of Fire

Obviously the most promising sites/locations of projects for earthquake research are around earthquake-prone areas (where instruments can be placed and constantly monitored, where the need for early warning is greatest). The more intense and frequent the earthquakes tend to be, the better it is for researching and testing instruments and or theories. Earthquake-prone areas, as has been established in a previous chapter, tend to lie along tectonic plate boundaries. The most active area, commonly known as the 'Ring of Fire' can be seen in the diagram below:

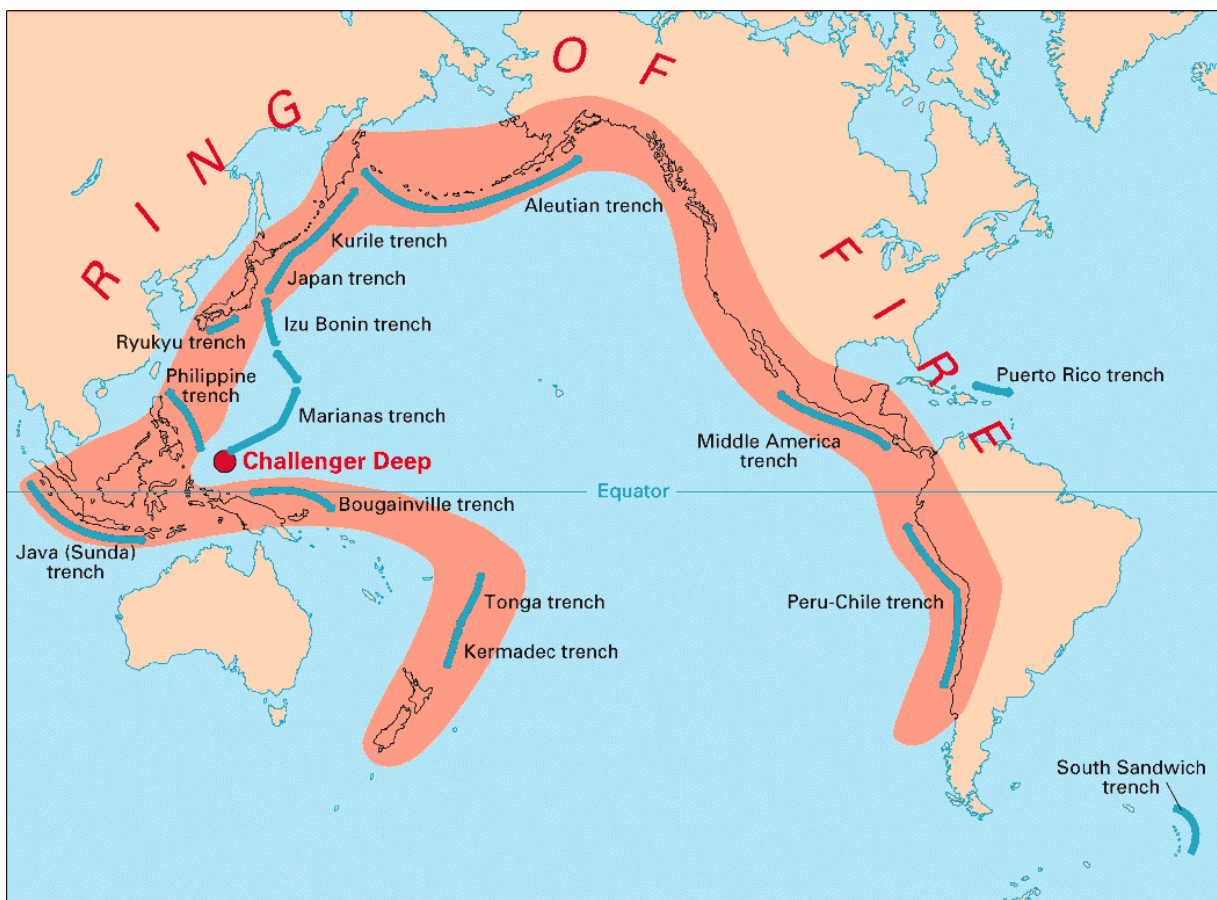
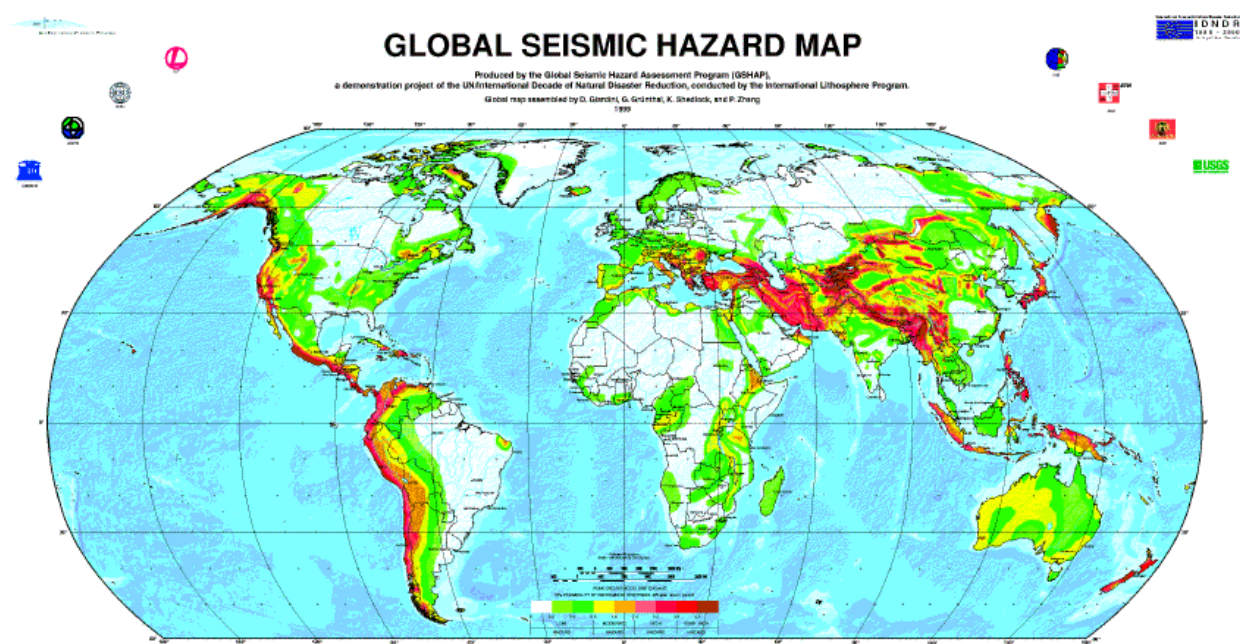


Figure 8: the Ring of Fire (Source: U.S. Geological Survey (ed.) N.D.c: online on 02.11.13)

As a comparison of all possible early warning research projects would have burst the frame of a master thesis, it seemed logical to focus on one area within the ring of fire.

The focus was thus set to research projects in California because this region is one of the most potentially hazardous zones in the world for earthquakes (Bryant 2005: 207). This can be seen on the Global Seismic Hazard Map (provided by the GSHAP – Fig. 9). The most hazardous areas (the darkest shades of red) in the GSHAP-map tend to be in Asia, New Zealand and along almost the entire west coast of the Americas.



This map shows the relative intensity of ground shaking and damage in California from anticipated future earthquakes. Although the greatest hazard is in the areas of highest intensity as shown on the map, no region within the state is immune from potential for earthquake damage. Expected damages in California in the next 10 years exceed \$30 billion.

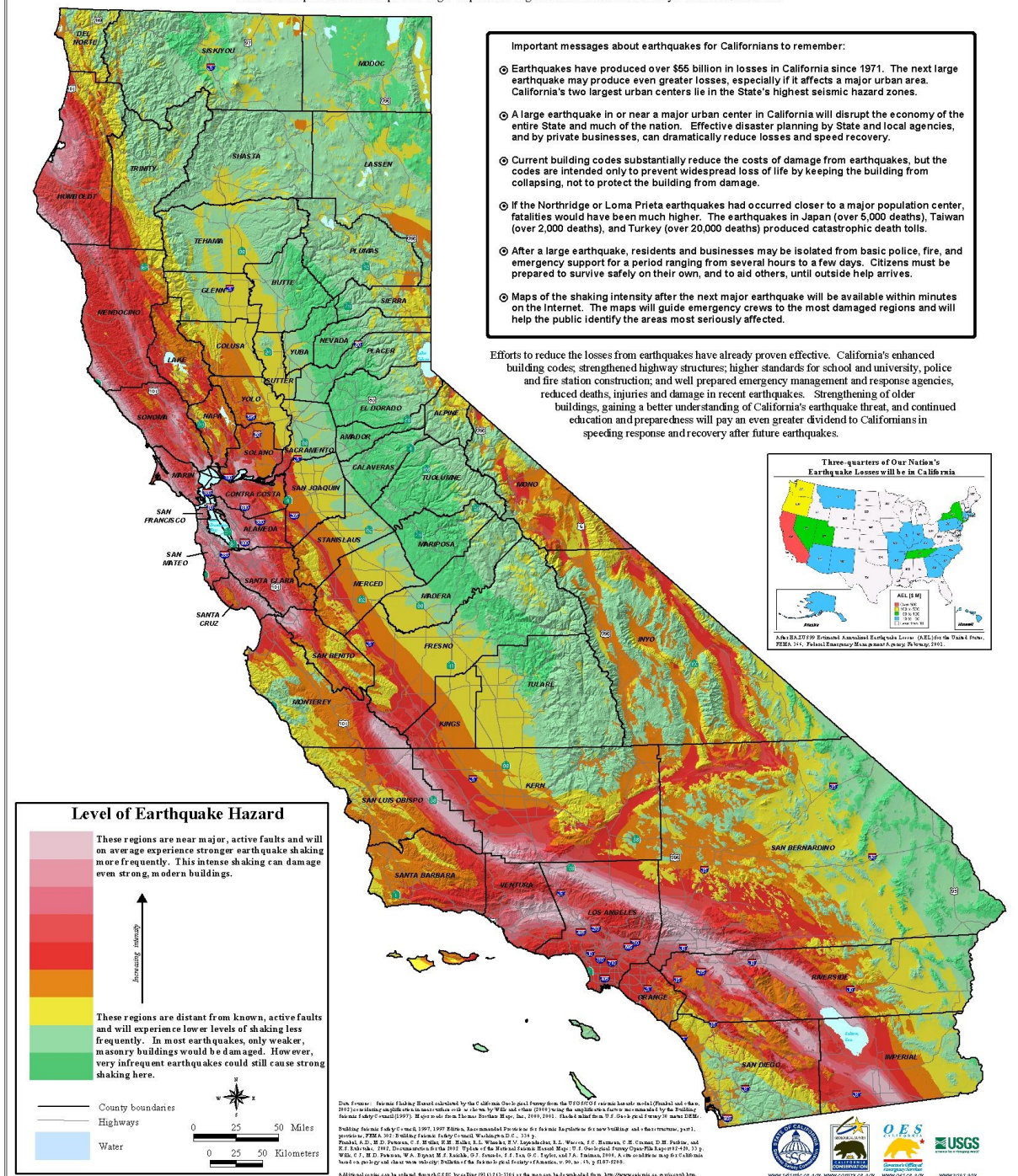


Figure 10: Earthquake shaking potential in California (Source: California Geological Survey (ed.) 2003: online on 02.11.13)

The Earthquake shaking potential map shows that along almost the entire Californian coastline the level of earthquake hazards is very high. All regions marked red or white will experience severe shaking more frequently as several faults run straight through these areas.

Figure 11 shows the major and active Faults in California:

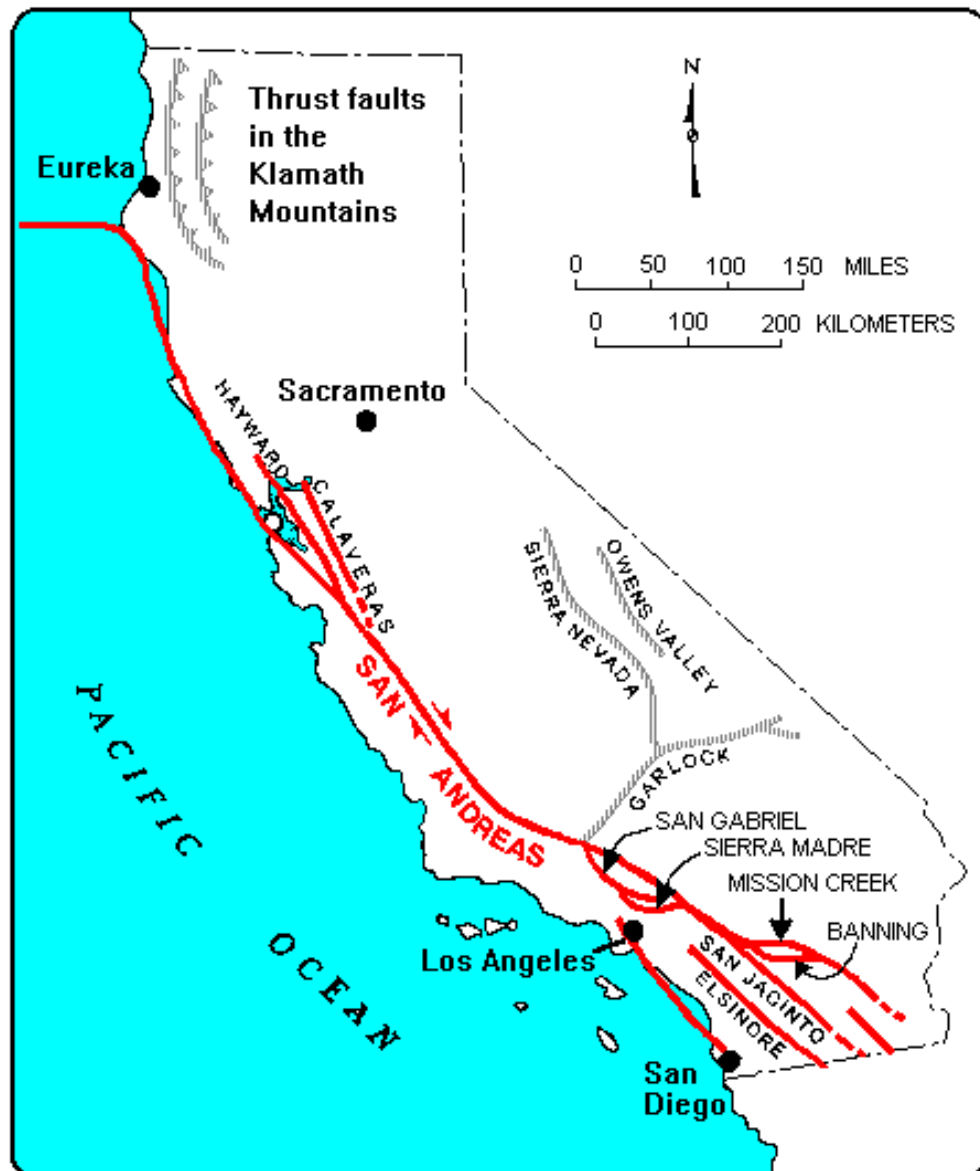


Figure 11: Major Faults in California (Source: Department of natural Resources, State of Louisiana (ed.) N.D.: online on 02.11.13)

As can be seen in Figure 11, California is riddled with several faults, which lie directly underneath large cities, stressing the importance of an effective EWS. The most well-known fault is the San Andreas Fault, but there are several smaller faults in this region such as the Hayward Fault, The Rodgers Creek Fault, the Calaveras Fault, the Elsinore Fault and the San Jacinto Fault.

5. Analysis

In order to start the analysis of the two research projects, it is necessary to first list the results from the search. Table 5 shows the first results from the primary literature pool search:

Table 5: Articles found on ElarmS and QuakeFinder website published by workgroup members. (Data basis: ALLEN, R. (N.D.b.): online on 08.11.13; QuakeFinder (ed.) N.D.a: online on 08.11.13; own visualisation)

No. of articles	ElarmS	Quakefinder
1	Allen, R.M. (2008) At First Jolt: Will we have warnings for the next big earthquake? <i>Geotimes</i> , 53 (10), p52-59	The Pulse Azimuth effect as seen in induction coil magnetometers located in California and Peru 2007–2010, and its possible association with earthquakes Nat. Hazards Earth Syst. Sci., 11, 1–21, 2011 www.nat-hazards-earth-syst-sci.net/11/1/2011/ doi:10.5194/nhess-11-1-2011 By: J. C. Dunson , T. E. Bleier , S. Roth , J. Heraud , C. H. Alvarez , and A. Lira
2	Shieh, J.T., Y.M. Wu, R.M. Allen (2008) A comparison of tau-c and tau-p-max for magnitude estimation in earthquake early warning <i>Geophys. Res. Lett.</i> , 35 , L20301, doi:10.1029/2008GL035611	Correlation of pre-earthquake electromagnetic signals with laboratory and field rock experiments Nat. Hazards Earth Syst. Sci., 10, 1965–1975, 2010 www.nat-hazards-earth-syst-sci.net/10/1965/2010/ By: T. Bleier, C. Dunson, C. Alvarez, F. Freund, and R. Dahlgren
3	Olivieri, M., R.M. Allen and G. Wurman (2008) The potential for Earthquake Early Warning in Italy using ElarmS, <i>Bull. seism. Soc. Am.</i> 98 , p495-503, doi: 10.1785/0120070054	Estimating the seismotelluric current required for observable electromagnetic ground signals. Ann. Geophys., 28, 1615-1624, 2010 /28/1615/2010/ doi:10.5194/angeo-28-1615-2010 By: J. Bortnik , T. E. Bleier , C. Dunson , and F. Freund
4	Allen, R.M. (2007) Earthquake hazard mitigation: New directions and opportunities, In " <i>Treatise on Geophysics</i> ", G. Schubert (ed.), Vol 4 (H. Kanamori ed.), p607-648, Elsevier.	Investigation of ULF magnetic pulsations, air conductivity changes, and infra red signatures associated with the 30 October Alum Rock M5.4 earthquake. Nat. Hazards Earth Syst. Sci., 9, 585-603, 2009 By: T. Bleier , C. Dunson , M. Maniscalco , N. Bryant , R. Bamberg , and F. Freund. (2009)
5	Tsang, L., R.M. Allen and G. Wurman (2007) Magnitude scaling relations from P-waves in southern California, <i>Geophys. Res. Lett.</i> 34 L19304, doi:10.1029/2007GL031077	The possible statistical relation of Pc1 pulsations to Earthquake, occurrence at low latitudes. By: Bortnik, J., J. W. Cutler, C. Dunson, and T. E. Bleier (2008),
6	Wurman, G., R.M. Allen and P. Lombard (2007) Toward Earthquake Early Warning in Northern Califor-	Characteristics of low-latitude Pc1 pulsations during geomagnetic storms J. Geophys. Res., 113, A04201,

	nia, <i>J. Geophys. Res.</i> 112 , B08311, doi:10.1029/2006JB004830	doi:10.1029/2007JA012867. By: Bortnik, J., J. W. Cutler, C. Dunson, T. E. Bleier, and R. L. McPherron (2008),
7	Allen, R.M. (2007) The ElarmS earthquake early warning methodology and its application across California, In " <i>Earthquake Early Warning Systems</i> ", P. Gasparini, G. Manfredi, J. Zschau (Eds), p. 21-44, Springer, ISBN-13 978-3-540-72240-3	CalMagNet – an array of search coil magnetometers monitoring ultra low frequency activity in California Nat. Hazards Earth Syst. Sci., 8, 359-368, 2008 By: Cutler, J., Bortnik, J., Dunson, C., Doering, J., and Bleier, T. (2008)
8	Wu, Y.-M., H. Kanamori, R.M. Allen and E. Hauksson (2007) Determination of earthquake early warning parameters, tau-c and Pd, for southern California <i>Geophys. J. Int.</i> 170 , 711-717, doi: 10.1111/j.1365-246X.2007.03430.x	Investigation of ionospheric electron content variations before earthquakes in southern California, 2003-2004, <i>J. Geophys. Res.</i> , 112, B02106, doi:10.1029/2006JB004447. (2007) By: Dautermann T., E. Calais, J. Haase, J. Garrison
9	Lockman, A.B. and R.M. Allen (2007) Magnitude-period scaling relations for Japan and the Pacific Northwest: Implications for earthquake early warning <i>Bull. seism. Soc. Am.</i> 97 (1), 140-150, doi: 10.1785/0120040091	An automatic wave detection algorithm applied to Pc1 pulsations, <i>J. Geophys. Res.</i> , 112, A04204, doi:10.1029/2006JA011900. (2007), By: Bortnik J., J. W. Cutler, C. Dunson, T. E. Bleier
10	Olson, E.L., and R.M. Allen (2006) Is earthquake rupture deterministic? (Reply) <i>Nature</i> , 442 , E6, doi:10.1038/nature04964	Using Nanosats as a Proof of Concept for Space Science Missions: QuakeSat as an Operational Example in Proceedings of the 18th Annual/USU Conference on Small Satellites, Logan, Utah, August 2004. By: Scott Flagg
11	Allen, R.M. (2006) Probabilistic warning times for earthquake ground shaking in the San Francisco Bay Area <i>Seismo. Res. Lett.</i> 77 (3), 371-376.	A CubeSat Derived Design for a unique Academic Research Mission in Earthquake Signature Detection, in Proceedings of the 16th Annual/USU Conference on Small Satellites, Logan, Utah, August 2002. By: Mathew Long, Allen Lorenz, Greg Rodgers, Eric Tapio, Glenn Tran, Keoki Jackson, Robert Twiggs, and Thomas Bleier
12	Simons, F.J., B.D.E. Dando and R.M. Allen (2006) Automatic detection and rapid determination of earthquake magnitude by wavelet multiscale analysis of the primary arrival. <i>Earth Planet. Sci. Lett.</i> 250 , 214-223, doi:10.1016/j.epsl.2006.07.039	
13	Lockman, A.B. and R.M. Allen (2005) Single station earthquake characterization for early warning. <i>BSSA</i> 95 (6), 2029-2039, doi: 10.1785/0120040241.	
14	Olson, E.L., and R.M. Allen (2005)	

	The deterministic nature of earthquake rupture. <i>Nature</i> 438 , 212-215, doi:10.1038/nature04214	
15	Allen, R.M. Rapid magnitude determination for earthquake early warning, (2004) in "The many facets of seismic risk" edited by G. Manfredi, M.R. Pecce, and A. Zollo, Napoli, Universita degli Studi di Napoli "Federico II", Napoli, Italy, p15-24. <i>Proceedings of the "Workshop on Multidisciplinary Approach to Seismic Risk Problems," Sant'Angelo dei Lombardi, September 22, 2003</i>	
16	Allen, R.M., and H. Kanamori (2003) The potential for earthquake early warning in southern California, <i>Science</i> , 300, 786-789.	

The articles highlighted in red in table 5 were excluded from the analysis as they cover either previous projects or other study areas. Table 6 shows the list of recent 'Papers by others' on the QuakeFinder website. The four relevant articles in green (left column of table 6) have been included in the Quakefinder analysis as these were underlined on the webpage, thus apparently deemed more important. This means a total of 15 articles will be analysed in the ElarmS section and a further 15 articles will be analysed in the QuakeFinder section.

Table 6: Papers by Others, 2005 and more recent (data basis: Quakefinder (ed.) N.D.b: online on 08.11.13)

ULF Signals ...		
	Near-seismic effects in ULF fields and seismo-acoustic emission: statistics and explanation, <i>Natural Hazards and Earth System Sciences</i> (2005) 5: 1–10 SRef-ID: 1684-9981/nhess/2005-5-1, O. Molchanov, A. Schekotov, M. Solovieva, E. Fedorov, V. Gladyshev, E. Gordeev, V. Chebrov, D. Saltykov, V. I. Sinitsin, K. Hattori, and M. Hayakawa	
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5.1. ElarmS

ElarmS is short for 'Earthquake Alarms Systems' and aims to reduce the damage, costs and casualties from earthquake events by providing a warning. In short, the system functions through a complex set of algorithms designed to detect the start of an earthquake event, calculate the size and exact location (epicenter) of the event and give warning to everyone in the area that will likely be affected by the earthquake. As mentioned previously, ElarmS is part of CISN's real time seismic system. (ALLEN, R. (N.D.a.), online on 04.11.13)

The basic concept behind ElarmS is that when an earthquake happens, the less damaging P-wave always propagates faster than the more damaging S-wave, and that upon arrival of the P-wave, a seismic station can rapidly detect and calculate the magnitude and location of the P-wave allowing a small time frame for a warning and mitigation measures (depending on distance to the epicenter) prior to the arrival of the S-wave. (ALLEN 2008: 54)

Research and progress in this area has been tedious over the last centuries, however, due to the vast improvement in computer technology, such warning systems are now able to compute the incoming P-wave information fast enough for important information on location and earthquake magnitude to become available seconds prior to the ground shaking (ALLEN 2007a: 608). Data from the P-wave is analysed as this increases the amount of warning time before the onset of the severer S-wave ground shaking. (ALLEN 2007a: 633)

There are several ways of implementing such an early warning system, either as a single-station warning system or a network-based warning system. The single-station approach focusses on estimating location and magnitude of the earthquake directly from the incoming p-wave and using data from only one instrument station. While this approach is very fast in comparison to the network-based approach, it does usually result in larger errors and uncertainties. The network-based approach first estimates the earthquake location through the prediction of time and location of peak ground shaking. The difference using this approach is that parameters are estimated by combining data from several stations rather than from just one, allowing for a better accuracy of results, but compromising the speed at which the information becomes available, particularly close to the event epicenter. Depending on the placement of the instruments, the network-based approach can also be implemented as a frontal detection system, where the instruments are strategically placed between a fault zone and a densely populated area (such as in Japan or Mexico). ElarmS is a network-based approach, but due to the faults in California lying directly underneath large population clusters, it should not be considered a frontal detection system. (ALLEN 2007a: 632-635)

A large range of instruments is used by ElarmS to obtain the best possible results, most of these instruments have been placed underground in boreholes so as to minimise the effect of human interference and natural interference (wind). A detailed ex-

planation of the instruments is given in ALLEN (2008: 52-59), but WURMAN et al. (2007: 2) sums up the instruments well: both strong and weak motion instruments are used to collect data, namely the high-gain, broadband velocity instruments and low-gain, strong motion accelerometers and the data is collected from two networks, NCSN (Northern California Seismic Network) and BDSN (Berkeley Digital Seismic Network).

Furthermore, the first results from analysing the data from the two instrument types has shown that high-gain velocity instruments have proven to be more effective at measuring smaller earthquakes ($M < 4.5$) and low-gain, strong motion accelerometers have proven to be more useful in defining the magnitude for larger events. (WURMAN et al. 2007: 2)

Telemetry and Communications is equally an important factor for the ElarmS methodology, where an upgrade in telemetry would be beneficial for the system in order to maximise the warning time. However, or rather, that the communication system should work on an institutional and personal basis has only been dealt with in theory. (ALLEN 2008: 57)

5.1.1. Background Theory

There are several theories that must be considered and elaborated on to be able to fully comprehend the ElarmS methodology. ALLEN (2007a: 609) explains Reid's theory on elastic deformation well, noting that when stress builds up on a plate boundary, rupture will then occur when stress exceeds the strength of the fault, the accumulated deformation will then collapse onto the fault plane.

While determining the location of the earthquake can be done more easily, estimating the earthquake magnitude is a more difficult task.

Triangulation is used to calculate the earthquake location. As most earthquakes in California occur at a very shallow depth – at less than 20km, the depth of all events is fixed to 8km, presumably to minimise the computation time. WURMAN et al. (2007: 3) describes this triangulation process well:

‘When the first station triggers, the event processing system will provisionally locate the event beneath that station. When a second station triggers the provisional location moves to a point directly between the two stations, based on the timing of the arrivals. Once trigger timers are produced at three or more locations, the event location and origin time is estimated using trilateration and a grid search algorithm to find the optimal solution.’ (WURMAN et al. 2007: 3).

Determining earthquake magnitude in ElarmS meant questioning previous assumptions on earthquake rupture. The underlying concept behind being able to determine an earthquake magnitude from the first few seconds of p-wave data is that earthquake rupture has to be deterministic, i.e. that the magnitude can be determined through the way the rupturing process initiates and continues. This goes against the most commonly cited conceptual hypothesis of the cascade model for fault rupture. In this model, the initiation of an earthquake ‘slip’ starts on a small patch and continues to rupture along the plane (due to stress along the fault), which continues up to the point where the energy required to rupture the next ‘patch’ is insufficient. This would suggest that small and large earthquakes start rupturing in exactly the same way and that the rupture process is not deterministic, meaning that the size of the earthquake can only be determined after earthquake rupture has ceased. (OLSON and ALLEN 2005: 212)

According to OLSON and ALLEN (2005: 212) *‘evidence for a scaling relation between the frequency content of the first few seconds of the P wave and the final magnitude has also emerged.’* This would mean that the cascade model theory may not be entirely correct, and that earthquake magnitude can be determined through the P-wave frequency content.

OLSON and ALLEN (2005: 212) explain how, smaller earthquakes with a $M < 6$ usually rupture for less than 4 seconds, meaning that the full rupture information is contained within the first 4 seconds of the P-wave data – and it is the first 4 seconds of P-wave data that ElarmS uses to determine magnitude and location. It can therefore not be claimed that earthquake rupture is deterministic by analysing smaller earthquakes. With larger earthquakes that last for more than 4 seconds however, a scaling relation between the T_d (the delay of the observation of the maximum amplitude spectrum/ predominant period, in short T_p^{max} , in the p-wave data) and magnitude would suggest that enough information becomes available within the first seconds of

the P-wave, to determine parameters like earthquake magnitude (thus meaning that earthquake rupture is deterministic). The delay of T_d ranges between 0.05 and 4s. (OLSON and ALLEN 2005: 212)

A scaling relation emerges as soon as the $T_p^{\max}$ data is plotted against the magnitude on a log-linear scale, OLSON and ALLEN (2005: 212) have calculated the following best fit relation:

$$\text{Log } T_p^{\max} = 0.14M - 0.83$$

Furthermore, a high linear correlation of 0.9 was calculated showing that information on the final earthquake magnitude of an event (of any size) is available during the start of an earthquake,' (OLSON and ALLEN 2005: 212)

Figure 12 shows this relationship in a diagram. As Figure 12 shows data from Southern California, Japan, Taiwan and Alaska, and the scaling relation stays clearly visible it can be confirmed that such an early warning method has the potential to function similarly and similarly well in all earthquake-prone regions of the world.

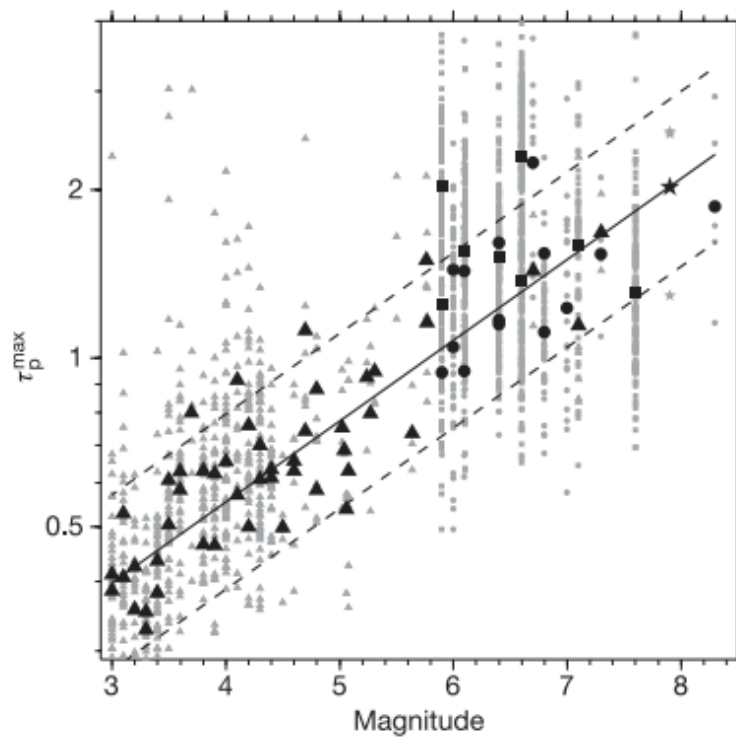


Figure 12: The relation between the maximum predominant period and magnitude in Southern California (triangles), Japan (circles), Taiwan (squares) and Alaska (stars) (Source: OLSON and ALLEN 2005: 214)

$T_p^{\max}$ observations have been known to vary according to individual site effects and other source related processes such as rupture behaviour, stress heterogeneity and other on-fault variables. It is suggested that the final earthquake magnitude can be determined through the first few seconds of rupture as well as the physical state of the surrounding fault plane, the second parameter can be used to explain any deviations between calculated and observed values as the exact state of the fault planes before and after rupture is not understood in absolute detail. (OLSON and ALLEN 2005: 213-214)

It is further suggested that the size of the earthquake could be defined through the size of the initial slip, *'if the rupture pulse initiates with a large slip, it is more likely to evolve into a large earthquake'* (OLSON and ALLEN 2005: 213-214).

The earlier paper by OLSON and ALLEN (2005) led to a further research paper by LOCKMAN and ALLEN in 2007 also focussing on the frequency content of the P-wave. Here, further data from Japan and the Pacific Northwest were included so as to be able to analyse more large-magnitude events and research different geological settings (LOCKMAN and ALLEN 2007: 141). This article was included in the analysis as the broader definitions of 'Pacific Northwest' include northern California.

The dataset used here contains 25 earthquakes (M3.5 to M6.8 occurring between 1989 and 2001) and the information used in the analysis includes all of the waveforms that were recorded within 150km of each event epicenter, provided they contained clear P-wave arrival without any clipping of incoming data within the first 5 seconds. The first 5 seconds of data were monitored for each event, after which the maximum predominant period was recorded, whereby $T_p^{\max}$ was usually recorded for a shorter period for smaller earthquakes. It must be noted however, that parts of the incoming data are excluded from the analysis due to the transient between non-event and event, these 'blackout' windows can range from 0.5s (in the Pacific Northwest) to 2s (in Japan), as this improves the magnitude-scaling relations. (LOCKMAN and ALLEN 2007: 141-144)

5.1.2. P-Wave data collection, magnitude and location estimates

Currently, ElarmS relies on continuous data input in the form of seismic waveforms through continuous broadband stations. (ALLEN 2007b: 35)

The best way to explain how the system functions is to explain the whole process from the initiating trigger to the completion of the warning process. In a first step, seismometers start to pick up P-wave motion as soon as an earthquake nearby occurs. As soon as more than two stations register the earthquake, the epicenter is calculated through triangulation (the time this takes is largely dependent on the density of the station network). The magnitude is then estimated from the frequency of the P-wave data after which the spread and severity of the shaking is predicted. This process should ideally be finished before the S-wave arrives at the stations. (ALLEN 2008: 55)

In the initial detection process, ground motion is monitored and the alert issues after ground motion acceleration exceeds a particular threshold, in ALLEN (2007a: 632) this threshold is set to ' *$\sim 0.04g$ (where g is the acceleration due to gravity), which is the level at which buildings and other infrastructure start to experience permanent damage*'.

Errors in these calculations are obviously the largest directly after the P-wave trigger as the least information is available at this time, but accuracy improves with every passing second of additional data. LOCKMAN and ALLEN (2005: 2033) have experienced large errors in computing the backazimuth of an earthquake (crucial in defining location of the epicenter and magnitude) when using only the initial 0.5 seconds of the P-wave data; they have found that the backazimuth can be derived from the P-wave data due to the fact that the P-wave vibrations are polarized. Similarly, several papers, e.g. ALLEN (2007a: 638), indicate that waiting for more data to arrive (from three rather than from one station) can significantly reduce the errors in location and magnitude of the earthquake. ALLEN (2007a: 640) has also determined that for data sets in California and Japan, the average absolute magnitude error at alert time (where the first 4 seconds of P-wave data have been recorded) lies at only 0.5 units. Furthermore, WURMAN et al. (2007: 9) have calculated the mean absolute errors in location and origin time; at alarm time (presumably the same as or similar to alert

time) the error in location is 13.7 ± 23.4 km, and the error in origin time is 2.3 ± 3.1 seconds.

The main drawback of waiting for more information to become available is that the direct epicenter of most earthquakes will have a reduced warning time. Particularly if there is a large urbanised area in the immediate surroundings, having 4 seconds more or less could potentially save lives. ALLEN (2008: 56) highlights this problem: *'The network method cannot provide warning directly at the epicenter of an earthquake because the S-wave arrives too quickly to be able to issue a warning to the population in the affected region.'*

The trade-off between a smaller error margin or more warning time should thus be thoroughly considered, as on the one side, potentially giving a few more seconds warning may help save lives directly near the epicenter, whereas otherwise, waiting for additional data is crucial to the process at the current state of technology (where waiting for data from 3 stations rather than 1 is preferred), because the magnitude and location errors become too large to handle otherwise. Additionally, another problem plays in through the delay in telemetry, which is calculated to be 5.5 seconds. (ALLEN, 2007a: 638-640)

The general consensus in the scientific community is that the amount of P-wave data (in seconds) required for an accurate estimate of magnitude is dependent on the size of the earthquake (the larger the earthquake, the more data is required for an accurate estimate):

- *'We also investigated the merit of using between 1 and 5 s of P wave data for determining P_d or P_v (peak velocity for HN and HL channels). Using less than 4s yielded greater errors, and between using 4 and 5 s there was little difference in performance'* (WURMAN et al. 2007: 4).
- *'the relation for low-magnitude events (mag<5 [...]) is determined using the maximum predominant period, T^p_{max} , within 2 seconds of the P-wave trigger having low-passed the data at 10 Hz. For larger magnitude events [...] better magnitude estimated require 4 seconds of data and a low-pass filter of 3Hz'* (ALLEN 2004: 17).

- *'For smaller earthquakes (magnitudes 3.0 to 5.0), broadband data low-pass filtered at 10Hz were used and a good magnitude estimate was possible given just 1s of data. With 2s of data the magnitude error reduced slightly, but additional data did not improve the estimate'* (ALLEN and KANAMORI 2003: 787).
- *'Although the moment rate function of real earthquakes are different from the synthetic ones, this test suggests that a duration of 3 s yields a good measure of the magnitude of the event up to $M = 7$ '* [Note: the focus of this study was on larger, damaging earthquakes] (WU et al. 2007: 713).

From these quotes, it seems fair to say that for stronger, more damaging earthquakes ($M > 5$) somewhere between 3 and 5 seconds of P-wave data should be used to calculate magnitude and location in order to minimise error margins. It seems legitimate to wait longer for this data to arrive, as the need to predict smaller earthquakes is not so large due to the fact that these usually cause much less damage to housing, infrastructure and lives, particularly where adequate building codes are in place and enforced.

After understanding how much data is needed for a good estimate, it is now equally important to understand the range of data being recorded and analysed. First of all, the P-wave must be detected as such. This is done using a waveform processing system, which sets off a trigger once the initial P-wave is detected. The method used here is a short-term/long-term averaging method developed by Allen in 1978 and involves a 0.5s and 5s timescale where thresholds are monitored using an algorithm. As soon as new data is available after the P-wave trigger (sampled every 10^{th} of a second) it becomes available for event processing for 4 seconds after the trigger. T_p^{max} (the maximum predominant period) and $P_{d/v}$ (peak displacement or velocity amplitude) are therefore only updated if their value changes, SNR (signal to noise ratio) data is equally sent for the same timestamp. By using an approach like this, where the incoming data is processed on site, several seconds can be spared in transferring the data via telemetry as the amount of data transferred is much smaller than if all data had to be transferred to be processed at an event processing system. The small sets of updated data are then sent to the event processing system, where the information on size, time and location of the event is computed and the event itself is validated or not. (WURMAN et al. 2007: 2-5)

Data processing relies largely on the frequency content of the P-wave. After the initial P-wave is detected, the frequency content is analysed to obtain values for the maximum predominant period within the first four seconds. This is then used to characterise whether the earthquake has a high or low magnitude. (ALLEN 2004: 17)

The only indication of the quality of data recorded is given by WU et al. (2007: 713); here, the *'signals are digitized at 100 or 80 samples per second with 24-bit resolution.'*

In order to calculate the magnitude, the first 0.5 seconds of the P-wave data must be ignored as it contains transients between the signal and background noise. The first estimate can therefore be given at around 1 second after the P-wave trigger. Every incoming event is considered to be a small event ($M < 4.5$) as this requires a shorter analysis and errors in computing are also initially smaller for small events. The filter applied to the data initially is a low-pass filter (at 10Hz) as smaller earthquakes generate a higher frequency signal. Should the event turn out to be a large event (where $T_p^{\max}$ is updated and results in a larger figure than before), the algorithm will change to a low-pass filter at 3Hz, and re-calculate the earthquake magnitude (which must then be $M > 4.5$) using 4 seconds of P-wave data. (ALLEN 2004: 17)

WURMAN et al. (2007: 6) further highlights the benefits of using $T_p^{\max}$ and $P_{d/v}$: *'The advantage of using $T_p^{\max}$ and $P_{d/v}$ means a better performance of the system because large events are less likely to be underestimated and there is less scatter in the smaller events.'* What is also considered is a weighting system that works progressively, with incremental steps that systematically weight $T_p^{\max}$ more strongly at lower magnitudes and weight $P_{d/v}$ more heavily at higher magnitudes. (WURMAN et al. 2007: 6)

Another factor that should be considered is that incoming S-wave data (for example when a station is very close to a triggering earthquake and the S-wave arrives within 4 seconds of the P-wave) must not interfere with magnitude calculations. Therefore a filter is added to exclude any incoming S-wave data which would otherwise cause a wrong magnitude estimate. A further criterion that is considered for data exclusion is the signal to noise ratio (SNR) which should allow for a good discrimination between noise and signal without excluding too much data as to hamper the calculation speed. (WURMAN et al. 2007: 3)

In the same article from WURMAN et al. (2007: 1) it is explained that ElarmS incorporates data using the peak amplitude and the maximum predominant period of the P-wave, while also including ground motion prediction equations from the ShakeMap to calculate the earthquake magnitude and to predict the S-wave ground motions in advance. Results in this study have shown that using both of these parameters does further increase the accuracy of the magnitude estimate provided by ElarmS (WURMAN et al. 2007: 2).

Complementing these results, a study by WU et al. (2007: 715) seems to suggest that just one measurement of a ground-motion period parameter and a displacement amplitude parameter should suffice for an onsite warning, but adding more parameters will greatly improve robustness of the estimates and warning.

The information on earthquake magnitude, data from the first second of P-wave data from the first station to trigger is initially used, before updated information from the first as well as other stations in the vicinity become available. As soon as other stations in the vicinity trigger, a grid search method is used to triangulate the epicenter of the earthquake more accurately. (ALLEN 2007a: 637)

A further study that should be noted at this point is by SIMONS et al. (2006: 215) where a fully automated algorithm is proposed and tested (that also concerns magnitude estimation within the first seconds of P-wave detection) largely relying on wavelet analysis.

Such a wavelet analysis seems to have many advantages; the most noteworthy seems to be the improved stability in estimating the magnitude and expected S-wave arrival time. Also, the wavelet transformation reduced the computation time significantly as it doesn't require the computation of redundant components which are not needed for the final estimation. The wavelet coefficients are also determined rapidly; during this transform process the amplitudes are extracted at individual scales, which are then used to derive the magnitude of the P-wave with errors of just one magnitude for earthquakes up to 150km away from the instruments. The algorithm has the capability to detect the P-wave autonomously, which would mean that a manned monitoring station is not necessary. Further costs can be cut due to the fact that the procedure is simple, meaning that not much power is needed for computation. (SIMONS et al. 2006: 216-221)

5.1.3. ShakeMap and AlertMap

The next step in the early warning process is to estimate the extent of the area likely to be damaged by the S-wave. So after the information on the earthquake magnitude and epicenter becomes available, calculating warning times becomes a priority. A value of 3.75km/s is used as a moveout speed for the S-wave, based on previous observations in southern California. Using this fixed value speeds up computation of the moveout speed. (WURMAN et al. 2007: 3)

The AlertMap which is then generated shows the expected distribution and propagation of the S-wave through PGA (Peak Ground Acceleration), PGV (Peak Ground Velocity) and MMI (Modified Mercalli Intensity). The map makes do with information from the available data collected from all nearby stations (100km or sometimes 150km radius of the epicenter) on location and magnitude estimates. An attenuation relation helps to predict the expected ground shaking. (ALLEN 2007a: 636-637)

To clarify, *'Attenuation relations describe how the amplitude of seismic waves decrease with distance and earthquake magnitude, and are commonly used to describe peak ground acceleration or velocity for large magnitude events'* (LOCKMAN and ALLEN 2005: 2032).

As soon as first information becomes available on the actual ground shaking, this is incorporated into the AlertMap as well, whereby the AlertMap then becomes the observed ShakeMap (ALLEN 2007a : 636-637). The ShakeMap therefore tries to gather ground shaking information as quickly as possible in order to incorporate it into a map of peak ground distribution during/after an earthquake (however, without incorporating earthquakes with $M \leq 3$) (ALLEN 2007a: 627).

In order to optimise the AlertMap calibration datasets from ShakeMap were incorporated (from past events where data such as PGA or PGV were available) into the ElarmS algorithms for Northern and Southern California (ALLEN 2007a: 637). This means that local factors such as geology and the exact characteristics of the fault zone are partially reflected in the algorithms.

Another study by WURMAN et al. (2007) has extensively adapted these algorithms in order to mimic geological amplification and site conditions in order to optimise how

ShakeMap works. This work included incorporated GMPEs (Ground Motion Prediction Equations) into the AlertMap algorithms, and testing these extensively in California. Particularly relevant are the individual corrections included for each instrument site, as the geology in the area varies and this has attenuation or amplification effects on the P-wave and S-wave frequencies. (WURMAN et al. 2007: 2-6)

WURMAN et al. (2007: 6) also goes to describe the process through which the updates occur in the ShakeMap well: *'As the event progresses and the S wavefield expands outward from the source, peak ground motion observations become available at each station. The observations are first corrected for the site condition at the station, and then the GMPE curve, based on magnitude and location is linearly scaled up or down to best fit the corrected observations.'*

The ElarmS system is optimised in order to create this AlertMap and Shakemap in order to optimise calculations and estimations of the propagation of the peak ground motions of the S-wave in Northern and Southern California. (ALLEN 2007b: 28)

5.1.4. Findings

To begin with, the findings of the offline testing of the ElarmS methodology should be explained and assessed, as an extensive offline testing has taken place in Northern and in Southern California.

A study by TSANG et al. (2007) focusses on the data used and results obtained by offline testing in Southern California. Here, 59 past earthquake events were used to evaluate the quality of calibration in the ElarmS algorithm, with particular attention paid to the best-fit period-magnitude and amplitude-magnitude scaling relations. (TSANG et al. 2007: 1)

The amplitude-scaling relationship in this study was calculated by analysing the peak displacement amplitude (P_d) during the first 4 seconds of the P-wave arrival. This scaling relationship was computed by using the linear averages of the magnitude estimates from ' T_p^{max} ', ' P_d ' as well as ' T_p^{max} and P_d '. (TSANG et al. 2007: 1)

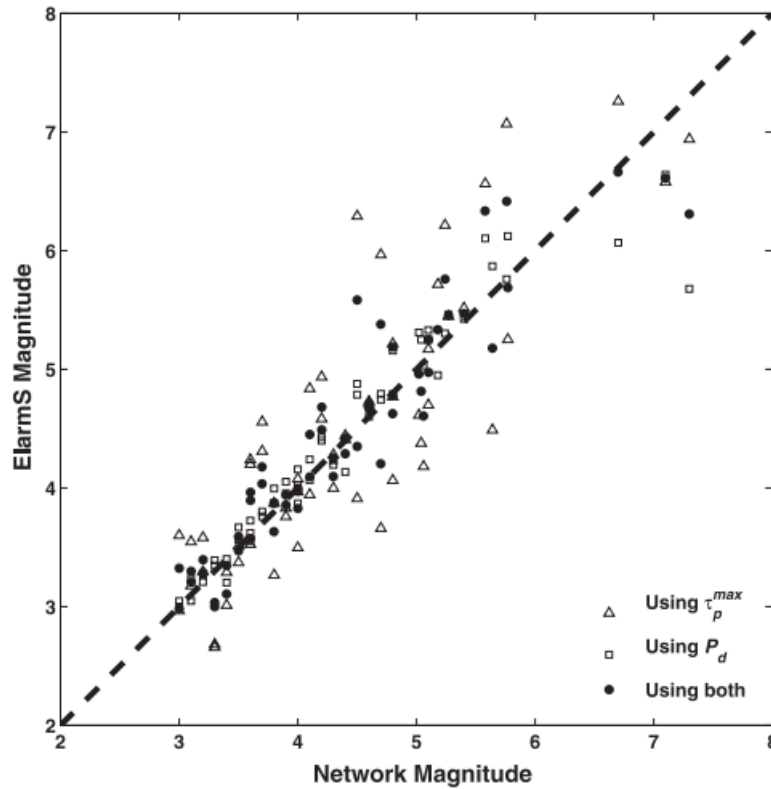


Figure 13: Plot of ElarmS and Network-based magnitude for the 59 earthquakes analysed in southern California (Source: TSANG et al. 2007: 3).

Figure 13 shows the results of this analysis, the relationship between the ElarmS magnitude estimates and the recorded network magnitude for the earthquake events is shown to be linear. Figure 13 also shows the relationship when T_p^{max} , P_d or both values (calculated by the ElarmS algorithm) are compared to the observed 59 earthquake events. Using just T_p^{max} , the results show that earthquake events with $M \leq 4.5$ have relatively low scatter compared to the observed network magnitudes, but as the magnitude increases, so does the scatter. While at the lowest magnitudes, the scatter lies at around 0.5 magnitude units, the scatter at the higher magnitudes reaches up to around 1 magnitude units. Using only P_d for the magnitude estimates results in

a similar pattern, although the scatter is generally a little lower than with $T_p^{\max}$. (TSANG et al. 2007: 3)

The most interesting estimates are using both values, $T_p^{\max}$ and P_d . The scatter using both values for the magnitude estimate is significantly lower compared to using the values individually, which means that using both estimated values could give the most accurate estimate of earthquake magnitude. (TSANG et al. 2007: 3)

There are however some discrepancies between Northern and Southern California. For example, Southern California has shorter $T_p^{\max}$ values, and thus higher frequencies than Northern California. This could be due to the regional characteristics of the crust. Northern California on the other hand, required two separate amplitude-magnitude scaling relationships; *'peak amplitude in displacement (P_d) was used for velocity instruments, whereas peak amplitude in velocity records (P_v) were used for accelerometers'* (TSANG et al. 2007: 4). This could be caused by the fact that the instruments in Southern California were placed at less noisy sites than in Northern California, one of the major noise factors could be ocean waves and tides as the stations in Northern California were generally installed closer to the ocean. (TSANG et al. 2007: 4)

WURMAN et al. (2007: 1) equally calibrated and tested this methodology, only using 43 earthquakes that occurred since 2001 for calibration and a further 75 between February and September 2006 for testing. This study however, had a stronger focus on the possible warning time that would be available under real-time conditions in the surrounding and potentially affected area.

Before the system was applied real-time, the method was tested using 43 earthquake events between M3.0 and M7.1 that had occurred since 2001. This served to calibrate the algorithms. After this, 75 events were analysed between February and September 2006, ranging from M2.86 to 5.0, again however, after the event had occurred, the data processing was therefore 'noninteractive'. (WURMAN et al. 2007: 2-8)

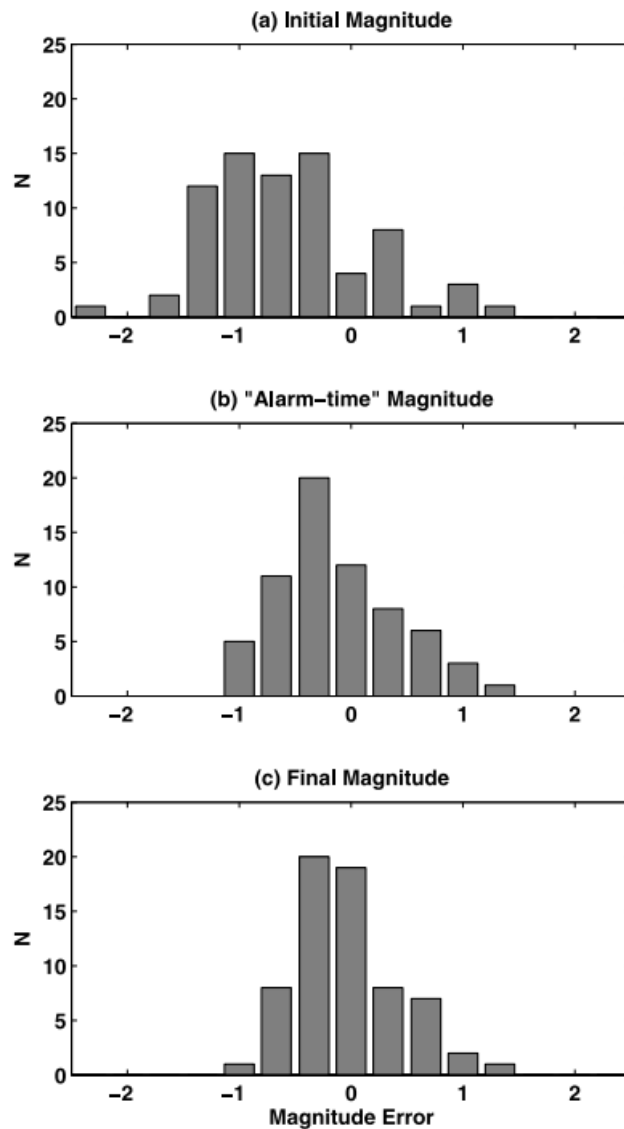


Figure 14: Diagrams showing magnitude estimate errors for (a) the 74 events 1s after detection, (b) at alarm time, 66 events with 4s of data and (c) 60 seconds after the event began with 66 events (Source: WURMAN ET AL., 2007: 8)

Figure 14 shows the results from this analysis:

Figure 14(a) shows the magnitude estimate output when only the first second of incoming P-wave data is used for the estimation. These results show a lot of scatter, with errors up to 2 magnitude units (WURMAN et al. 2007: 7-8).

Figure 14(b) shows the magnitude estimates using 4 seconds of P-wave data. The magnitude error, however not all events were detected due to their modest size (WURMAN et al. 2007: 8).

Figure 14(c) shows the final magnitude errors, being similar to 14(b) shows that the results obtained with 4 seconds of data were very good and that largely, the overall calibration could still be improved (WURMAN et al. 2007: 8).

While such results are certainly good enough to allow for an implementation into a full EWS, several problems did occur, for example, the mislocation of events because the earthquakes occurred out of 'range' of the instruments, which in turn led to the S-wave arrival time being calculated earlier than in what it was in the actual event. (WURMAN et al. 2007: 8)

In a further step, the median warning time for the major population centres in the SFBA were calculated. ElarmS would allow for the majority of the population in these population centres to have 49 seconds of warning prior to the severest ground shaking. (WURMAN et al. 2007: 1)

The final results for median warning time (averaged through all 66 events) in the cities after initial detection (1 second of P-wave data) were 56 seconds in Oakland or San Francisco, and 48 seconds in San Jose. When alarm condition is reached (4 seconds of P-wave data) the median warning time is 39 seconds for Oakland, 39.5 seconds in San Francisco and 40 seconds in San Jose. While this is only an analysis of previous events, it can be assumed that future earthquakes will occur along the same fault lines as the previous events. (WURMAN et al. 2007: 8)

Furthermore it should be noted that the further step of actually warning the population and the time this would take is not included in these median warning time estimates.

A similar study by ALLEN and KANAMORI (2003:788) yielded similarly positive results: *'thirty km from the epicenter, the magnitude would be available ~8s before the S-wave arrival, and at 60km the magnitude would be available ~16s before the S-wave arrival.'*

In another paper by LOCKMAN and ALLEN (2005) results from California and Japan were compared in order to investigate the effect of geology and local site effects at different site locations and in different regions. Basin geometry for example can play a large role in diffracting rays, causing multiple ray paths that may interfere with the predominant period observations. (LOCKMAN and ALLEN 2005: 2035-2036)

The results of the analysis show that a dense network of instruments could benefit from using station-specific scaling relations (between predominant period and event magnitude) provided such scaling relations can be developed over time. This would require a significant history of data in existing stations, including earthquake data to be available. For any new stations this would mean that network-averaged scaling relations need to be implemented until enough data is available from these new stations so that these can be calibrated individually. By adjusting the data from the sites according to how signals at these sites are amplified or attenuated could benefit the magnitude estimates. (LOCKMAN and ALLEN 2005: 2037-9)

Comparing the California and Japan dataset it became apparent that although there are differences in geology, the results remain similar meaning a possible implementation of this system in all earthquake-prone regions may well be possible. Similarly here, a regional network-averaged scaling relation would benefit the final magnitude

estimates, but in theory the relationship remains largely linear meaning adaptations in the algorithms and formulae should be possible. (LOCKMAN and ALLEN 2007: 146)

5.1.5. Pros and Cons

It becomes apparent through various statements that there are problems with the absolute accuracy of the calculations. These are mentioned and/or justified in several papers:

- *'[...]but accurately describing the relation between the P wave and magnitude has proved difficult'* (LOCKMAN and ALLEN 2007: 140).
- *'Ground motion parameters must be detected at one location and estimated for another; this introduces uncertainty'* (ALLEN 2007a: 633).
- *'There is still a risk of false alarms or missed alarms'* (ALLEN 2008: 55).

This indicates that although the results so far look promising, there are still enough uncertainties that their implications must be considered. These problems may just need time in intense research/testing to be eradicated. Also, the results still show a significant amount of scatter, making discrimination between smaller and larger (more damaging) events difficult. (WURMAN et al. 2007: 3)

If there is still a considerable risk of false or missed alarms, then the system should be tested further before implementation as false alarms may reduce the willingness of a population to react to a warning, as *'a high incidence of false alarms will drastically reduce the credibility and utility of the warnings'* (WURMAN et al. 2007: 3).

There are also advantages and disadvantages to the single-station and multiple-station approach. While the single station allows for a rapid computation of estimated location and magnitude, the uncertainties of this approach are so large that it is hard to rationalise an implementation of a single-station system unless, for example, it's a mobile system designed to warn for aftershocks. In such a case, there would be fewer issues with the inaccuracy of the single-station system. (ALLEN 2007a: 635)

With a multiple-station approach the time required for computation increases to such an extent, that the chances are high that no warning is available directly at the epicenter of the earthquake. While this would be less worrisome for regions where faults lie several tens to hundreds of kilometres from the most densely populated areas, for California, where the faults lie directly under large cities, this proves to be a severe drawback of this method. (ALLEN 2008: 55)

However, at least the multiple-station approach is far more accurate at estimating location and magnitude, which is necessary for justifying the final implementation into a full EWS. The higher accuracy, particularly in estimating the magnitude, equally justifies waiting for more information to become available.

Another drawback of the multi-station approach is that it requires a rather dense network of instrument stations, *'California currently has ~300 seismic stations that are telemetered in real-time and appropriate for use in an early warning system... to install an additional 600 instruments would cost between \$6 and \$30 million, depending on the instrumentation used, to operate that network would cost between \$2 and \$6 million per year'* (ALLEN 2007a: 642). If the instrument network were less dense, it would take more time for more stations to trigger, thus reducing the speed in which an accurate magnitude and location estimate can be given.

The dense network is a high-priority requirement for implementation of the EWS as it would speed up the data processing for a four or 5 station average of magnitude and location. If the instrument network were less dense, the amount of time it would take to get a five station average would be much longer, thus reducing the time for an effective warning. (WU et al. 2007: 715)

Further drawbacks of the ElarmS system become apparent when taking into account what has been included and not included in warning times. For example, the warning times obtained through the ElarmS methodology are usually maximum warning times and do not consider delays in telemetry, processing or dissemination. While the processing time should remain relatively low (around 1s with updates arriving at 1s intervals), telemetry delays are currently at around 10s and dissemination delays cannot be quantified. (WURMAN et al. 2007: 13-15)

The fact that dissemination delays cannot be quantified at all is a severe drawback. No insight is given as to how people might be warned and what effective time for reaction can be assumed once individuals in the affected area have received the warning.

The only advantage ElarmS provides for telemetering data is that the volume of the data is extremely low with data only being sent if values used for computing magnitude ($T_p^{\max}$ or $P_{d/v}$) change. Also, after the waveform has been processed, data is sent for event processing every tenth of a second. This explains the extremely low processing time. (WURMAN et al. 2007: 4-5)

All in all however, such delays would reduce the effective warning times for the at-risk population, meaning that the blind zone near the epicenter, where the damage is likely to be highest, is larger than may initially be assumed (ALLEN 2007b: 32). There are only a few cases, such as the 1989 Loma Prieta earthquake, where over 80% of the deaths occurred further away from the epicenter and *'there could have been more than 10 seconds of warning with a functioning ElarmS'* (ALLEN 2008: 56).

Contrasting the optimistic warning time, one study by ALLEN (2004) does show that concerning the S-wave arrival, the earliest onset of peak ground motion at the earth's surface is used. The onset of the severest ground motion is therefore a conservative estimate due to the fact that for large earthquakes, the severest ground shaking only starts a few seconds after the S-wave has arrived (ALLEN 2004: 19). This is favourable as an early warning system should rather assume a worst case rather than a best case scenario for warning times.

The main reason these telemetry delays are so large is because neither the NCSN nor the BDSN were designed to optimally allow for the system to be used as an EWS (WU et al. 2007: 716). The systems can however be improved significantly by distributing the broadband velocity and strong motion accelerometer stations more evenly throughout California. Another drawback of the NCSN and BDSN network is that station coverage only allowed for good measurements and observations from 2001 onwards. (WURMAN et al. 2007: 2-15)

Furthermore, station specific differences have been observed. These range from attenuation of the incoming signal to amplification of the incoming signal and can in-

clude diffraction due to geology and basin structure. There are also '*near-surface amplification effects, such as rock versus soil, which are responsible for much of the scatter in the acceleration observations*' (ALLEN 2004: 20).

These differences in the individual stations mean that these stations either overestimate or underestimate the hypocentral distance. The best way to deal with this problem is by using a correction factor for distance, and if necessary, the magnitude estimate. While this requires a significant amount of station data to be available, this is the best option for achieving the most reliable results. (LOCKMAN and ALLEN 2005: 2032)

There is also an inconsistency of data depending on if strong motion or broadband velocity sensors data are analysed: '*the comparatively large magnitude error highlights the utility of waiting for more data to become available rather than issuing the alarm immediately, based on information from a single station only. In this case, the large error is due to the first station triggered being a strong motion accelerometer. Most of the stations to the north of the bay area are strong motion accelerometers, which are susceptible to noise pollution below $M \approx 5$. For large earthquakes this is not a problem, but in smaller events high-gain broadband velocity sensors yield superior data*' (WURMAN et al. 2007: 11). This again highlights the extreme importance of a dense network where both strong motion and weak motion instruments in order to reduce magnitude errors and improve warning times.

One advantage considering site placement and network coverage is that most attenuation effects within a 100km radius of the instrument stations can be ignored as this only affects the data and resulting magnitude estimates at larger distances (WU et al. 2007: 716). Provided that the regional coverage is sufficient, this is at least one less factor that needs to be considered.

All in all, the ElarmS methodology seems to have reached a point where real-time, online implementation in California should be possible in the near future (WURMAN et al. 2007: 19). While the system still has a blind zone, where no warning would be possible in the vicinity of the epicenter, such a warning would still give enough time to stop trains, shut down or prepare shutdown of refineries, power stations, utility plants as well as close bridges and airports. Even with little warning, individuals may be giv-

en a slight time frame in which to take precautions for their personal safety. (ALLEN 2008)

Finally, while such a system might be '*highly effective at reducing deaths*' it may have little or no influence on reducing the cost of earthquakes (ALLEN 2007b: 23).

5.1.6. Résumé

The evidence that there is a scaling relation between incoming P-wave frequency data and earthquake magnitude makes this method possible. The theory is sound and reproducible and results have shown that the linear correlation between the maximum predominant period and earthquake magnitude lies at around 0.9. (OLSON and ALLEN 2005: 212)

Determining the earthquake location and magnitude using the ElarmS methodology can take from 1-2 seconds up to 4-5 seconds depending on if the network-based or the single station approach is used. Particularly smaller earthquakes require less time for computation; although it would be more important for large events to be determined as quickly as possible as these generally imply more damage to livelihoods. Being able to give warning for smaller events may not be so relevant to California, where solid building codes are in place and enforced so that housing and infrastructure substance should be able to withstand smaller earthquakes.

Noteworthy are also the error margins achieved by ElarmS. While having a magnitude error of one unit may be questionable when considering the full implementation of the ElarmS methodology into an EWS, the algorithms achieved a magnitude error of only 0.5 magnitude units in later studies, for example TSANG et al. (2007: 3). Using 3-5 seconds of the incoming p-wave data would probably be sufficient for full implementation of the system. Furthermore, with a known possible error margin of 0.5 magnitude units, the potentially affected population could probably assess the impact the earthquake will have on them sufficiently to weigh up the best possible mode of action. The AlertMap and evolved ShakeMap have proven to be an equally useful tool in assessing possible warning times for affected populations.

To answer the first research question:

How well can the P-wave/S-wave modelling (ElarmS) be used to predict earthquakes?

At the current level of research, with current error margins in magnitude estimates, a full online implementation of the ElarmS system to predict earthquakes is thinkable. The largest drawback that would speak against a full online implementation is that the system has only been tested offline with data from past events. A test run in an online environment would be beneficial to improving the system's robustness in a real-time setting.

Can this method (as used by ElarmS) be applied to all fault types?

The results show that this method is very promising for implementation into a full EWS in California. Also, although it is less relevant to the study area of this thesis, it is nonetheless significant that similar results could be achieved in other regions such as Japan, with only slight differences in the linear correlation between maximum predominant period and magnitude. So it seems that although there are regional differences through geology and site effects, with some calibration measures it should be well within the possible to implement this kind of EWS to all fault types.

What time-span prior to an earthquake would this method allow?

The possible time-span allowed for warning is anywhere between 0 seconds and 50 seconds at the current state of research. Giving any warning time directly at the earthquake epicenter will probably remain a large challenge in the ElarmS system, but further from the epicenter a significant amount of warning time can be given. One drawback that remains is that the time for the dissemination of information to the affected population is not and cannot be considered at this stage of research.

On a further note it is also important to mention possible improvements which should be considered in order to further reduce magnitude estimate errors and computation time:

- The implementation of a progressive weighting system as suggested by WURMAN et al. (2007: 6).
- Further improve the robustness of the algorithm to local site effects.
- Improve the coverage of both high-gain broadband velocity sensors AND strong motion accelerometers.

5.2. QuakeFinder

QuakeFinder is a humanitarian research project of Stellar Solutions and is currently trying to develop methods for earthquake detection and forecasting based on the detection and analysis of electromagnetic precursors. (Quakefinder (ed.) 2014: online on 29.01.14)

QuakeFinder has received funding from its parent company Stellar Solutions, government agencies such as NASA and also receives private donations in order to build up a network of instrument sites, mainly in California but also in Peru, Taiwan and Greece. Magnetometers are the most important feature of these sites, the system of magnetometers works to detect and monitor electromagnetic (EM) changes in the surrounding area. (DUNSON et al. 2011: 2086)

QuakeFinder's focus lies on ULF (ultra-low-frequency) electromagnetic emissions. ULF electromagnetic activity has been recognised, in several studies, as a precursory earthquake phenomenon. Furthermore, *'ULF (ultra-low-frequency) electromagnetic emission is recently recognized as one of the most promising candidates for short-term earthquake prediction'* (HAYAKAWA et al. 2007: 1108).

The topic of precursory ULF-EM activity prior to earthquakes is much discussed in the scientific community. There are *'studies that report no correlation, or only occasional correlation between earthquakes and some of the phenomena previously reported as precursors'* (BORTNIK et al. 2008b: 2825). This is because precursory

phenomena and the mechanisms responsible for their occurrence are not fully understood, which makes researching in this field a challenge. (BORTNIK et al. 2008b: 2825)

As the physics behind the processes that occur prior to and during earthquakes are still poorly understood, a plethora of theories have emerged ranging from these EM emissions occurring due to piezoelectric effects due to stress changes or induction effects caused by the motion of electric charges in the geomagnetic field, all the way to the release of gas and ions or positive hole defects in minerals. (DAUTERMANN et al. 2007: 1)

The ultimate goal would be to forecast large earthquake events hours or days before they occur. The largest hurdle is however the task of observing and recording enough data to successfully link ULF-EM activity to precursory earthquake activity, statistically prove the linkage in order to move forward to reliable earthquake prediction. (BORTNIK et al. 2010: 1615)

Quakefinder tries to do this by focussing on the '*the statistics of the pulse properties, the character of the bursts, the pulse dispersion characteristics, statistics of their angles of arrival, multi-site observations, etc.*' as these characteristics have not been fully analysed and explored to date (DUNSON et al. 2011: 2086).

5.2.1. Instrumentation

While QuakeFinder focusses largely on EM phenomena, other factors such as surface ion changes, ground motion as well as temperature and humidity are also monitored at each instrument site. The network of instruments in California is called the CalMagNet and tries to bring more light to the possible relationship between ULF-EM phenomena and earthquakes. (CUTLER et al. 2008: 360)

CUTLER et al. (2008: 359-360) goes into more detail on site selection and data collection in the CalMagNet. First of all, the site selection strategically tries to locate stations as close as possible to land-based earthquakes with a magnitude greater than 5.0 in California. A relatively dense network is required for optimal results, where instruments should be within a 10km range of an earthquake epicenter.

The first sites (named QF-HS) were installed in 1998 as part of a high school educational program. These were upgraded from 2001 onwards to more commercial versions which proved to be both more sensitive and more reliable and renamed to QF-1000. The year 2003 and funding from NASA allowed a further 20 instrument systems to be built and installed, old instrument sites were also upgraded with GPS time synchronisation, air conductivity sensors and geophones (QF-1003). There are also a few high-performance systems installed by 2008, these QF-1005 enable more detailed measurements of ULF-EM activity. Alongside some stationary QF-1005 systems there is also a transportable system for short-term field campaigns ranging from weeks to months. (CUTLER et al. 2008: 360-363)

Since new instruments and sites are costly, statistical methods have been used to identify regions with a higher probability for large future earthquakes. The method used is the PDPC (Phase Dynamic Probability Change) method and helps to identify these areas. The CalMagNet is then expanded into these higher-probability areas to improve the chances of gathering data of a nearby future event. (CUTLER et al. 2008: 360)

Each modern Quakefinder instrument site therefore contains the following monitoring equipment:

- Three magnetometer coils that monitor triaxial magnetic activity. This technique is called geomagnetic depth sounding (GDS). In order for the measurement to be triaxial, one coil must be aligned in the geodetic north/south direction, a second coil must be aligned in a geodetic east/west direction and the third coil is installed vertically. Positive signals in the N/S coil would indicate a magnetic field vector in a northerly direction, positive signals in the E/W coil would indicate a magnetic field vector pointing east and a positive signal in the vertical coil would indicate a magnetic field vector pointing down. Noteworthy is that these coils are calibrated twice daily (at around 12:00 and 24:00) with the calibration lasting for 5 minutes. (CUTLER et al 2008: 359)
- As these magnetometers are sensitive to motion (causing noise in the measurements) these instruments benefit from a nearby seismometer station which can provide a reference for ground motion and any possible noise this may induce. For this reason, Giscogeo geophones SN4-4.5 were installed to monitor

any physical ground motion. These are five times more sensitive than the induction coils of the magnetometers allowing for a very good discrimination of ground motion noise (EM-signal contamination). (CUTLER et al. 2008: 362)

- Air conductivity sensors are equally located at each station. BORTNIK et al. (2010: 1615) and BLEIER et al. (2009: 596) report ‘an air conductivity sensor’ and BLEIER et al. (2010: 1966) reports two Trifield Air Ion Counters. Contamination can however occur when these sensors are exposed to rain, condensation or by relative humidity (RH) values exceeding 95%. This causes the conductivity signal to saturate, the signal during this time is therefore unusable which is why temperature and humidity sensors have also been installed at all modern sites. (BLEIER et al. 2009: 596; CUTLER et al. 2008: 360)

An additional difficulty is that there is a large range of natural or man-made noise sources that can interfere or ‘swamp’ the signals being recorded, which is another reason why such a range of instruments are placed at each station and such a range of data is collected. (BORTNIK et al. 2008b: 2825)

Regarding the EM measurements, interference or noise can occur for example through cultural sources (public transportation, any kind of electronic current, farming machinery, moving ferromagnetic items) or natural sources (lightning, wind causing movement through tree root systems, movement of the coil in the earth’s magnetic field). The best way to deal with this noise is to be able to identify the source which means the interfering/unwanted signals can then be excluded from the analysis. One way to do this would be to characterize and catalogue these various noise characteristics. (CUTLER et al. 2008: 363-365)

There are also solar-terrestrial effects that can interfere with the ULF-EM signals being recorded. Alongside the movement of the coil in the earth’s magnetic field mentioned above which is caused by the natural geomagnetic variation, there are other phenomena like geomagnetic storms (solar storms) which can equally cause a higher level of noise in the data collected. Such solar-terrestrial effects must therefore be monitored alongside ULF-EM activity at the earth’s surface in order to be able to define what is noise and what is signal in the recorded data. (HAYAKAWA et al. 2007: 1120)

All in all, each QuakeFinder instrument site can store raw data for up to 600 days in case of a power failure. Data is stored in 8 channels sampled at 32 Hz and 24bits and then converted from an analog to a digital signal. Every night, data is transferred to a datacentre over satellite-based internet links. (CUTLER et al. 2008: 361-362)

5.2.2. EM theory, data and results

'Low-frequency (0.01-10 Hz) (usually termed ULF) and high-frequency (80 KHz) magnetic noise has recently been suggested to precede earthquakes' (JOHNSTON et al. 2006: S207).

Up until today, there have only been three events where anomalous ULF magnetic activity has been recorded prior to a large earthquake:

- Spitak, Armenia on the 8th December 1988, Magnitude 6.9
- Loma Prieta, California on the 18th October 1989, Magnitude 7.1
- Guam, Pacific Ocean on 8th August 1993, Magnitude 8.0

Through these earthquakes it has become apparent that some ULF emissions take place prior to large earthquakes. It can be expected that these precursory EM effects may well lead to the development of an EWS should similar emissions occur for all large earthquakes in a given region. (HAYAKAWA et al. 2007: 1108-1119)

There are currently two ways in which these EM earthquake signals can be observed. These signals can either be monitored through the direct observation of EM-emissions at the earth's surface, or through the indirect monitoring using radio sounding (the propagation anomaly of the initial EM-signal). The main mode of observation that QuakeFinder uses is the first method. The observation of these EM-phenomena needs to take place in the local surroundings of the epicenter as larger distances cause stronger attenuation of the ULF signal. ULF-EM signals are particularly favoured for measuring and monitoring precursory earthquake phenomena as higher frequencies are attenuated much more strongly within the ground and often do not propagate to the surface where they can then be measured. (HAYAKAWA et al. 2007: 1108-1119)

The suggested cause of these ULF-EM emissions is that during the preparation phase of an earthquake (the last phase where stress is built up before reaching the critical point where shear stress exceeds shear strength) a self-organized criticality phenomenon takes place. At this point, micro-fracturing is expected in the focal region of the hypocentre, followed by an increasing number of micro-cracks which then begin to coalesce during which ULF-EM activity or emissions are suspected to occur. (HAYAKAWA et al. 2007: 1119)

If this process can be proved to be the cause for the ULF-EM emissions, then earthquakes occurring in the same region would all behave in a similar way, emitting similar precursory signals which would allow for repeatable precursory behaviour to be recorded (BORTNIK et al. 2008b: 2826). This has sadly not been the case so far, on the other hand, many more instruments are installed today than were present during the past few decades meaning at least the chance of recording data from a nearby large earthquake event is slightly larger than it previously has been.

Several of the following papers in this subchapter are concerned with either recording and characterising noise sources or identifying pre-seismic ULF-EM emissions. To begin with we will look at the results concerning all possible noise sources.

First of all, BORTNIK et al. (2008b: 2826) is concerned with Pc1 pulsations recorded at Parkfield, California. These Pc1 pulsations can be defined as a continuous magnetic pulsation in a frequency range between 0.2 to 5 Hz and usually last from minutes to hours.

To identify these and link these to a source, data from the triaxial coil magnetometers from the period February 1999 to July 2006 are used. As it was less important to find the orientation of these Pc1 pulsations, only the data from the horizontal channels was used. The pulsations are identified and characterised automatically using a previously developed algorithm. Also, using only the horizontal channels added to the robustness of the characterisations as these are less susceptible to noise contamination than the vertical coil channel. (BORTNIK et al. 2008b: 2827)

During the analysed period, the M6.0 Parkfield earthquake took place (on the 28th of September 2004), which meant that these results could be directly compared to the 7 year period to see if the ULF-EM data during the pre-earthquake and earthquake pe-

riod shows any anomalies compared to the remaining period. For the correlation between pre-seismic and seismic Pc1 pulsations and Pc1 pulsations from other sources, data from the USGS NEIC (National Earthquake Information Center) catalogue were used. All earthquakes occurring during the study period within a range of 3000km to the magnetometers were used for this correlation. (BORTNIK et al. 2008b: 2827)

The data showed several interesting results:

- *'The relative probability of occurrence of Pc1 pulsations is significantly higher during the day time hours, ~ 5-15 days prior to the earthquake occurrence, by a factor of ~26'* (BORTNIK et al. 2008b: 2828).
- *'Suggest that even though Pc1 pulsations are strongly correlated with geomagnetic activity, and are also apparently well-correlated with earthquakes, geomagnetic activity and earthquakes do not show any direct correlation'* (BORTNIK et al. 2008b: 2830).
- *'If the correlation of Pc1 pulsations and earthquakes is indeed real, as it appears to be, then those midday Pc1 pulsations that precede earthquakes probably originate from a source other than geomagnetic storms'* (BORTNIK et al. 2008b: 2830).

If the source of the Pc1 pulsations that occurred prior to the earthquake is different to the usual Pc1 pulsations recorded during the remaining period, it becomes viable to say that these Pc1 pulsations are generated due to the build-up of electric currents within the earth (rather than through geomagnetic storms) and that the transmission of Pc1 pulsations may be altered between the ionosphere and the ground due to the earthquake. (BORTNIK et al. 2008b: 2830)

BORTNIK et al. (2008b: 2831) does hint that the results should not be cause for a generalisation and remain suggestive to the actual cause of the heightened Pc1 pulsations until such results can be repeated with data from other earthquakes.

In a later article, BORTNIK et al. (2010: 1616) the Alum Rock earthquake (M5.4) from the 31st of October 2007 is remodelled to see if similar magnetic signals could be observed. For this study, the Alum Rock earthquake was set as the Californian earth-

quake stereotype and tested/modelled to see if the magnetic signals observed really were generated by a source of electric current at the earthquake hypocentre.

(BORTNIK et al. 2010: 1616)

This was done by modelling the earthquake, and setting a simple underground current source at the earthquake hypocentre, that would generate an electric current with a magnitude that should make it theoretically possible to measure the said current at the surface using magnetometers. The results showed a smaller current range of ~10-100kA than what would have been expected for the magnitude and based on previous estimates. (BORTNIK et al. 2010: 1621)

Also surprising was the result that when distributing the propagated EM signal as a 2-D distribution within a 50km range of the epicenter, '*deep nulls in the signal power develop in the non-cardinal directions relative to the orientation of the source current, indicating that a magnetometer station located in those regions may not observe a signal even though it is well within the detectable range*' (BORTNIK et al. 2010: 1615). These nulls occurred because the wave signal that should have propagated from the hypocentre to the earth's surface was attenuated by over 4 orders of magnitude. This highlights the difficulty of monitoring these phenomena and the importance of a dense network that offers full coverage so that these EM signals may be picked up. (BORTNIK et al. 2010: 1615-1621)

Several explanations are offered to explain these results. First of all the authors stress that the model is obviously a simplification of the actual geological setting and that regional or local variances may cause amplification or further attenuation of the EM signal. Furthermore, the Parkfield region has a large value of ground conductivity which could also help to explain why the precursory magnetic signal was not observed in the way it should have been. A last suggestion is that the result may also be dependent on how the incoming EM data is analysed and that by using time-limited pulses rather than a continuous waveform for the analysis the results might be more positive, as in the article by BLEIER et al. (2009). (BORTNIK et al. 2010: 1619-1621)

BLEIER et al. (2009: 586) looks at correlations in space and time between the M5.4 Alum Rock earthquake on the 31st of October 2007 and ULF-EM signals, IR signals and air conductivity changes. The theoretical basis for these analyses lies in much of

what Friedemann Freund has published in the past 10 years. The simplified theory suggests that p-hole (positive hole) charge carriers are generated during the asymmetric stressing of rock which then in turn generates the electric underground currents and the ULF-EM signals. (BLEIER et al. 2009: 586)

Also important, is a further focus that potential contamination sources for EM signals should be investigated, as well as, if the 'signal' truly does emerge from earthquake processes. BLEIER et al. (2009: 586) tries to bring some light into this matter.

The first results from the Alum Rock earthquake highlighted that there were pulsations prior to ground motion in the EM data at a 5Hz bandwidth that could not be associated with any calibration processes of the magnetometer system. Furthermore, a co-seismic EM signal was also recorded. Post-earthquake, further EM pulses were registered throughout the following night. All these recorded pulses could further be characterised as being positive only, negative only or 'regular' bi-polar pulses. Every pulse count counts for a change in the local magnetic field as the type of magnetometer used is an induction magnetometer. (BLEIER et al. 2009: 586-587)

The characteristics of these pulses help to identify the source causing them. Bipolar waveforms can usually be explained through man-made noise pulsations. Waveforms with just a single polarity usually mean that some type of current or disturbance started abruptly and then relaxed slowly over several seconds without changing polarity type. One such natural phenomenon is lightning. As lightning has a very short pulse duration (under one second), it can still be clearly discriminated from the EM-signatures that may be caused by a pre-seismic, co-seismic or post-seismic effect. (BLEIER et al. 2009: 588)

In order to discriminate all the man-made noise in the data, noise surveillance tests were carried out to identify all possible noise sources within 100m of the instruments. These included cars and trucks (roads), power tools, water pumps and nearby testing facilities. The tests were specifically performed on a Sunday in order to ensure a relatively quiet environment which presumably aided the discrimination of individual bipolar pulses and pulse types. During these tests, all man-made noise sources were successfully identified. Testing the set of instruments to see if these too could be the cause for noise interference was equally important, but no pulse counts were regis-

tered or identified as coming from the instruments themselves. (BLEIER et al. 2009: 589-591)

The threshold set for defining the pulsations, is that a pulse is typed and counted as soon as its amplitude becomes two times greater than the site background noise. (BLEIER et al. 2009: 593)

The results of this study show elevated pulse counts throughout the summer months, with a peak of pulse counts around the end of October 2007 (when the earthquake happened). There were also two shorter periods where the pulse count built up over a week, both of these build-up periods led to an earthquake between M3 and M4. Prior to the Alum Rock earthquake, the pulse count built up as well, but to a higher level and for a sustained period of around 2 weeks before decreasing again after the earthquake. It is believed that this period of heightened pulse counts for over 2 weeks before the earthquake happened may be linked to the processes occurring during the heightened stressing of the rock (before the deformation processes avalanche into an earthquake). (BLEIER et al. 2009: 589)

In order to prove that no further noise interference was caused by lightning, a lightning survey was purchased providing lightning and storm data for California in October 2007. This report proved that there was generally little lightning in California in October, meaning that only very few pulse counts recorded were due to lightning 'noise'. On the two days where pulse count was highest prior to the Alum Rock earthquake, the 17th and 24th of October, no lightning strikes were recorded in California. In future, characterising lightning strikes by their pulse duration may make it possible to exclude lightning pulses from being counted in the EM data by setting a pulse duration threshold (without having to rely on the purchase of lightning reports). (BLEIER et al. 2009: 589-590)

Solar generated continuous micropulsations (Pc1 pulsations) were also recorded. While this counts as noise, these pulsations can be discriminated well from the remaining signal due to the long period of the disturbances (50-100 second pulses in the 0.01 to 5Hz band lasting from hours to days). Furthermore, these solar generated Pc1 pulsations can be detected world-wide, again simplifying the discrimination of this noise as it would simultaneously show up on the recordings of all instrument sited. Some Pc1 pulsations were detected at East Milpitas (the instrument site closest

to the Alum Rock epicenter) that were not detected elsewhere, suggesting a different source for these large pulses. (BLEIER et al. 2009: 589-592)

Some of the pre-seismic pulses were unique to the previously mentioned patterns. They generally lasted between 1 and 30 seconds and were largely uni-polar. Uni-polar means, *'they had either a positive only or, a negative only component relative to the DC mean value of the time series data'*. (BLEIER et al. 2009: 592-593)

Table 7: Counts of individual Pulse types at Alum rock (E. Milpitas) (Source: BLEIER ET AL. 2009: 593)

Pulses	2006-2007	5 to 31 Oct 2007	% of Total
Up	11282	4108	36
Down	9176	3119	34
Bipolar (up)	5993	2689	45
Bipolar (down)	4757	1707	36

Table 7 shows the results of the types of pulse counts both in the whole study period and in the two weeks leading up to the Alum Rock earthquake. The % values in the last column indicate the % of pulses in the 2 week pre-seismic period compared to the 2 year period. This two week period represents only 2% of the total time in the 2 year period, but accounts for 34-45% of all the pulses counted in the 2 year data set. (BLEIER et al. 2009: 593) This suggests that significantly more EM-signals were being emitted in the pre-seismic period which supports the idea that these signals were generated due to the extreme stressing of rock prior to the rupture.

Alongside the fixed station at East Milpitas, four temporary stations were installed, collecting data on the day after the earthquake to determine the maximum range at which the EM-pulses could be detected. One of these mobile stations did not show any correlation of data, probably because it was located 6.6km away and perpendicular to the fault trace. (BLEIER et al. 2009: 594) This relates strongly to the pattern recorded in BORTNIK et al. (2010: 1615-1619).

Another interesting point that was noted between the fixed and the temporary sites is that there is a temporal offset between the arrival of the EM-pulses, whereby the fixed site was 2km and the temporary site was 3km away from the earthquake epicenter. In order to explain this, a propagation speed of 200m/s was assumed. The calculated offset with this propagation speed is 5 seconds; the actual offset was slightly higher at 8 seconds. This suggests that EM-pulses may propagate at a slightly slower rate than was previously assumed. (BLEIER et al. 2009: 598)

ULF data from the Parkfield earthquake (M6.0 on the 28th of September 2004) was also available for this analysis. Around 15 days before the earthquake happened, a similar pulsation period started with the local area and solar activity being relatively quiet/ negligible. The instrument site was at a relatively quiet location on a farm, and as a lot of the pulsations were recorded during the night time, the likeliness of human interference/man-made noise was low. Similar to the Alum Rock earthquake, EM-signals were still recorded up to a few days after the event. Just like in the Alum Rock data, these high pulse counts could not be attributed to aftershocks. It is suggested that these post-seismic pulsation counts could be due to the stress redistribution in the rock (redistribution of stress causing the generation of electric current). (BLEIER et al. 2009: 594-595)

One difference between the data from the Parkfield and the Alum Rock earthquake could be distinguished. The pulses counted at Parkfield were smaller than those recorded at Alum Rock, possibly due to the closest recording site being further away from the earthquake epicenter at Parkfield than at Alum Rock. (BLEIER et al. 2009: 594-595)

JOHNSTON et al. (2006) also analysed data from the M6.0 Parkfield earthquake from 2004, equally focussing on pre-seismic, co-seismic and post-seismic EM-observations. In this study, data is sampled synchronously every 10 minutes and immediately transmitted to the USGS. (JOHNSTON et al. 2006: S207-S208)

The parameters analysed in this study were noise amplitude spectra, recorded at seven synchronised magnetometer stations in the region. The results showed no significant differences in noise amplitude before and after the earthquake. Furthermore, the study showed no changes in strain, pore pressure, micro-seismicity or ground

displacement. The authors suspect there is no significant correlation between EM-phenomena and earthquakes. (JOHNSTON et al. 2006: S213-218)

It can however be assumed that, due to the fact the data was collected in 10 minute intervals and not continuously sampled, that this may have had a smoothing effect on any pulsation counts. Furthermore, only 2 magnetometer stations were within a 10km range of the epicenter which would mean that stations further away may not have registered any data due to the strong attenuation of the signal. (JOHNSTON et al. 2006: S208) It would be interesting to see if the method used by BLEIER et al. (2009) would have led to similar results using the data from the two closest stations to the Parkfield earthquake epicenter.

The last study to be analysed is by DUNSON et al. (2011) and is also the most recent study published directly by QuakeFinder. The importance of not just recording anomalous ULF-EM signals, but also being able to discriminate their characteristics is highlighted in this study (DUNSON et al. 2011:2088).

It also critically reflects on studies that have focussed on averaging data (for example over half an hour), suggesting instead that the focus should be on defining ULF pulses which allows for '*signals of interest*' to '*grow more steeply due to the short nature of the signal*', while particularly the Pulse Azimuth Cluster technique should help to add another criterion for discrimination (DUNSON et al. 2011: 2088). The Pulse Azimuth Cluster technique maps the direction of the incoming pulses to identify and discriminate narrow bands of pulses which can be identified as being earthquake-related (DUNSON et al. 2011: 2089-2090).

The following steps make up the process of this technique:

1. Bad data events are masked out from the analysis
2. Mean removal and highpass filters are applied to reduce the effect that other noise sources such as solar-generated Pc1 pulsations would have on the analysis
3. Uni-polar pulses are detected by applying an amplitude threshold to the signal

4. The azimuth histogram is then computed by projecting the value of the azimuth onto a circle using the formula 'azimuth = atan2 (NS, EW)' and binning these pulses into one degree wide bins (360 bins total)
5. Azimuth cluster evaluations are conducted in order to find spatial (appearing in a small angle of the circle of step 4) and temporal (ranging from hours to days). (DUNSON ET AL., 2011: 2089-2093)

Figure 15 explains how the pulse azimuth effect works. There are two variables in the angle of the azimuth, namely either the variable position of current flow to the site or the variable orientation of that current vector (j). If one of these factors changes (either the angle to the location of the current flow or the angle of the field near that current flow) then the coils will record a change in the ratio of the projected energy. (DUNSON et al. 2011: 2093)

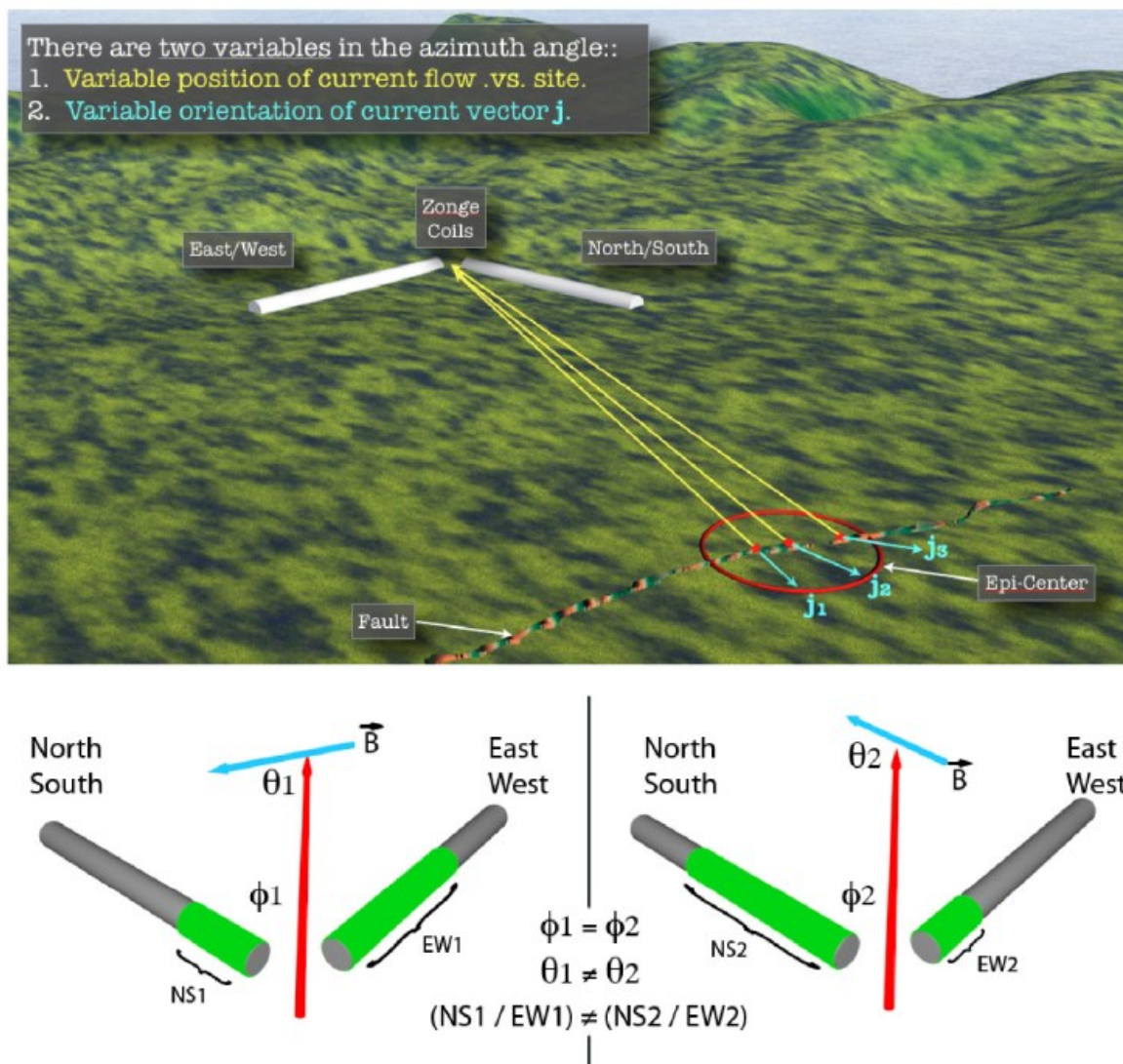


Figure 15: Model of the Pulse Azimuth Effect. (Source: DUNSON et al. 2011: 2093)

This pulse azimuth cluster technique improves the repeatability of azimuth computations for earthquakes with a high signal to noise ratio. Those earthquakes with a low signal to noise ratio however, still suffer from weak results. For the two Alum Rock earthquakes (M5.4 on the 31st of October 2007 and M4.0 on the 7th of January 2010), almost all of the pulse bursts were recorded within a window of 8°. For the Tacna, Peru earthquake (M6.2 on the 6th May 2010) showed a much wider range window of 30 to 45° for the pulses. (DUNSON et al. 2011: 2093-2094)

This level of discrimination for the individual uni-polar ULF pulses allows several further observations to be made. For example, prior to the 2007 Alum Rock earthquake, the pulses observed could all be located from a similar source (a 7° window of pulse clusters) and lasting for several days. In such a case it is easy to eliminate lightning as a possible source, as this would have required a stationary storm system over that exact locality for several days. Due to the unlikeliness of such an event it is easy to exclude this as a possible noise source, meaning the pulses are caused by another phenomenon. (DUNSON et al. 2011: 2095)

In the case of the Tacna, Peru earthquake, it is hard to specify a temporal or spatial window from which the ULF activity is coming from due to the relatively large variance in angles the signals were recorded in, in the azimuth histogram. The pulses sampled in Tacna also showed shorter pulses than the Alum Rock quake (~0.2–5s compared to 2–10s) which is also a small drawback as these pulse lengths are more similar to what has been measured during, and associated with, lightning. It can be noted that around 14 days before the event, more azimuth clusters were recorded, and that all of the clusters recorded lasted for several days which is conform with previously stated theories like BLEIER et al. (2009). So while the results are not as clear and definite as for the Alum Rock earthquakes, having the possibility of further discrimination through the pulse azimuth cluster technique is a great advancement in the QuakeFinder methodology. (DUNSON et al. 2011: 2097-2103)

All in all, the pulse azimuth cluster technique offers new ways of discriminating ULF pulses which can be considered an advantage and a step forward, towards a fully functional EWS. One drawback of the system is that the results seem to vary depending on the region. While the results in California have been promising so far, the results from the Tacna, Peru earthquake were less optimal due to the larger variance in pulse angles and the generally shorter pulses. To improve the technique it would

be worthwhile trying to find the cause for these differences, for example in local geology or fault characteristics.

One further project was launched by QuakeFinder in 2003, in order to monitor ELF (extremely low frequency) emissions by satellite. The idea behind this satellite mission lay in the findings of two satellites that were not originally designed to detect ELF signals (the Cosmos 1809² and Aureol-3³) which '*have detected ELF signals that might have been associated with earthquakes in the early 90's*' (FLAGG et al. 2004: 2). One such case was the Spitak earthquake in Armenia, 1988, where wide band bursts of energy were recorded by the Cosmos 1809 satellite. The question QuakeFinder wanted to answer was if a satellite designed specifically to monitor such data could effectively detect and correlate such signals to earthquake activity. (FLAGG et al. 2004: 2-8)

QuakeSat was designed to weigh less than 5kg and is less than 150cm long when fully deployed and houses a single axis magnetometer as well as a secondary electric field sensor. The mission was to target likely earthquake regions in order to potentially record any ELF signals, as well as collect post-earthquake data in order to determine which breadth of frequencies would be best to monitor. (FLAGG et al. 2004: 3-8)

QuakeSat was successfully launched on the 30th of June in 2003 and started collecting data on the 2nd of July the same year. Sadly, the system itself was a significant noise sources (CPU, internal modem, battery charge controller, power supply), a problem that could only be partially corrected by uploading new software to the system. One significant drawback of the QuakeSat is that contact time was limited to a maximum of 150 minutes per day, meaning the amount of data relayed to the earth had to be limited. (FLAGG et al. 2004: 6-7)

The satellite spent around 7 ½ months in orbit until the battery packs failed. The results collected during this time show a higher level of noise than had been expected. Some signals that could be earthquake related were recorded during the half year period where the satellite was in orbit and fully functioning. These signals had a wide band frequency and time span and were recorded shortly after the South Island, New Zealand earthquake (M7.2 on 21st of August, 2003), the San Simeon, California earthquake (M6.5 on 22nd of December, 2003) and the Kazakhstan-Xinjiang Border

region earthquake (M6.0 on 1st of December, 2003). (FLAGG et al. 2004: 4-8) Further results were collected that could be related to previous findings. Here a cataloguing process was started in order to identify these signals (for example as lightning). (FLAGG et al. 2004: 7-12)

A reason for the higher noise levels and few potentially earthquake-related results was successfully identified, *'the dawn dusk nature of our orbit has us flying over our targets while the ionosphere is in a turbulent transition period between night and day, these are likely reasons why we have seen only a few signals of the type we believe may be similar to the earthquake signals Cosmos 1809 detected over Spitak-Armenia'* (FLAGG et al. 2004: 9).

5.2.3. Air conductivity theory, data and results

QuakeFinder also records data on positive and negative air ions in the air near the ground surface level. There are several theories that try to account for a change in air ionisation prior to earthquakes.

The first theory suggests that air ionisation is produced through natural radioactivity in the ground (through radon in the earth's crust spreading towards the surface); this happens through chemical reactions which cause water to condense at these newly formed ions, further resulting in the release of latent heat of evaporation which increases the surface temperature and could relate to the thermal anomalies that have been observed prior to earthquakes. (PULINETTS 2007: 217-218) *'The ionosphere will grow over the earthquake preparation area and create a horizontal potential difference with undisturbed ionosphere outside the modified area'* (PULINETTS 2007: 218).

The second theory suggests the existence of stress-induced charge carriers (positive- or p-holes) which can move within the rock structure generating current pulses and associated magnetic pulses, as well as air conductivity and temperature changes at the surface and changes in the TEC (total electron content) in local ionosphere. (BLEIER et al. 2010: 1966)

The instruments used to measure these changes are co-located with the magnetometers and count positive and negative ions. At the East Milpitas site, closest to the

Alum Rock earthquake, the air conductivity sensors were installed about a year before the earthquake happened and were tested in order to assure they function properly. In May 2007, the system was modified slightly in order to minimise the possible contamination of the air conductivity sensors (as these are sensitive to moisture) by covering the sensors so that rain could no longer cause complete saturation of the result. Air conductivity measurements for the Alum Rock event then showed saturation of the air conductivity sensor for almost 13 hours prior to the quake with no significant rainfall. (BLEIER et al. 2009: 596)

One possible interference factor that cannot be excluded through further modification of the instruments is moisture and fog on the plastic plate separators, which can equally contaminate the data by causing full saturation of the signal whenever the relative humidity exceeds 95%. Prior to the event however, when the saturation of the air conductivity sensor occurred, the relative humidity was well below the 95% threshold meaning the saturation of the air conductivity sensors was caused by a different phenomenon. Furthermore, it could be distinguished that the vast majority of ions counted were positive ions shortly before the event took place. In the hours before this positive ion burst, four periods of negative charge bursts could also be clearly distinguished. (BLEIER et al. 2009: 596)

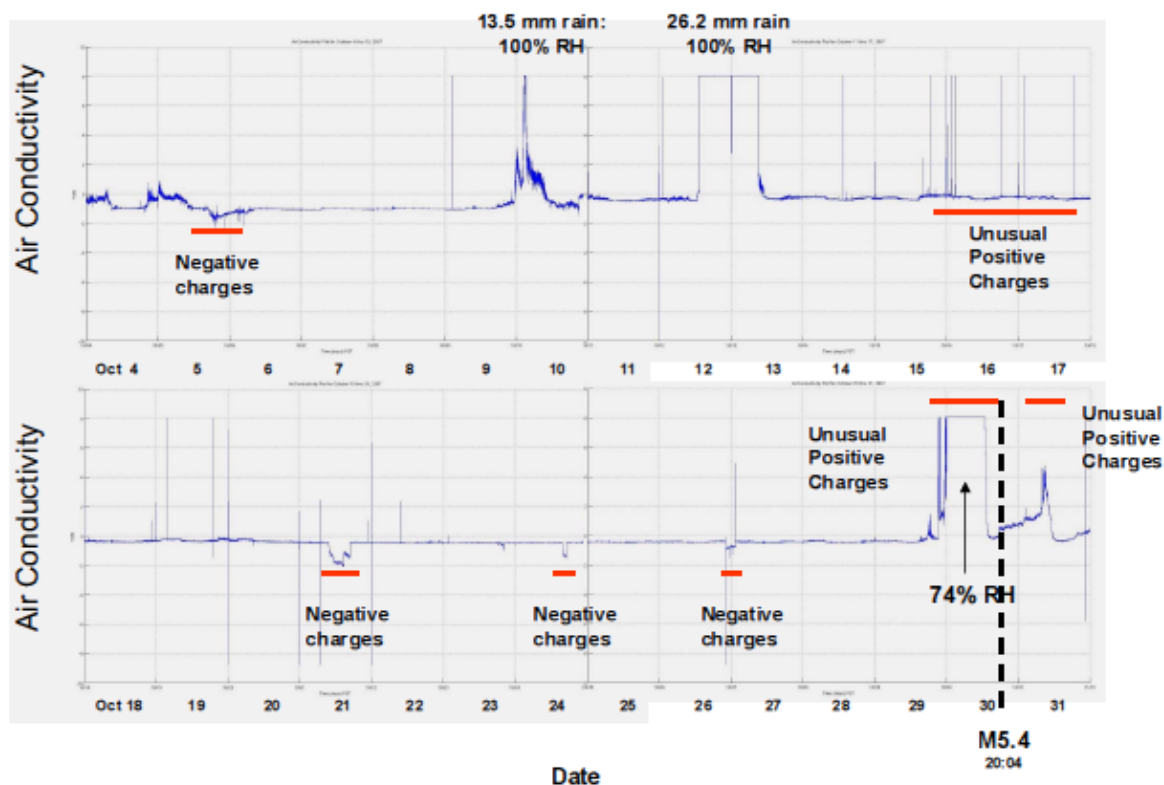


Figure 16: Air conductivity measurements at the East Milpitas site during October 2007 (Source: BLEIER et al. 2009: 599)

Figure 16 shows these results. Unusual negative charges were recorded between the 5th and 6th of October, followed by two periods of rainfall. Unusual positive charges were then recorded on the 16th and 17th of October, followed by 3 short periods of negative charges on the 21st, 24th and 26th of October. One last recording of unusual positive charges was recorded shortly before the earthquake, starting in the night of the 29th, lasting until shortly before the earthquake occurred on the 30th, and peaking again the day after on the 31st of October.

The difference between these positive ion bursts and negative ion bursts could be explained through the p-hole theory. It is suggested that before the positive ions emerge at the surface, the positive charges build up at the surface due to the arrival of p-holes from the stressed rock further underground (at the hypocentre). Thus, positive holes are generated in the stressed rock, these p-holes move to the surface, and cause the field-ionisation of air molecules. The negative ion bursts are explained through corona discharges, which occur *'when the positive fields at the rock surface become so strong that the positive air ions are accelerated away from the rock surface to velocities sufficient to impact-ionize neutral gas molecules and thereby initiate a corona discharge'* (BLEIER ET et al. 2009: 600). It is also suggest that these corona discharges are the cause for light phenomena that have been observed during some earthquakes (termed earthquake lights). (BLEIER ET et al. 2009: 600)

Retrofitting old CalMagNet stations began in 2009 in order to be able to measure relative humidity directly at the sites as well, making the discrimination of the incoming air conductivity signals easier. Also, modifications of the air conductivity sensors are to be implemented in order to eliminate any contamination through humidity. (BLEIER et al. 2009: 596-602)

The second study focussing on TEC (total electron content) is DAUTERMANN ET AL. (2007), who tries to correlate TEC measurements to earthquake phenomena from data recorded in 2003 and 2004. Data from the SCIGN (Southern California Integrated GPS Network), a densely spaced network of GPS stations located in and around the Los Angeles basin is used for this study and includes the San Simeon earthquake (M6.6 on the 22nd December 2003) and the M6.0 Parkfield earthquake. Three different models are used in order to spatially and temporally correlate the recorded TEC anomalies to the earthquakes. (DAUTERMANN et al. 2007: 2)

The results of the study showed several significant TEC patterns. For example, there are diurnal and semidiurnal periods where TEC measurements are affected by solar activity and lunar tides. Also, there is a significant pattern over a 27 day period which can be attributed to the equatorial rotation rate of the sun, as well as an annual pattern relating to seasonal variations in solar activity. (DAUTERMANN et al. 2007: 3)

While these results are useful for defining and characterising the usual patterns in TEC activity it gives little information about anomalous TEC signals which could be earthquake-related.

For the San Simeon earthquake in December 2003, the nearest site was located 56km away and showed a probability of only 1.2% of picking up any anomalous TEC measurements the day before the earthquake. Also, the chance for a false alarm is equally at 1% if there is no signal, leading to a very large chance of a false detection and very low chances in detecting the anomalous TEC signal. (DAUTERMANN et al. 2007: 14-15)

Also, while some anomalous TEC data was found among the data, it could not be correlated (in space or time) to the two earthquakes that had taken place within the 2 year period. The results were also suboptimal in that although isolated cases for anomalous TEC content could be found, it was only either detected at one or multiple stations and only using one of the three methods with the other two methods showing no results. A further disadvantage is that the anomalous TEC signal could also have been due to other causes. (DAUTERMANN et al. 2007: 4-19)

While these results seem somewhat disheartening, it is suggested that *‘systematically combining measurements from independent sensory such as GPS (for the ionospheric TEC) and ground or space-based electromagnetic measurements will help to understand the origin of the observed signals.’* (DAUTERMANN et al. 2007: 19)

5.2.4. Other theory, data and results

The theories described in the previous subchapter were also concerned with the emission of latent heat at the surface and temperature changes near the ground prior

to earthquakes. Such a phenomenon can be monitored through satellites measuring IR heating or apparent heating processes. (BLEIER et al. 2009: 586)

Such pre-seismic anomalous heating phenomena have been recorded for several large earthquakes (PULINETS 2007: 217).

BLEIER et al. (2009) set out to analyse GOES satellite data from the IR imager in order to identify if such heating had occurred prior to the 2007 Alum Rock earthquake. The focus lay in analysing long wave infrared data ($10.7\text{--}12\text{ }\mu\text{m}$), the spatial resolution of the data allowed for 4km pixel dimensions. (BLEIER et al. 2009: 596-597)

The analysis showed that the apparent heating cannot be measured in local ground temperature, but rather as energy in the IR signal, which is in accordance with several laboratory tests by Friedemann Freund on this topic. (BLEIER et al. 2009: 597)

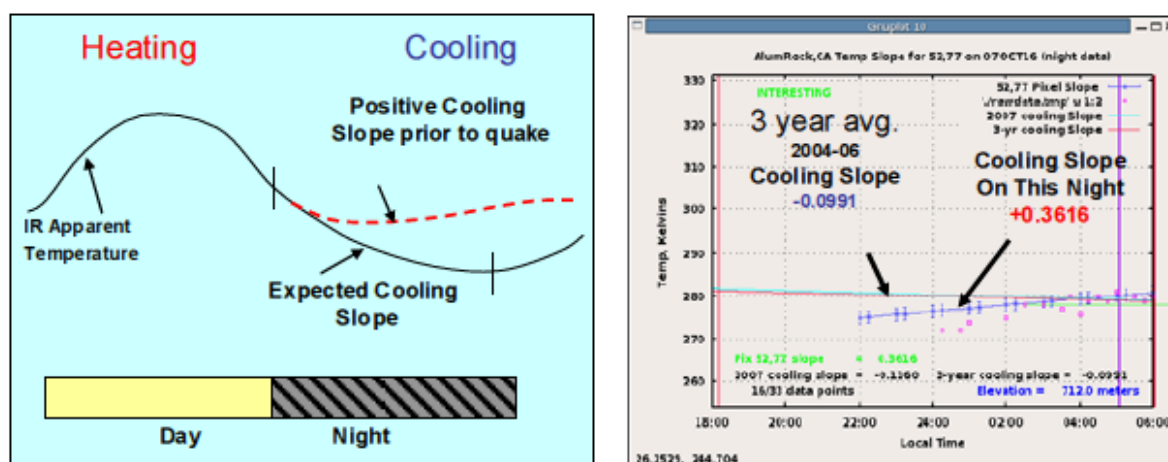


Figure 17: Typical IR nighttime cooling (left) and compared cooling slopes at Alum Rock (right) (Source: BLEIER et al. 2009: 599)

Figure 17 shows a typical Infrared cooling scheme between day and night on the left. The black curve indicates the heating and cooling average over a region under normal conditions (with no impending earthquake). The dotted red line indicates the change towards a positive cooling slope that can develop in the nights before an earthquake. On the right side the actual values around Alum Rock were averaged over 3 years (from 2004 to 2006) and had a night time cooling slope of -0.0991° per hour. On the night leading up to the earthquake however, the cooling slope was positive rather than negative, meaning the ground heated up rather than cooling down

between 22:00 and 06:00 the next day, at a rate of $+0.3616^{\circ}$ per hour. (BLEIER et al. 2009: 596-597)

Even the two weeks leading up to the earthquake showed an increased IR signal, with night time cooling values being lower than usual (signifying less overnight cooling than usual). During the same time that these changes in IR activity became visible, more positive ions were counted by the air conductivity sensors. The authors suggest caution however, in that the SNR was not overwhelming with the explanation that this was probably due to the earthquake being only a magnitude 5.4. (BLEIER et al. 2009: 598)

One further phenomenon related to earthquakes was also briefly looked at, namely light phenomena that have been observed during earthquakes. Earthquake lights have been related to changes in the electric and magnetic fields that can occur before, during or shortly after earthquakes. (LOSSEVA and NEMCHINOV 2005: 649)

Most importantly, in order to relate these sudden bursts of light to earthquake activity, one must try to exclude any other sources that could emit similar light patterns. One such source that could cause interference is the weather (thunderstorms and lightning). The role of such weather conditions on phenomena like corona discharges, arching, lightning initiations and EM pulse propagation should thus be investigated to see how the phenomena interact. (LOSSEVA and NEMCHINOV 2005: 653-654)

Further research on the topic of earthquake lights would be beneficial, as the main source of information is based largely on eye-witness reports. Being able to link earthquake lights to EM-phenomena and corona discharging as well as excluding other possible noise sources would help drive the current state of research forward.

5.2.5. Rock-breaking experiment

BLEIER et al. (2010) conducted a rock-breaking experiment on the 20th to 21st of August 2009. The theoretical background of this experiment was again based on the laboratory research conducted by Friedemann Freund. The goal of the experiment was to see if the same semiconductor effects could be detected in a larger rock sample in a field location (natural humidity and temperature). Going by the theory, the

results of the experiment should therefore show magnetic pulsations occurring before, during and after the 'rock-breaking', the pulses shapes and polarities should be similar to the laboratory experiments. (BLEIER et al. 2010: 1966-1968)

The boulder that was selected for the experiment was a 2 x 1.5 x 1.5m boulder located on a hillside near Bass Lake, California. In order to simulate an earthquake in the boulder, a way of first stressing the rock then causing the rock to break was necessary. As a first step, four 5cm diameter and around 1.1m long holes were drilled into the rock, along the centreline of the boulder. The rock was then left untouched for three weeks in order to assure the rock had dried out and the stress with the rock had redistributed. (BLEIER et al. 2010: 1966)

The following instruments were installed for the experiment:

- Two Zonge Eng. Model ANT4 induction type magnetometers
- Two Trifield Air Ion Counters
- A 'capacitor-type' surface charge detector
- A 4Hz geophone
- A Buckler Model EM27 IR spectrometer with Sterling-cycle cooler
- 3 temperature sensors (in the center hole, on the East and on the West face of the boulder). (BLEIER et al. 2010: 1966)

On the day of the experiment (20th of August, 2009), BustarTM, an expanding concrete, was poured into the holes at 10 p.m. which then started to expand causing the rock to fracture at around 5.30 a.m. on the 21st of August. (BLEIER et al. 2010: 1967)

The first signals occurred around midnight and were visible across the magnetometers, the air ion counters, the surface charge detector and the geophone. Starting with the magnetometers – these were '*located on the ground, in shallow trenches, approximately 1 m north and 1 m to the south of the boulder, with the axis of the magnetometer pointed toward the base of the boulder*' (BLEIER et al 2010: 1967). Sadly, magnetometer data is only available until around 2 a.m. as a power supply failed at around this time. (BLEIER et al. 2010: 1966-1967)

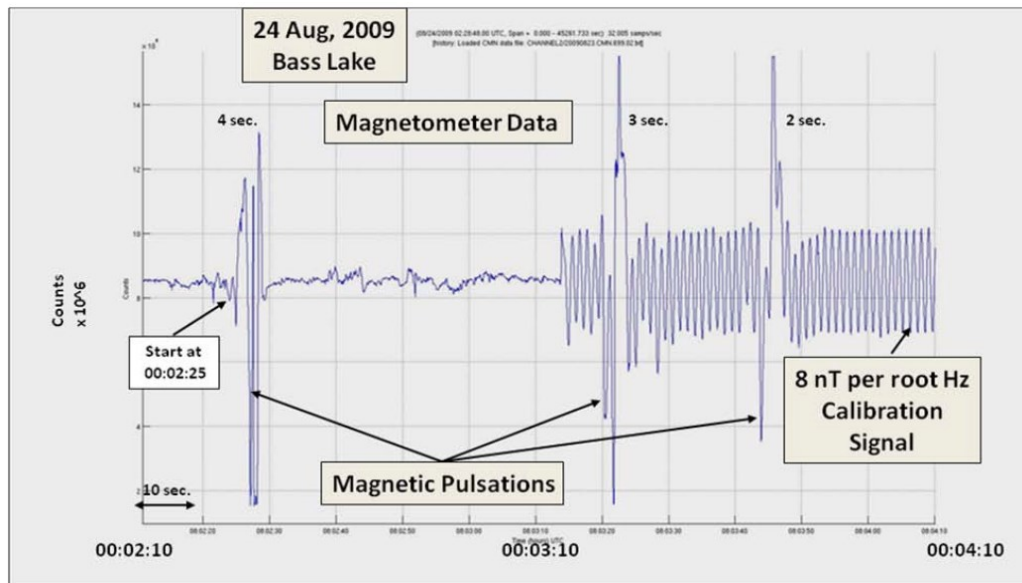


Figure 18: Midnight recordings of the magnetic pulsations from the rock breaking experiment.
(Source: BLEIER et al. 2010: 1969)

Figure 18 shows the most important results of the magnetometer data from around midnight. Further EM-pulsations were also recorded at around 10 p.m.; these were however attributed to the setup of the experiment up to the pouring of the cement (as metallic objects and physical ground movements caused for example by walking can equally cause EM-activity). The three pulses recorded just after midnight coincide well with the other signals also recorded around this time. The pulses generally had a length of between two and four seconds and were presumably caused by mechanical rock failure. (BLEIER et al. 2010: 1967-1968)

The data collected by the air ion counters was sadly also not optimal. One of the meters did not register any pulsations (presumably due to a wrong setup) and the other ion counter registered only negative pulses (but this successfully). Both instruments were suspended around 20cm above the boulder. The results of the ion counters showed large concentrations of ions, which were either largely positive or largely negative. These either positive or negative pulse periods were short and stopped shortly after midnight. (BLEIER et al. 2010: 1966-1971)

What was also beneficial to the experiment is that there were no weather conditions that could have affected these results negatively, the background noise levels were low and the ion count bursts occurring near midnight '*could not be explained by any local activity (natural or human) other than the rock stressing activity*' (BLEIER et al. 2010: 1971).

One of the temperature sensors was crushed during the experiment (the one that had been inserted into one of the bore holes). The results from the temperature sensors were not mentioned further. The surface charges on the other hand showed some clear results as can be seen in figure 19. Between pouring the concrete and the start of the first EM activity at around midnight, the surface charge remained positive. Midnight showed some activity after which the surface charge became negative and remained negative until the boulder ruptured at around 5:30 the next morning. (BLEIER et al. 2010: 1966-1968)

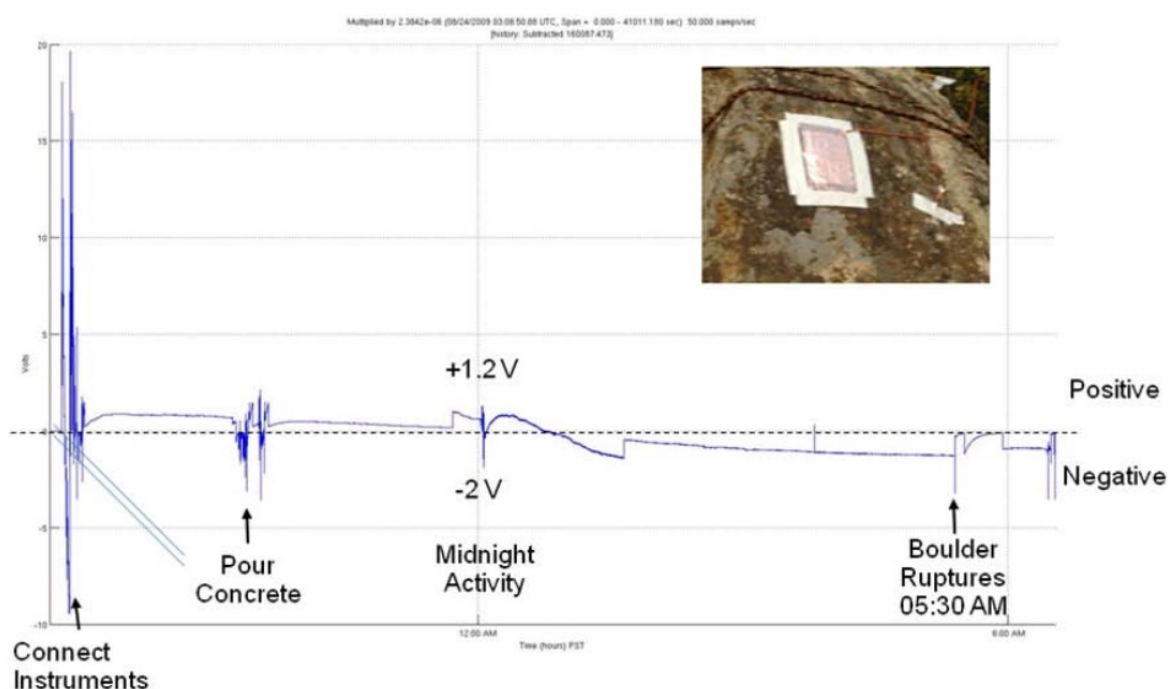


Figure 19: surface charge changes during the rock breaking experiment (Source: BLEIER et al. 2010: 1970)

The data from the Bass Lake rock-breaking experiment was then compared to three other earthquakes where a similar amount of data was available, namely the M5.4 Alum Rock earthquake, the M5.1 San Juan Bautista earthquake near Hollister and the M6.0 Parkfield earthquake. Whereby the Alum Rock data is particularly valuable in that it is the only case where two years of data is available prior to an earthquake. (BLEIER et al. 2010: 1966-1972)

The EM pulses in the rock experiment turned out to be similar in duration to those that had been recorded at Alum Rock in 2007. Figure 20 shows the EM pulse data from the M5.4 Alum Rock quake and the two years of data from the East Milpitas station leading up to the earthquake. (BLEIER et al. 2010: 1968-1971)

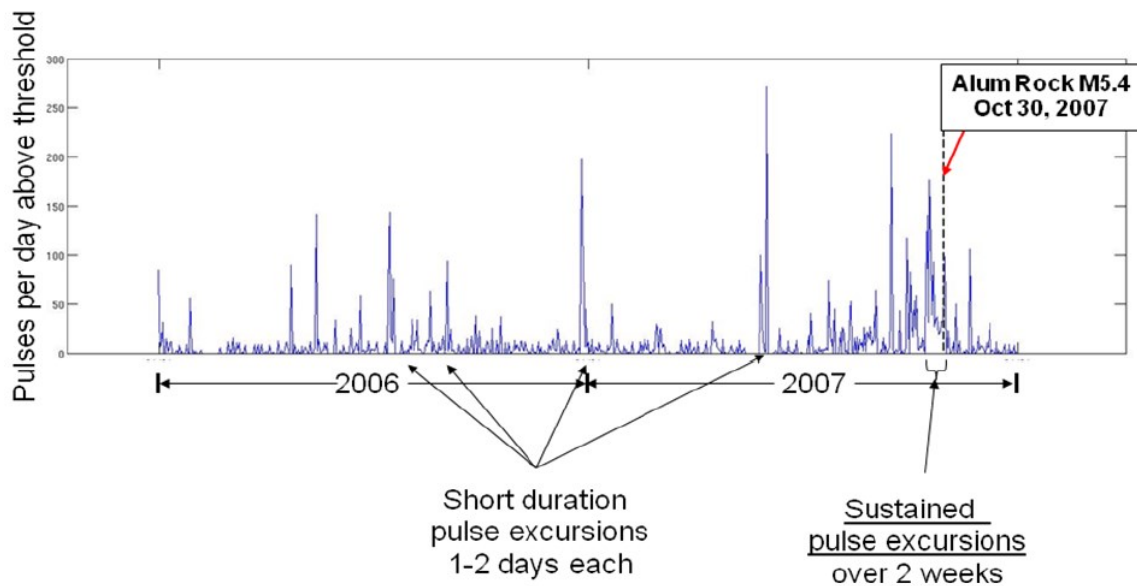


Figure 20: Two year pulse count for East Milpitas leading up to the M5.4 Alum Rock earthquake in 2007. (Source: BLEIER et al. 2010: 1971)

The fault near Alum Rock showed several periods of EM activity whilst building up towards the large earthquake in October 2007. These periods of pulse bursts were however relatively short (lasting between 1 and 2 days each). In the two weeks leading up to the earthquake, a similar period of pulse bursts was recorded; this however lasted for a much longer period of time (for over two weeks!). Several pulse excursions were also recorded after the earthquake, but at a much lower level than in the 2-week build up period prior to the earthquake. (BLEIER et al. 2010: 1971)

Through the rock-breaking experiment it became apparent that the EM, ion and surface charge activity occurring during the build-up of stress prior to the rock-breaking occurred at around the same time. Being able to discriminate earthquake-related activity through their combined occurrence could be useful in terms of clearly identifying a useful signal from a possible noise source. During the rock-breaking experiment, the magnetometers, the air ion counters as well as the surface charge detector showed a higher level of activity around midnight, 5 ½ hours before the rock fractured. For the Alum Rock earthquake, three indicators (magnetic pulse counts, air conductivity and infrared) were correlated. Figure 21 shows the results. (BLEIER et al. 2010: 1972)

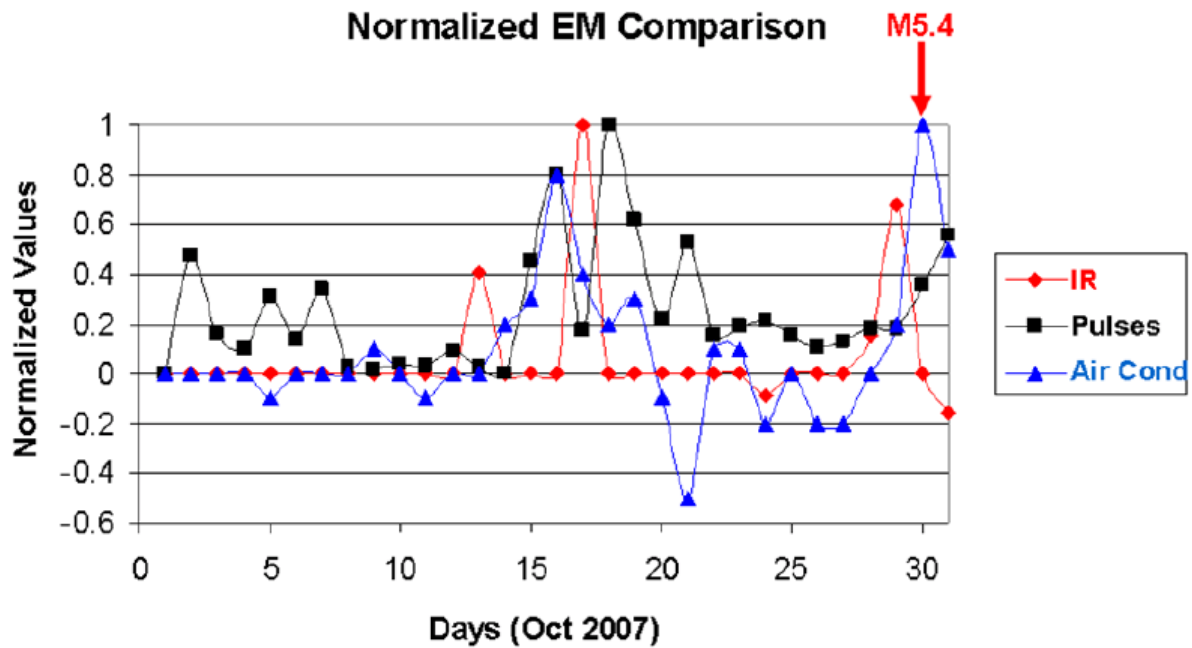


Figure 21: Comparing magnetic pulse counts, air conductivity and infrared measurements from the Alum Rock earthquake data. (Source: BLEIER et al. 2010: 1972)

The results in Figure 21 are clear. 10-15 days before the earthquake occurred, higher levels of signals were recorded from all three indicators. The first indicators to change were the EM-pulses and air conductivity on the 16th of October. An IR-heating effect was recorded the day after, followed by an even higher value of EM-pulses on the 18th of October (compared to the normalised values). The EM-pulses and IR-values then dropped back to normal until a few days before the earthquake. The air conductivity values showed negative results in the 10 days leading up to the earthquake (exactly the same pattern as seen from the surface charge changes during the rock-breaking experiment!) with the exception of the last two days where all values rose to well above the normalised values.

A suggestion is made that further indicators (such as earthquake swarms, earthquake lights, TEC changes, cloud patterns, underground water level changes, chemical or gas changes) could be added to this correlation in order to increase robustness and confidence levels. (BLEIER et al. 2010: 1972)

The Parkfield earthquake showed no such magnetic field changes in an analysis conducted by Malcolm Johnston (Note: same as JOHNSTON et al. 2006), but attributes these missing signals due to the fact that the magnetometers used were not induction type, but total field magnetometers with lower sampling rates. The data from

both the Parkfield and the San Juan Bautista earthquakes were recorded by the Berkeley Seismo-Lab. (BLEIER et al. 2010: 1972)

The second earthquake occurring at Parkfield on the 30th of October 2004 (M5.0) showed much smaller pulse patterns and a lower total pulse count than the M6.0 Parkfield earthquake from the 28th of September 2004. This seems to suggest that the number of pulse counts as well as the pattern of pulse counts may be linked to the final size of the earthquake. This second Parkfield earthquake in 2004 also showed considerably less pulse activity prior to the event, but much more activity between the aftershocks when the redistribution of stress along the fault occurs. (BLEIER et al. 2010: 1974-1975)

Data from the San Juan Bautista earthquake showed only minor signals, but a lot of man-made noise segments had to be excluded from the analysis. Large solar storms were also identified as taking place during the event meaning further data had to be excluded. A suggestion is made as to why only a few signals were detected from the Hollister station data, *'The use of 1 to 30 min energy averages is a good technique if the signals are continuous. However, when the signals are infrequent 1-10 s pulsations, this method tends to "average out" the signal amplitudes over the 60-1800 s samples period'* (BLEIER et al. 2010: 1972). Some similar pulse activity to the Alum Rock earthquake and the rock-breaking experiment were seen, but only two days before the earthquake took place. This shorter period of sustained pulse activity could be attributed to the fact that the Hollister (San Juan Bautista) earthquake took place at a highly fractured section of the San Andreas and Calaveras fault where the fault tends to rupture more often, meaning such large stress levels as at Alum Rock rarely build up. (BLEIER et al. 2010: 1972-1973)

In summary, the rock-breaking experiment and subsequent analyses of past events showed that the correlation of magnetic pulsations, air conductivity, and infrared signals may be key to analysing or detecting pre-seismic data prior to a large earthquake event. However, the sample size of such data patterns is still small, meaning further data is necessary to improve the statistical significance of such results. (BLEIER et al. 2010:1975)

5.2.6. Pros and Cons

The physical theory behind QuakeFinder remains largely unsolved as not enough data has yet been collected to be able to statistically correlate EM-signals to earthquakes. Precursory signals are largely studied empirically. (DAUTERMANN et al. 2007: 2) If enough data can however be collected to statistically correlate EM-activity to precursory seismic activity then this would be a large step forward on the research front.

The controversy about the previously recorded results needs to be cleared. Johnston highlights a further issue here, namely that the signals recorded largely occur before or after the earthquake, bemoans that there are only few co-seismic signals observed when the most energy is released during the earthquake. (JOHNSTON et al. 2006: 207)

The largest obstacles at the moment lie in recording more earthquake data in order to prove the relationship between EM-activity and earthquakes. The chances of the instruments being located in the right place for the next earthquake remain small, the chances of repeating events is even smaller, meaning the chances of gathering enough evidence to statistically prove the relationship remain slim. (DAUTERMANN et al. 2007: 2)

Making it equally difficult to get reliable data is the fact that by monitoring the separate parameters, noise from natural and man-made sources will always be an issue (BLEIER et al. 2009: 585-586). The only way of overcoming this problem is by monitoring possibly noise sources (through the geophone, humidity and temperature sensors) and by cataloguing other noise sources by their characteristics in order to be able to successfully discriminate between signal and noise.

One large benefit of previous results is that the pulses recorded can be discriminated well by their source. Bi-polar pulses usually result through human activity or phenomena like wind causing movement through tree root systems or chain fences swinging. The significance of uni-polar pulses as being related to earthquake phenomena, Pc1 pulsations or natural phenomena like lightning that relate to the movement of charges in the ground can definitely be considered a step forward in research. (DUNSON et al. 2011: 2099-2100) Equally a step forward is that the importance of a high temporal

resolution of data collection in order to capture every EM-pulsation, as these pulsations have been shown to have the best correlation to earthquake activity so far, as implied in the article by DUNSON et al. (2011).

Further difficulties may arise due to the fact that seismological regions all around the world have differentiating geological characteristics which may make the implementation of this kind of warning system more difficult. Another fact that must be considered is that these EM-signals have a wide variability making earthquakes difficult to predict. (DUNSON et al. 2011: 2085)

Refining pulse detectors is seen as a high priority. Automated monitoring on a daily basis would equally simplify processing pulse data. An automated system where a prompt would occur when a certain pulse threshold is crossed is suggested. A further priority lies in optimising cost of the magnetometer coils in order to be able to install more stations in future. Such a system, called 'QFIDO' has been recently developed. (DUNSON et al. 2011: 2094-2104)

5.2.7. Résumé

EM-activity has been recognised as an earthquake precursor in several of the studies analysed, such as BLEIER et al. (2009, 2010); BORTNIK et al. (2008, 2010); DUNSON et al. (2011). These studies have been able to show some kind of relationship between EM-activity and earthquakes, but not in all of the studies have shown such results, such as JOHNSTON et al. (2006).

Even though the phenomenon of how EM-signals are created is poorly understood and hard to prove scientifically, ULF frequency bands have been identified as being the most suitable for measuring signals associated with these pre-seismic phenomena. It has become clear through the analysis that research in this field is very challenging, but progress has clearly been made.

The reasons why these phenomena take place could be considered secondary as long as the relationship between the anomalous EM phenomena and earthquakes can be statistically proven. Being able to prove the physical theories behind the pro-

cesses taking place would only benefit the implementation of such an EWS in a different geological setting as implied by HAYAKAWA (2007: 1108-1119).

Ultimately, the way forward in verifying the relationship between EM-activity and earthquake activity, judging by previous results, is finding a set of indicators that can be monitored at every CalMagNet station (such as EM pulses – particularly uni-polar EM pulses, air conductivity) and statistically proving that these phenomena are anomalous, correlate well with each other and correlate to earthquake activity. Using IR-satellite imagery as a further indicator should equally be considered.

One of the biggest hurdles yet to be overcome is the levels of noise and interference. Important for future site placement is that they are located in places with the highest possible probability of an earthquake happening in the region in the future as well as low levels of noise. With the optimal location of an instrument being less than 10km away from a future earthquake epicenter the required density of the network is very high. This density is further important considering the deep nulls that were recorded in the model by BORTNIK et al. (2010: 1619-1621). By having a dense network, it may be possible to pick up EM signals from an event at more than one station, reducing the chance that a station may be located directly in one of the non-cardinal directions of the impending earthquake.

At this point, the second set of research questions can be answered:

How well can electromagnetic- and air ion precursors be used to predict earthquakes?

At the current level of research, the prediction of an earthquake may well be possible provided noise levels aren't too high and the network coverage is sufficient to pick up EM, and air conductivity signals. A denser network and further research are still considered necessary before full implementation of the system can be considered.

Can this method (as used by QuakeFinder) be applied to all fault types?

This question cannot be answered sufficiently at the current state of research as the physical theory behind the EM signals that have been recorded in some, but not all cases, is still on shaky ground. Results from the study by DUNSON et al. (2011) suggest there may be regional differences, making the application of the system in different parts of the world more difficult, but as QuakeFinder is still expanding the international instrument sights it is probably too early to judge whether this method can be applied to all fault types or not.

What time-span prior to an earthquake would this method allow?

The EM-signals that have been successfully recorded prior to earthquakes suggest there needs to be a prolonged period of anomalously high EM-pulses, preferably spanning 1-2 days. In the best case, if such data can be successfully recorded and such a prolonged period of high EM-activity can be identified, it may be possible to give between a few hours and 10 days warning prior to an earthquake event.

5.3 Comparison

Comparing the theoretical base of both early warning methodologies, it becomes clear that ElarmS has the simpler basis compared to QuakeFinder which is based both on a more complex and a much younger theory (in the sense the theory is not yet fully validated).

ElarmS is also at a further stage of research, the next step here would be to test the methodology in a real-time setting rather than with non-interactive data. QuakeFinder still requires more data in order to firmly establish and prove the relationship between EM-phenomena and earthquakes. It must also be said though, that progress on previously untested theory is difficult and considering this, the progress made so far has been promising.

Error margins in the ElarmS methodology are relatively low with magnitude errors in the most recent studies (e.g. TSANG et al. 2007: 3) being only 0.5 magnitude units.

Errors in the QuakeFinder methodology, or rather, noise in the recorded data needs to be dealt with successfully as there is no way of excluding noise upon recording the data. The way forward here seems to lie in the pulse azimuth cluster technique, or in correlating multiple parameters (such as EM-pulses, air conductivity, IR-images) as these methods have yielded the best results for discrimination so far.

When looking at the research questions that were answered in the résumé's (chapter 5.1.6. and chapter 5.2.6.), a comparison of these factors should also be undertaken.

Concerning how well the methods can be used to predict earthquakes, it quickly becomes apparent that ElarmS, being at a more advanced stage in research has had more successes in predicting earthquakes. Even so, going by the papers analysed, both systems have only focussed on non-interactive processes, analysing the data after the earthquake events had terminated. ElarmS is at the stage where the system can and should be tested in an interactive environment. QuakeFinder would still benefit from further research into EM-activity but it could equally benefit from interactive testing (meaning data should be regularly checked for anomalous, uni-polar EM-pulses in the hope of detecting earthquake activity).

Considering the application of both systems internationally, both systems have potential, whereby ElarmS has the security that the physical phenomena being measured is guaranteed to happen at all fault types. QuakeFinder does not have this security yet, as the physics behind the processes causing EM-activity have not yet been statistically or physically proven. DUNSON et al. (2011: 2104) picks up on this: *'the first and foremost priority is to encourage others in Japan, Greece, Italy, et al. who may have similar data sets to try the Pulse Azimuth Cluster method on their data.'*

Concerning the possible warning time, QuakeFinder has a definite head start concerning the potential warning time. QuakeFinder suggests a warning may be possible between hours and days before the earthquake event happens. ElarmS offers a few seconds to a minute warning time with the current computation speed, the time needed for dissemination of information not being included.

One factor both systems have in common is that an extension of the existing instrument network remains important. The focus in ElarmS is to improve the coverage of both high-gain and low-gain instruments and ensuring these are distributed evenly.

QuakeFinder aims to have between 200 and 300 instruments installed in order to cover California completely (FLAGG et al. 2007: 2).

At this point, a further research question can be answered:

Which of these two systems would work best in a comprehensive early warning system?

If the two systems were to be compared by the analysis of papers and their current state of research, then it must be said that ElarmS would probably work better if the systems were to be applied as early warning systems right away. This however seems unfair as the ElarmS methodology is based on well-founded physical theory and therefore much further on in the research process than QuakeFinder. Should QuakeFinder be able to progress to the same level of research, with similarly successful results as in BLEIER et al. (2010) and DUNSON et al. (2011) then this system would give a significantly longer warning time, improving the range of mitigation measures that could be implemented, possibly even making this the preferred early warning system.

6. Implications for Geoethics

In this chapter, a total of 10 articles concerning geoethics were looked at. These articles were all published in the Annals of Geophysics, Volume 55 which appears to have a special focus on geoethics. Not all of these articles were entirely relevant to geohazards such as earthquakes, only 5 were effectively used but they do suffice for a general introduction to the ethical concerns geoscientists must be aware of and be able to deal with.

It seems appropriate to start analysing the most general articles first. LAMBERT (2012: 337) offers some insight as to how he views the concept of geoethics, indicating he considers the terms 'best practise' and 'a social licence to operate' as encompassing what defines geoethics. This seems to strengthen the idea that geoethics has been present in (geo-) sciences for a longer period than the specific term. In recent years it seems that the need for a clearer definition of best practise in order to improve the feeling of social responsibility. LAMBERT et al. (2012: 378) sees the success in the application of geoethics in the *'increasing levels of employment in governments and companies, to help achieve these ends.'*

The main fields of geoethics is seen by LIMAYE (2012: 381) in the ethical behaviour concerned with developing geo-resources or dealing with geohazards and picks up on the need for social responsibility: *'Geoscientists have a duty to educate society on prudent and eco-friendly use of these resources, and also to increase the preparedness of society on dealing with geohazards'* (LIMAYE 2012: 381).

MATTEUCCI et al. (2012: 366) has a similar opinion: *'Even if geologists have limited power to impose the correct choices on decision makers, their ethical obligation is to propose them and to report wrong actions and behaviour'* and adds that both politicians and the public may have inadequate information to be able to deal with decision in the medium and long term of the human and economic costs if geological phenomena are not adequately regarded and analysed. Furthermore, the importance of being able to evaluate the costs and benefits as a geologist should not be underestimated (MATTEUCCI et al. 2012: 366).

MATTEUCCI et al. (2012) further gives insight in the direct field of action where geologists (but presumably all kinds of geoscientists) may find themselves in when concerned with the implications of geoethics. These two scenarios are as follows:

- *'Direct actions, when a commissioned study reflects the interest of private or public customers, but also has geoethical implications in terms of the systemic interests of the territory involved and its dynamics, and in general of our Planet (often the short-term and long-term interests of the territory and of its population do not coincide)'* (MATTEUCCI et al. 2012: 367).
- *'Indirect actions, which are aimed at acquiring scientific information that will be useful for public opinion and decision makers, so that all of the actions that involve the equilibrium of the territory and our Planet and its natural environment follow geoethical principles'* (MATTEUCCI et al. 2012: 367).

While the former of these cases seems to have inspired much of the focus on geoethics since 2009, the latter of these cases specifically concerns the two early warning systems being compared in this thesis.

To elaborate on the former are two articles focusses specifically on the L'Aquila earthquake in Italy 2009, where scientists came into the crossfire between media and politics and were subsequently put on trial for manslaughter due to the information they passed on to politicians and media (PIEVANI 2012: 349-350). The scientists found themselves in quite a predicament, PIEVANI (2012) describes, *'this is because of the reassuring statements that were disseminated during the seismic swarm of the low-level tremors and the inability to predict the catastrophic earthquake of April 6, 2009, in the city of L'Aquila and its surroundings. The position of the scientists is paradoxical, because in the case of a dramatic and generalized warning to the population with every seismic swarm, in the absence of the subsequent earthquake (like in the majority of historically reported cases), they might have been charged with the opposite accusation, of instigating a false alarm and panic'* (PIEVANI 2012: 350).

Further information on this case shows that the misleading communication that caused the affected population to disregard further seismic tremors seemed to be driven by *'political and contingent demand for calming news'* with the difficulty in disseminating the scientific lying in the difficulty of understanding probabilities and un-

certainties(PIEVANI 2012: 350). PIEVANI (2012: 350) even goes far enough to compare probabilistic hazard predictions of risk as '*prophecy*'!

More chance for miscommunication is allowed through the concept of 'natural phenomena or disasters, which suggest that scientists and politics are allowed to underestimate their responsibility. The responsibility of such disaster lies in society and politics. (PIEVANI 2012: 349-352)

PEPPOLONI and DI CAPUA (2012) show a similar opinion, that emphasises that scientist too, should take their role more seriously in the weighing of the value of their actions, and transferring their knowledge to society. Another focus made clear in this paper is the relationship between geoscientists, the media, politicians and citizens, which needs to improve in order to successfully deal with natural hazards. (PEPPOLONI and DI CAPUA 2012: 340)

In the following subchapters, several themes and factors will be covered, and the possible implications of the two EWS on such factors will be analysed. The effects on the at-risk population, including different types of elements at risk (households, office buildings, industry and infrastructure) will be elaborated on.

6.1 ElarmS

To start with, the most important element at risk – individual households will be looked at. The ElarmS methodology allows several seconds possibly up to a minute warning (at best) with the current state of technology. This would allow for people living in houses and structures with less than two storeys to move down to the ground floor and potentially find cover under a desk or in a doorway. Such actions could be possible with the suggested warning time. For people living in other housing types such as large apartment blocks with a higher number of storeys, this warning time is insufficient to evacuate people from the higher levels. If the amount of warning time could be increased, there may be enough time to turn off electricity and gas within the household to reduce the risk of secondary hazards such as fires occurring. These mitigation measures would equally count for schools. Nonetheless, a warning in such scenarios can still save lives and reduce casualties. Also, '*getting under a desk for a*

false alarm is not that costly – in fact, it is a good drill, part of a necessary user education’ (ALLEN 2008: 56).

In office buildings or similar buildings such as hospitals, different measures can or should be undertaken in the case of an earthquake. Evacuation of an entire office building (with presumably more than 5 storeys) is not an option with under a minute warning time. Equally in a hospital, evacuation of the residents is most likely not possible, however, power generators could be manually turned on in order to reduce the effect a temporary power outage would have. Similar measures could be taken in office buildings where a power outage would mean loss of data. In this case, a warning could save lives, prevent casualties as well as possibly reduce the cost of earthquakes that may occur due to power outages.

Industry is an equally important factor to consider. Elements at risk may include all types of production or manufacturing sites, as well as refineries and (nuclear) power plants. A warning of 10-40 seconds could mean that shut down processes could be initiated, which could reduce damage to machinery or reduce the chances of secondary hazards such as nuclear leakage or fires. Also, if the dissemination of the warning includes data on the estimated magnitude of the event, more detailed plans of action could be implemented depending on the type of industry involved in order to reduce economic losses (for example, if a nuclear power plant was built to withstand an M6.0 earthquake then shutting down the facility for a M4.0 earthquake may not be economically feasible). Similarly, it may be useful to allow users to decide for themselves if they wish to take measures immediately, taking into account a higher magnitude error or waiting for an update with a more accurate magnitude estimate, before taking potentially costly mitigation measures (ALLEN, 2004: 21).

Particular infrastructure such as bridges and tunnels pose a large risk to the people using them during earthquakes. Moving trains can equally be derailed due to the ground motion, which could equally cause a large number of casualties or deaths. While evacuating a tunnel or a bridge may not be possible in under a minute, the number of casualties or deaths could still be reduced through the warning as access to the bridge or tunnel could be closed off in time. A reduction of casualties or deaths would equally be possible for public transport facilities, as a reduction of speed is possible within seconds of a warning.

One of the most important factors to be considered is the reliability of the system and the implications a false alarm may have. If a false alarm were to occur, then it can be presumed that any future earthquake warning notification may not be taken as seriously or ignored, meaning parts of the at-risk population would not take any mitigation measures. For industry or infrastructure, the economic losses that would occur due to a false alarm would be marginal; as usual activities could be taken up again minutes after the warning.

Surprisingly, ALLAN (2008: 59) made one of the most important statements that need to be considered in any earthquake early warning system, and this is that political will and financial investment is necessary to successfully apply geoethics in an EWS.

6.2 QuakeFinder

Households would have a much longer preparation period if a time span between a few hours and a few days warning of an imminent earthquake were possible. One can presume that households would stock up on basic survival goods, such as gas, water, long-life foodstuffs, potentially even first aid equipment and emergency housing supplies (tents, sleeping bags, blankets). A few days would probably also be enough to provisionally reinforce any older, weaker structures in order to potentially reduce any damage the earthquake may or is likely to cause. In any case, although the exact time of the earthquake remains unpredictable, once the earthquake occurs the population may be less taken by surprise and may react more quickly. One drawback of having a longer warning period is that local shops and gas stations may quickly sell out and cause panic among the population. Appropriate measures would need to be taken to inform and school the population on how to act during such a long warning period.

Concerning office buildings and working hours, several issues need to be considered. One advantage is again the higher preparedness of the event, meaning the affected population may react faster when the p-wave is felt. Another question that remains unanswered is the potential fallout of workforce should a commercial area be located in the vicinity of the predicted earthquake epicenter. In this case, the risk of large fallout of economic productivity is to be expected.

Industry could use such information as an advantage, production and manufacturing could be customised depending on the goods produced, and whether demand will change due to the impending earthquake.

Infrastructural issues equally need to be taken into account. Here, an informed decision needs to be made whether in the day or days where the earthquake is expected, dangerous structures such as bridges or tunnels could be closed off completely without causing congestion, or economic fallout. Scientists and city/county councils would need to work together in order to be able to make the best possible decision.

The consequences a false alarm may have are more drastic in the case of QuakeFinder than in the case of ElarmS. This is due to the fact that if mitigation measures have been made that cause some economic productivity fallout, then the society will have to carry these costs in the long term. These costs have the potential to be much higher, as the exact estimated arrival time of the earthquake cannot be predicted. Should particular industries located near the epicenter choose to shut down production in the predicted earthquake time window (which may be as large as a few days) then this leads to a severe economic gap in productivity and reduced profits.

Two further points should also be mentioned. Firstly, the chances of mass panic are much larger in a QuakeFinder earthquake prediction scenario than in an ElarmS prediction scenario as there is more preparation time and time to properly evacuate any populated regions that may be located directly at the epicenter of an impending large earthquake. This raises the point that political action is needed, possibly police enforcement to counter such mass panic. Secondly, one issue that cannot be adequately assessed is the consequences such a prediction might have concerning the insurance of property or lives. This is an issue that would need to be dealt with at the economic/political interface.

7. Conclusion and Evaluation

Through the analysis of the ElarmS articles it has become clear that this early warning system is based on a sound theoretical basis and has received much attention and research over the past years. The current state of knowledge allows for good earthquake location and magnitude estimates when concerned with non-interactive event processing. Various studies have shown to yield similar results, and the algorithms and instruments have proven to be robust and conclusive. The linear correlation between the maximum predominant period and earthquake magnitude lies at around 0.9 (OLSON and ALLEN 2005: 212).

Determining location and magnitude can take between 1 and 5 seconds, depending on earthquake magnitude, whereby the results show relatively low error margins varying between 0.5 and 1 magnitude unit (TSANG et al. 2007: 3). The warning time at the epicenter remains extremely low, particularly in the case of a large earthquake that requires a longer period of time to compute accurately. Several kilometres and tens of kilometres from the predicted epicenter, warning times of several seconds to tens of seconds are possible, however not including the time it would take to disseminate the warning information to the at-risk population.

Finally, the algorithms may still be improved through weighting systems (WURMAN et al. 2007: 6). The robustness to site effects should equally be reduced for example by using correction values, and the instrument coverage could equally still be improved.

The more recent studies by QuakeFinder (BLEIER et al. 2009, 2010; DUNSON et al. 2011) have shown that EM-activity seems to be correlated to earthquake activity and that parameters like ULF-pulse counts, air conductivity, surface charge as well as IR-images yield good results (particularly when combined) that support this theory.

The focus lies on statistically proving a relationship between EM-pulses and earthquake activity, particularly in precursory ULF-EM activity, as low frequency bands yield the best results with the least attenuation. Research in this field remains challenging although progress, particularly in technology and data processing has been made. Scientifically proving the physical theories behind the processes taking place

would benefit the implementation of such an EWS in a different geological setting (HAYAKAWA 2007: 1108-1119).

One drawback of the QuakeFinder methodology is the potential noise level in each of the measured channels, for example electrical currents, Pc1 pulsations and physical movement in the magnetometer data, humidity in the air ion sensors and clouds in the IR data. The focus for future development should lie in statistically proving the relationship between anomalous EM-activity and earthquake activity, improving the instrument network to cover the fault zones California completely and attempting to improve noise discrimination further.

Comparing both systems was a challenge, as the theoretical bases as well as the stages of research are rather different. The focus of both systems has been largely on validating the methods using non-interactive processes. ElarmS is at the stage where online-implementation (for testing, not warning) of the system is necessary, while Quakefinder still needs to consider further testing due to the lower amount of high-quality EM-data available, but could equally benefit from online-testing.

Both systems have the potential for application in other geological settings and both systems currently also have international partnerships to test various geological settings.

ElarmS has the potential to offer a warning time between a few seconds to a minute. Quakefinder offers a completely different time frame, ranging between a few hours to several days. These warning times also have implications on geoethical reflections.

In short, ElarmS is by far the less complicated system to implement when concerning geoethics. The vast majority of mitigation actions have to be made in the short warning time. For QuakeFinder however, the geoethical implications and possibilities reach a much more complicated level due to the substantially longer warning time allowing for a much larger range of mitigation actions to be taken. These mitigation strategies can have vast consequences (both positive and negative) on a society and will therefore require much more planning and resources to successfully implement this system. On the other hand, the reward for this much higher effort is a much better chance at reducing the cost of an earthquake, where ElarmS has significantly less elbowroom.

At this point it makes sense to summarize the outcomes according to the research questions:

How well can the P-wave/S-wave modelling (ElarmS) be used to predict earthquakes? The method can be successfully applied and is ready for a real-time testing environment.

Can this method (as used by ElarmS) be applied to all fault types? Although there are regional differences, the system can be applied to different fault types.

What time-span prior to an earthquake would this method allow? ElarmS allows a very short time-span for warning, ranging from seconds to approximately a minute with the current state of the art.

How well can electromagnetic- and air ion precursors be used to predict earthquakes? Although the theory has not been proven successfully, the most recent results look very promising that anomalous EM-phenomena can be applied as earthquake precursors.

Can this method (as used by QuakeFinder) be applied to all fault types? There has been a case study where data from Peru is analysed, the results in California were however much better. Possibly, the method as used by Quakefinder has the potential for application to all fault types.

What time-span prior to an earthquake would this method allow? QuakeFinder would allow a time-span for warning ranging between a few hours to around 10 days.

Which of these two systems would work best in a comprehensive early warning system? ElarmS is currently at the stage where implementation should be possible, QuakeFinder would still benefit from testing and verification of the correlation as the data pool for testing is much smaller and not representative. Potentially, both systems could work very well in a comprehensive warning system, whereby QuakeFinder would give the best warning times and ElarmS would be easier to implement when considering geoethics. An interesting and probably the most fruitful solution would be applying both warning systems, allowing for a longer preparation period and higher preparedness for when the event happens as well as a short-term warning to ensure personal safety.

What problems concerning geoethics would be raised through these prediction methods? ElarmS would raise fewer geoethical issues with a full online implementation, QuakeFinder (due to the longer warning time) raises a much larger range of issues that will require a range of experts and much more effort to deal with, but equally has a larger potential for reducing the cost of earthquakes.

Is it thinkable that earthquakes will become predictable in the near future (50 years)? ElarmS is likely to reach full implementation in hopefully a few years, QuakeFinder will likely need a longer time span for further research and testing before full implementation could be possible. All in all, scientists and researchers on both sides are working very hard to solve the remaining issues, reduce error margins and making earthquake early warning possible – so yes, it is definitely thinkable that earthquakes will become predictable in the near future.

Reaching the end of the conclusion, a reflection on the methods and results is necessary. Concerning the goals of this thesis, one may be inclined to think that ElarmS should not be considered state of the art research as the most recent articles date back to 2008. In 2008 the ElarmS project had reached the stage where implementation into the next step of the CISN: Earthquake Early Warning project called the ShakeAlert decision module was possible (CISN (ed.) N.D.b: online on 05.02.14). This however, is principally involved with a different stage of the early warning system ('dissemination and communication' rather than 'monitoring and warning service' as described in UN (ed.) 2006: online on 28.10.2013) and could thus not be further considered for this thesis.

Furthermore it must be said that the analysis of the geoethics articles was less successful than had been hoped for. While some articles highlighted valuable information concerning geohazards the information was not very specific, meaning the previous articles on ElarmS and QuakeFinder as well as own thoughts and ideas had to be relied upon much more strongly.

On a last point, three ElarmS articles (ALLEN 2006; SHIEH et al. 2008; OLSON and ALLEN 2006) and three QuakeFinder articles (BORTNIK et al. 2008a; BORTNIK et al. 2007; LONG et al. 2002) contained little or no further relevant information for the main analysis.

8. Outlook

Society will always have to deal with natural hazards, and these will always be costly events: *'The number of people killed in earthquakes continues to rise in poorer nations, and the cost of earthquakes continues to rise for rich nations'* (ALLEN, 2007a: 608).

Furthermore, the risk concerning natural hazards is equally being concentrated, with people continually migrating to large cities, this raises concern, particularly when concerning earthquake risk: *'The largest cities today are in locations with a greater seismic risk than the largest cities in 1950'* (ALLEN 2007a: 613).

Equally, while improving mitigation strategies and testing early warning systems for future implementation may help to reduce the cost of earthquakes, losses occurring due to geohazards will remain unavoidable. Communication and education remain equally important factors that will help to reduce the cost of earthquakes. Strict building codes and earthquake resistant building are still vital hazard mitigation measures and equal effort should be spent on maintaining these mitigation strategies.

In future, the role of public responsibility in geoethics must not be underestimated. Both political actors and scientists must feel responsible and take action to work together with the media and the public in order to make the best possible long-term decision.

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Appendix:

Zusammenfassung

Durch die Analyse der ElarmS Artikel ist klar geworden, dass dieses Frühwarnsystem auf einer fundierten theoretischen Basis aufgebaut ist und viel Forschung in den letzten Jahren auf diesem Gebiet betrieben wurde. Der aktuelle Stand des Wissens ermöglicht (bei einer nicht-interaktiven Ereignisverarbeitung) eine gute Einschätzung der Lage und Größenordnung vom eintreffenden Erdbeben. Verschiedene Studien haben dabei grundlegend ähnliche Ergebnisse erzielt, die Algorithmen und Messungen der Instrumente gelten als robust und schlüssig. Weiters ist auch das Ergebnis der linearen Korrelation (zwischen T_p^{max} und M) von 0,9 erfreulich (OLSON und ALLEN 2005: 212).

Die Bestimmung/Schätzung der Lage und Größe der Erdbeben dauert durchschnittlich zwischen 1 und 5 Sekunden, dauert jedoch tendenziell umso länger, je größer das Erdbeben geschätzt wird. Der Fehler beim Schätzen der Erdbebengröße liegt durchschnittlich zwischen 0,5 und 1.0 Größenordnungen (von M) (TSANG et al. 2007: 3). Die Vorwarnzeit ist in der Nähe vom Epizentrum am geringsten, insbesondere im Falle eines großen Erdbebens wo die Berechnungszeit entsprechend länger ist. Einige Kilometer bis mehrere 10 Kilometer vom Epizentrum entfernt beträgt die Vorwarnzeit zwischen einzelnen Sekunden und einer knappen Minute, diese Warnzeit inkludiert jedoch nicht die Zeit die benötigt wird um die Informationen an den Endkunden (Bevölkerung) weiter zu leiten.

Die Algorithmen könnten durch ein Gewichtungssystem verbessert werden, da die zwei Instrument-Typen die Größenschätzung unterschiedlich definieren. Eine zusätzliche Kalibration der einzelnen Standorte (um Standorteffekte zu vermindern), sowie eine Erweiterung des Netzwerks an Instrumenten könnte ebenso vorgenommen werden.

Die neuersten Studien von QuakeFinder (BLEIER et al. 2009, 2010; DUNSON et al. 2011) haben gezeigt, dass es sehr wohl einen Zusammenhang zwischen der ULF-EM-Aktivität und der Erdbebenaktivität gibt. Besonders die Parameter ULF-Pulse, Luftleitfähigkeit, Oberflächenladung und IR-Bilder eignen sich besonders gut zur Erkennung dieser Phänomene, insbesondere die kombinierte Beobachtung von mehre-

ren dieser Parameter können hilfreich sein, die physikalische Theorie dahinter zu belegen.

In Zukunft sollte der Fokus darauf liegen, diese Beziehung zwischen EM-Phänomenen und Erdbeben Aktivitäten nachzuweisen. Die Forschung in diesem Bereich bleibt dennoch sehr anspruchsvoll, besonders im Bereich der Technologie(Instrumente) und Datenverarbeitung. Ein wissenschaftlicher Beweis, für die zugrunde liegende physikalische Theorie, würde den Einsatz eines solchen Frühwarnsystems in anderen geologischen Regionen befürworten.

Der größte Nachteil der QuakeFinder Methodik, sind die hohen Lärmpegel die bei praktisch jeder Messung und jedem Instrument entstehen können (elektrische Ströme, Pc1 Pulsierung bei den Magnetometern, Feuchtigkeit in den Luftleitfähigkeits-sensoren, Wolken in den IR-Bildern). Der Schwerpunkt für die zukünftige Entwicklung sollte daher einerseits in der Verbesserung der Diskriminierungsmöglichkeit für Störungsquellen, sowie dem Ausbau von Standorten liegen.

Bei dem Vergleich der Systeme hat sich herausgestellt, dass sie sich auf unterschiedlichen Entwicklungsstufen befinden. ElarmS ist durch die intensive Forschung und Datensammlung der letzten Jahrzehnte wesentlich weiter fortgeschritten als QuakeFinder, wo die Auswertung der spärlich vorhandenen Daten mühselig ist. Beide Systeme haben sich bisher hauptsächlich mit der Validierung der Methoden in nicht-interaktiven Prozessen gewidmet (offline-testing).

Beide Methoden haben ein hohes Potenzial auch an internationalen Standorten mit unterschiedlicher Geologie erfolgreich zu sein, beide Systeme werden aktuell auch (durch internationale Partnerschaften) an Standorten außerhalb Kaliforniens getestet.

Durch ElarmS entsteht die Möglichkeit, wenige Sekunden bis einer Minute vor einem bevorstehenden Erdbeben eine Warnung zu geben. Quakefinder hingegen, stellt eine Vorwarnzeit von etlichen Stunden bis mehrere Tage in Aussicht. Daher ist es wichtig auch die Auswirkungen einer solchen Vorwarnzeit auf die potenziell betroffene Bevölkerung zu erörtern.

ElarmS ist hinsichtlich der Geoethik im Wesentlichen unkompliziert. Der Großteil der Schadenminderungsmaßnahmen müssen in der sehr geringen Vorwarnzeit durchgeführt werden. Bei QuakeFinder hingegen, stellen sich ganz andere Probleme in den

Vordergrund. Die Auswirkungen einer solchen Warnung auf die Bevölkerung sind deutlich weitgreifender, das Potenzial für eine Schadensminimierung ist daher aber ebenso größer. Schadensminimierungsstrategien müssten für eine Anwendung des QuakeFinder-systems deutlich gezielter ausgearbeitet werden, man kann ebenso annehmen, dass dies wesentlich mehr Ressourcen in Anspruch nehmen wird. ElarmS erlaubt hier deutlich weniger Spielraum hinsichtlich der Schadensminimierung.

Nun zu den ursprünglichen Forschungsfragen:

Wie gut kann die P-wave/S-wave Modellierung (ElarmS) verwendet werden, um Erdbeben vorherzusagen? Das Verfahren kann erfolgreich angewendet werden und ist bereit für eine interaktive Anwendung (online-testing).

Kann diese Methode (wie von ElarmS verwendet) an allen seismisch aktiven Störungen/Plattengrenzen angewendet werden? Es gibt zwar regionale Unterschiede, dass System wurde aber bisher überall erfolgreich eingesetzt und getestet.

Welche Vorwarnzeit vor einem Erdbeben würde diese Methode ermöglichen? ElarmS ermöglicht eine sehr kurze Zeitspanne für die Warnung, von Sekunden bis zu knapp unter einer Minute (nach aktuellem Stand der Technik).

In wie weit ist es möglich, mithilfe von Elektromagnetischen- und Luftleitfähigkeits-phänomenen Erdbeben vorherzusagen? Obwohl die Theorie noch nicht erfolgreich bewiesen worden ist, sind die jüngsten Ergebnisse vielversprechend.

Kann diese Methode (wie von QuakeFinder verwendet) an allen seismisch aktiven Störungen/Plattengrenzen angewendet werden? Die Ergebnisse aus Kalifornien sind bis dato die besten, es gab jedoch auch Ergebnisse aus Peru, wo die anomalen-ULF-Pulse ebenfalls erfolgreich identifiziert wurden.

Welche Vorwarnzeit vor einem Erdbeben würde diese Methode ermöglichen? QuakeFinder ermöglicht eine längere Zeitspanne für die Warnung, von wenigen bis zu mehreren Tagen.

Welche dieser beiden Systeme würde am besten in einem umfassenden Frühwarnsystem funktionieren? ElarmS könnte in der derzeitigen Forschungsphase als Frühwarnsystem eingesetzt werden, bei Quakefinder fehlt noch weitere Forschung, damit der Zusammenhang zwischen EM-phänomenen und Erdbeben wissenschaft-

lich oder statistisch bewiesen werden kann (hier ist die bisherige Datenmenge zu gering oder von zu geringer Qualität, daher nicht repräsentativ). Möglich wäre ebenso eine Anwendung beider Systeme, welches viele Vorteile mit sich bringen würde und ebenso helfen würde, wesentliche geoethische Probleme die bei der QuakeFinder Methode zu berücksichtigen wären, zu mindern. Beide Frühwarnsysteme würden es ermöglichen sich sowohl längerfristig auf das Erdbeben vorbereiten zu können, dabei aber auch die unmittelbare Handlungsbereitschaft in den Sekunden vor dem Beben erhöhen.

Welche Probleme hinsichtlich Geoethik würden durch diese Vorhersagemethoden entstehen? ElarmS würde weniger geoethische Probleme mit sich bringen. QuakeFinder (aufgrund der längeren Vorwarnzeit) wirft eine viel größere Palette von Themen und Problemen auf, die berücksichtigt werden müssen und wahrscheinlich eine Reihe von Experten und viel mehr Aufwand benötigen, um sie zu bewältigen. QuakeFinder hätte aber ebenso ein höheres Potenzial, die Kosten zu reduzieren, die durch ein Erdbeben entstehen könnten.

Wäre es denkbar, dass Erdbeben in naher Zukunft vorhersehbar werden (50 Jahre)? Alles in Allem, arbeiten Wissenschaftler und Forscher auf beiden Seiten sehr hart um Restprobleme bei der Methodik des jeweiligen Systems zu lösen. ElarmS wird wahrscheinlich in einigen Jahren so weit sein, dass das System vollständig umgesetzt werden kann, QuakeFinder wird hierfür wahrscheinlich etwas länger brauchen, da hier Großteils noch Daten fehlen um repräsentative Ergebnisse zu erzielen. Ja, es ist auf jeden Fall denkbar, dass man in naher Zukunft Erdbeben vorhersagen kann.

An dieser Stelle sollen noch die in dieser Arbeit angewandten Methoden reflektiert werden. In Bezug auf Titel und Ziele der Arbeit, könnte man meinen, dass ElarmS nicht den neuesten Stand der Technik darstellt, da die neuesten Artikel aus 2008 sind. In diesem Jahr wurde das CISN-Projekt (wovon ElarmS ein Teil ist) in die nächste Phase, namens ShakeAlert, gebracht (die sich eher mit der „Informationsverbreitung und Kommunikation“ als mit dem „Überwachungs- und Warndienst“ beschäftigt, wie in UN (Hrsg.) 2006: online über 2013.10.28 beschrieben wird und somit für diese Arbeit nicht relevant ist) (CISN (Hrsg.) o.J.b.: online am 05.02.14).

Weiters war die Analyse der Geoethik-Artikel weniger erfolgreich als erwartet. Die Artikel haben zwar wertvolle Informationen betreffend Geoethik im Allgemeinen hervorgebracht, waren aber für die Fallbeispiele von ElarmS und QuakeFinder nicht sehr geeignet. Somit musste in einem höheren Ausmaß als erwartet auf die Informationen der ElarmS und QuakeFinder Artikel, sowie auf eigene Überlegungen zurückgegriffen werden.

Weiters muss noch erwähnt werden, dass auch nicht alle Artikel von ElarmS (ALLEN 2006; SHIEH 2008; OLSON und ALLEN 2006) und QuakeFinder (BORTNIK et al. 2008a; BORTNIK et al 2007; LONG et al. 2002) in der Hauptanalyse verwendet worden sind, da sie wenig neue oder relevante Information für die Hauptanalyse enthielten.

Curriculum Vitae

Personal Information:

Name: Doris Marie Bleier, BSc.

Work Experience:

May 2013 –	Project Assistant (Vienna University of Natural Resources and Life Sciences)
October 2013	Work with ArcGIS, QuantumGIS, Google Earth to find potential site locations for EM-Instruments in Indonesia.
October 2012 –	Tutor and Project Staff (University of Vienna, Department of Geography and Regional Research)
February 2013	Providing assistance for fellow students as Tutor for a course in soil analysis as well as 3 days in the field collecting soil samples.
July 2012 –	Intern (QuakeFinder, Palo Alto, Ca.)
August 2012	Recycling old equipment, assisting in organising an experiment at the NASA Ames facility, Moffett Field, Ca.
August 2011 –	Intern (Standort + Markt, Baden bei Wien)
September 2011	Work with ArcGIS and MS-Excel, catchment area analyses in the retail industry, expansion directory updating per email and phone contact
July 2010 –	Intern (Standort + Markt, Baden bei Wien)
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July 2008 –	Part-time tour guide and full-time summer intern (Schloss Esterhazy Management Ges.m.b.H., Eisenstadt)
August 2009	Tour guide in German and English, shop assistance incl. sales

Personal Skills:

Mother tongue(s):	English, German
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Computer skills:	Excellent knowledge of MS-Office and OpenOffice, good knowledge of ArcGIS and QuantumGIS, excellent research skills
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