# A Review on Electromagnetic Earthquake Precursors Using Remote Sensing Technology

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## Abstract

Among natural disasters, earthquakes have attracted special consideration for their enormous capability to kill, to damage, and to trigger other disasters (tsunami, landslides, technical failures...). This review is an attempt to highlight an emerging trend in seismological hazard research. While, on the one hand, traditionally there has been a focus on quake's rock and soil mechanics hence building pure seismological probabilistic models; On the other hand, recently there is a growing trend towards researches discussing the so-called "electromagnetic precursors" as possible clues for an impending earthquake. The underlying principle is that strain accumulation generates electromagnetic effects through various mechanisms. But, so far, identifying these noisy perturbations and refining them continued to be a lost challenge for scientists due to several complexities including quake nature, measurements sensitivity, and data refinement. These complications always question the reliability all over the prediction process. The usage of remote sensing satellites with the appropriate temporal monitoring and the new promising physical explanations reactivated researches toward detecting pre-earthquake EM precursors.

## 1 Introduction

Quakes represent one of the most harmful natural phenomena. They Generated losses exceeded 100th of Billions USD and fatalities topped 800,000 during the last 2 decades according to EM-DAT database (EM-DAT, 2012). So far, the risk reduction process remains focused on the resistivity of the construction designs and the effectiveness of the emergency response.

People kept populating seismic risk areas mainly because of unawareness and economic reasons. Global exposure of people and goods to seismic risk has built to huge levels, whose spatial distribution is being mapped in the context of the Global Earthquake Model project (GEM, 2011). Obviously, in this situation, a capability to predict an impending earthquake would make a great difference in minimising human and economic losses. Various ways have been proposed to predict earthquakes, including animal behaviour (Schaal, 1988), Radon emissions (Cicerone et. al, 2009), patterns of seismic activity (Mogi, 1969), and others. In this paper we will however focus on geo-electric precursors, which seem to be the most promising in terms of both sound scientific background and possibility to aim at operational earthquake prediction at some point in the future.

The geo-electric precursors indicated a linkage between the quake occurrence and the observed EM signals. This led to a further reasoning that the mechanical process of the rupture strain is the source of the crustal currents. Thus, the electromagnetic emissions are consequences of time-varying electric currents flowing in the ground. The generation mechanism of the crust currents was illustrated by different processes: piezoelectricity (Bishop, 1981) & (Finkelstein et. al, 1973), streaming potentials (Oommen, 1988), and positive holes recombination (Freund, 2003).

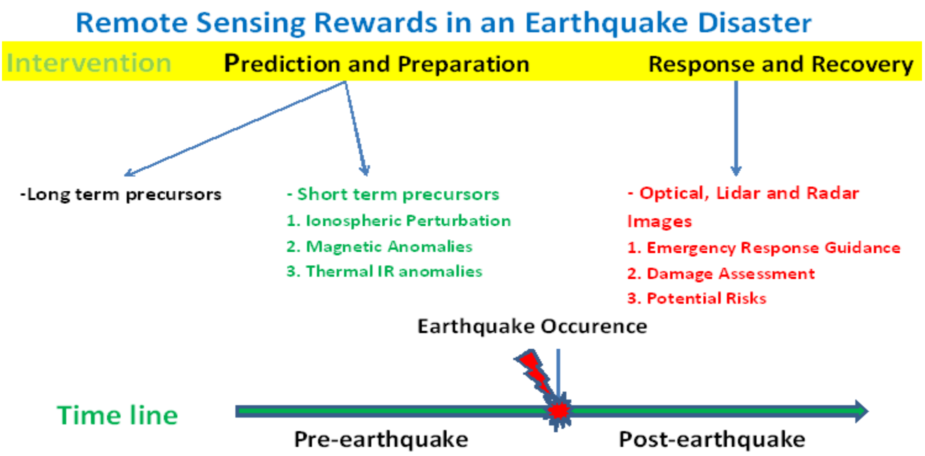



Figure 1. List of the main remote sensing activities related to an earthquake event.

The admission of satellite remote sensing technology into the scene in the middle of the 20th century helped in the detection of electromagnetic earthquake precursors (Gorny et. al, 1988)and (Bernardi, 1989). Remote sensing was recognizable due to its rewards in monitoring large areas with high resolution in short time.

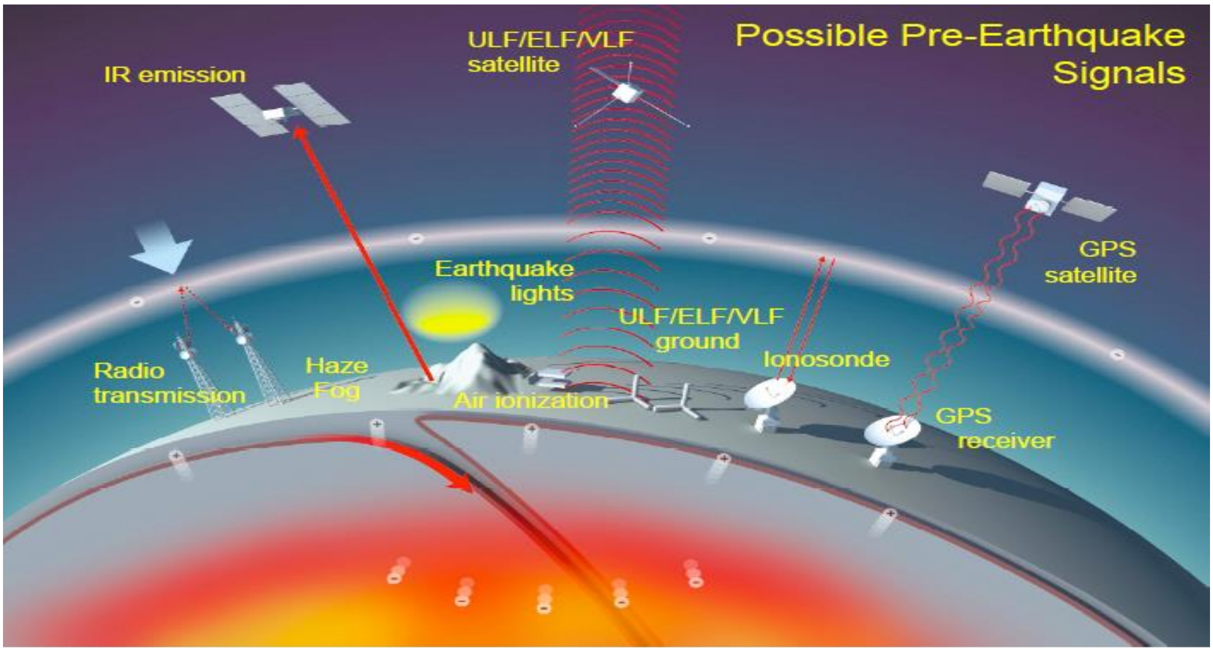



Figure 2. The main modern observational tools used in detecting EM pre-earthquake signals, (Freund, 2009).

Several theories were proposed, which tried to provide a possible explanation for this electromagnetic phenomenon. The attempts were not fully successful in uncovering the mystery of the irregular behaviour of the observed EM signals.

## 2 Electromagnetic Precursors

The studies of electromagnetic phenomena associated with earthquakes have been controversial in science since 50 years ago. Every now and then it was questioned for its efficiency and at some point they were even considered a waste of time and effort (Geller et. al, 1997).

More recently, quake electromagnetic phenomena were supported by several encouraging hypotheses (Geng et. al, 1998); (Freund, 2003); (Tronin et. al, 2004). The hypotheses tried to illustrate the fundamental physics of the phenomena and link it to seismology. The accumulated statistics and the improvement of the observational means confirmed the seismo-electromagnetic linkage and approved the necessity to extend the analysis. Thus, EM quake precursors moved to be a prospective candidate for the short-term earthquake predictions. In the modern history, there are extensive studies pointing on the coupling between lithosphere and ionosphere before major earthquakes (Ondoh, 2000); (Pulinets, 2004); (Pulinets et. al, 2004); (Chen et. al, 2011); (Hayakawa & Fujinawa, 1994); (Hayakawa, 1999); (Hayakawa et al., 2000); (Hayakawa & Molchanov, 2003). In that context, several projects were launched to understand the lithosphere-atmosphere system. These projects used diverse mechanisms and technologies that covered a wide frequency range from ULF to HF (ground stations, remote sensing aerial and satellites, subsurface measurement of seismogenic and acoustic emissions). In the following subchapters, the various manifestations of earthquake precursors are dealt with according to the following scheme:

- Ionospheric perturbation (Ch. 2.1) – freed electrical charges impact on the charges in the ionosphere
- Magnetic anomalies (Ch. 2.2) – motion of freed electrical charges perturbs the local Earth-generated magnetic field
- Unexpected IR emission (Ch. 2.3) – Earth surface positive holes recombination stimulates photon emission in the IR wavelength range.

## 2.1 Ionospheric Perturbation

Ionosphere is a plasma region of the atmosphere starting at altitude of 90-100 km with layers of ions and electrons. These layers are formed when Sun radiation ionize atoms and molecules in the upper atmosphere creating plasma of ions and free electrons. The distribution of electron density in ionosphere is a complex function related to the orbital motion of earth and to the seismic, geomagnetic and solar activities. The ionospheric layers are extremely dynamic and their density and thickness change day and night.

Distinctive perturbations were observed in electron densities of the F region of the ionosphere few days before a strong seismic event. These disturbances disappeared 1 to 3 days after the earthquake. The first observation of this phenomenon dates back to the Alaskan earthquake of March 1964 (Liu et. al, 2000). The scientists deemed such perturbations as a possible earthquake precursory signature. They propose the existence of a charge on the earth surface to which ionosphere responds (Liu & Chuo , 2004).

It is difficult to expect significant ionospheric perturbations. So, a detection of ionospheric perturbations related to earthquake imposes an extensive study for the usual day-to-day variability and to be attentive also to the variations due to solar and magnetic activities.

The studied results on Wenchuan Earthquake, P.R. China, 2008 showed anomalous variation of the electron density in the ionosphere before the earthquake. It was also noticed that the variations from seismo-ionospheric signals (electromagnetic mechanisms) were much greater than those caused by vertical motions of the Earth surface after the quake (mechanical mechanism) (Ma et. al, 2011).

So far two techniques have been used to monitor the ionospheric response related to electric field change due to an earthquake.

**1.** Using the ground stations (Ionosonde and radio transmission): the quantity used to trace such perturbation in the electron density is the total electron content (TEC). TEC is proportional to the number of electrons in a column with cross sectional area of one square meter into the atmosphere (el/m$^2$).

   Several observations of TEC showed a decrease several days before an EQ; this sign could be attributed to seismic activity only if the geomagnetic activity is relatively quiet.

   TEC measurements are taken mainly by the international GPD Service (IGS). IGS is a global network structure of communication system between GPS receivers on ground and satellites over the ionosphere. Its objective is to continuously monitor the ionospheric excess variation related with the earthquake occurrence.

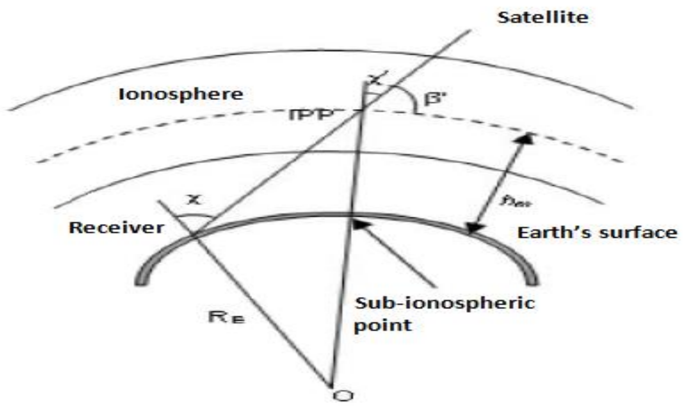
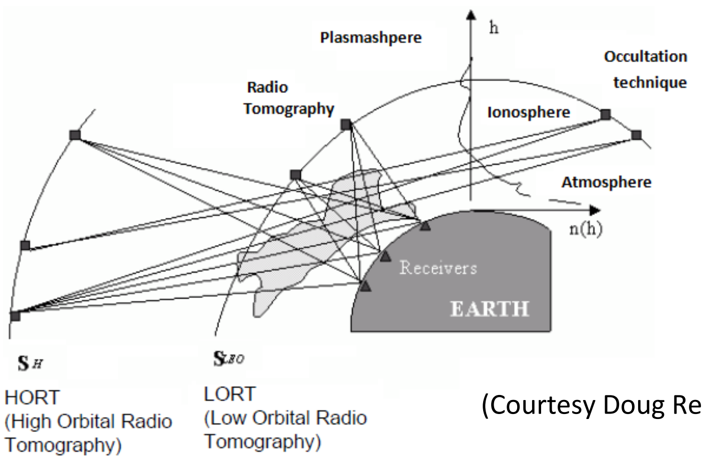



Figure 3. IGS Networks, GPS receivers on ground and satellites above the ionosphere, (Mubarak et. al, 2009).

2. Using Ratio-tomography of the ionosphere (RTI): this technology depicts a two dimensional projection of the ionospheric anomaly, detected when the natural variation is excluded (fig. 4). This produced an encouraging idea still being actively investigated (Indian Space Station, 2011). The idea is to design software and techniques that give a near real time tomography for the ionospheric perturbation over quake-prone areas.




(Courtesy Doug Rekenthaler 2008)

Figure 4. llustration of Ratio-tomography of the ionosphere process (RTI), (Freund, 2009).

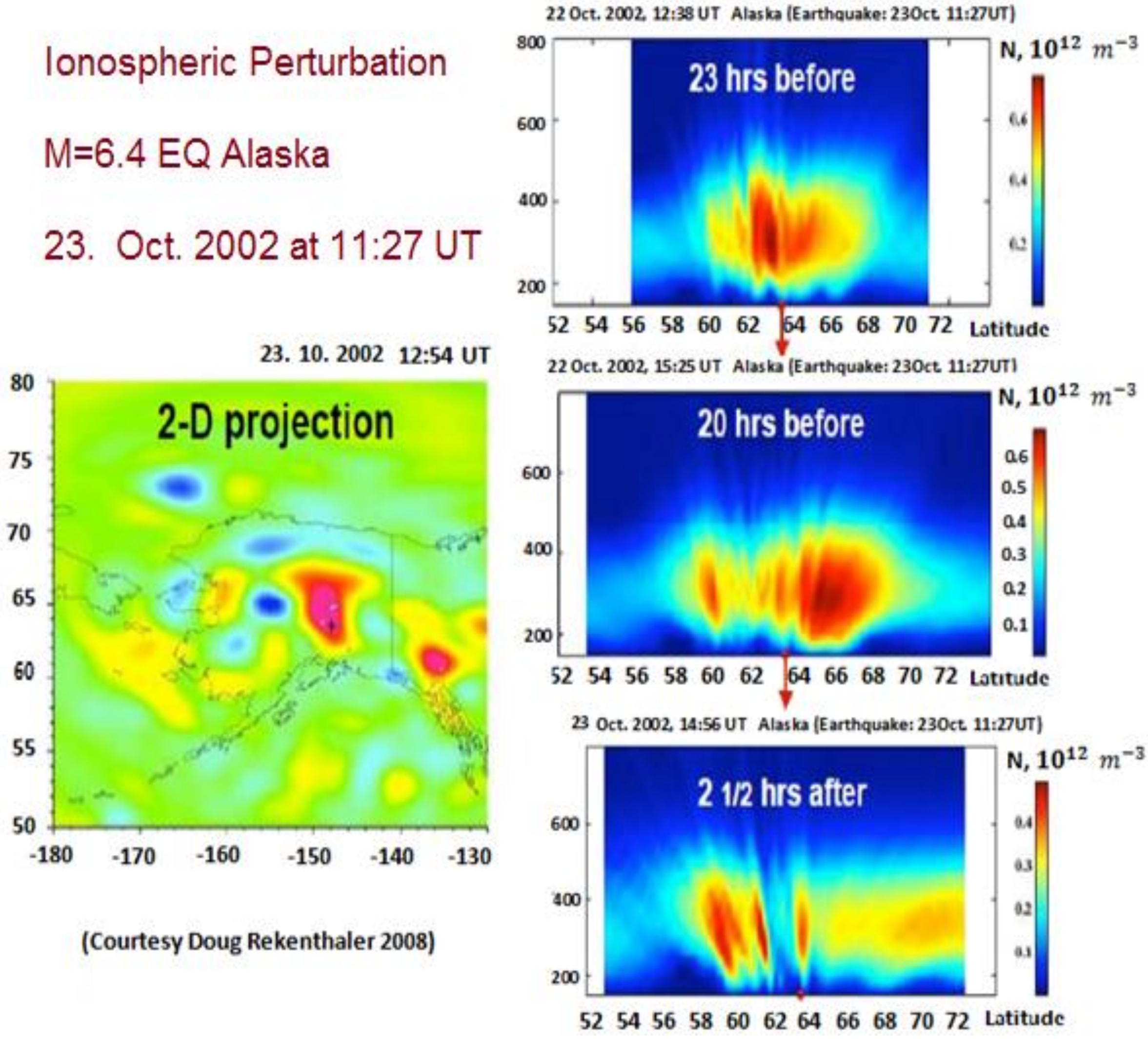



Figure 5. An application for Ratio-tomography of the ionosphere (RTI), (Freund, 2009).

## 2.2 Magnetic anomalies

Many studies have been published indicating observable anomalies in the Earth magnetic field related to quakes. These abnormalities were infinitesimal, in the nTesla scale. The adopted physical explanation points out that stressed rocks at the hypocentre release charges when they start to crack. The freed charges create large currents that slightly perturbate the

Earth's magnetic field. These disturbances create EM radiations with low frequencies ULF, ELF, and VLF.

Scientists chose to focus on the ULF data because the records were mainly dominated in this range and ULF data showed more anomalous features (Varotsos & Alexopoulos, 1987); (Bernardi, 1989). The ULF signals (1 MHz-1Hz), known also as geomagnetic pulsations, were the most widely detected thanks to their ability to penetrate kilometres of solid rocks with relatively little attenuation. Low frequency waves are less absorbed.

Monitoring stations have reported that several earthquakes were clearly preceded by spikes in ULF activity. (Fraser-Smith et. al, 1990); (Kentucky FC, 2010)

However, the obtained data sets are superposition of several signals and contain noise from manmade activities. Therefore, only appropriate recording sensitivity for a nearby station with effective discrimination method will be able to detect the minor weak peaks related to earthquakes. As usual with EM precursors, the large number of expected false positives is the main issue.

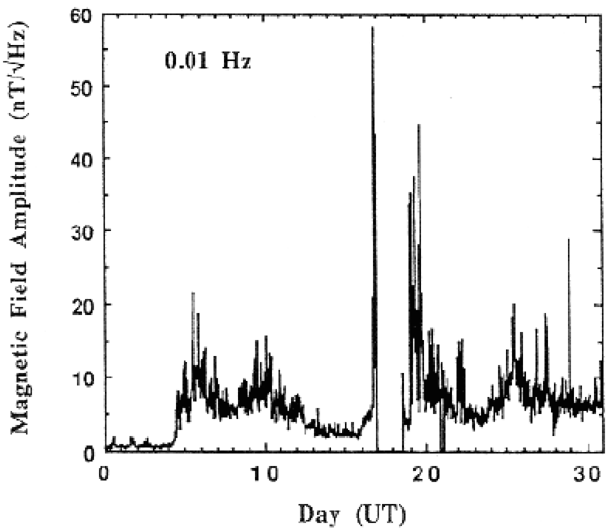



Figure 6. Graphical representation of ULF magnetometer during, Loma Prieta earthquake, Oct 1989, notice the occurred power failure, (Fraser-Smith et. al, 1990).

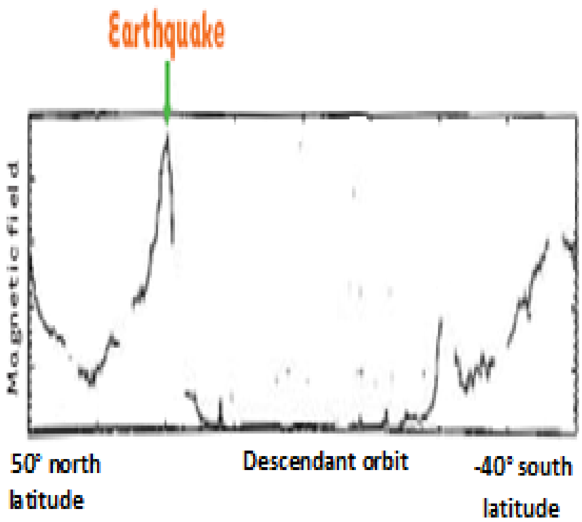



Figure 7. Variations of the magnetic field detected by Aureol 3 satellite during a magnitude 5.4 EQ in 1982, (Safaee & Alimohammadi , 2004).

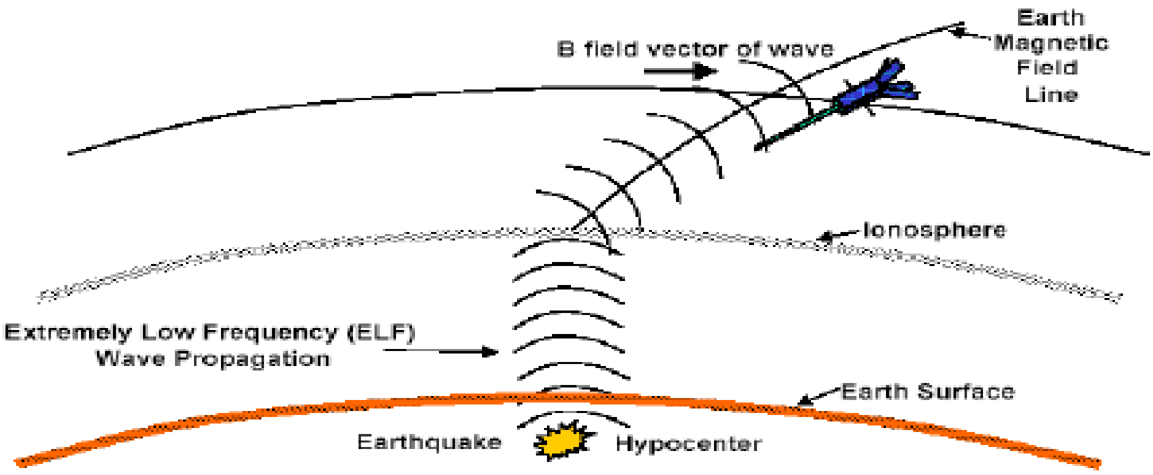



Figure 8. Nano SAT model for monitoring ElF emissions; QuakeSat mission, (Safaee & Alimohammadi , 2004).

Several Nano satellites were launched to trace the slight magnetic anomalies (Cosmos 1809, Auerol 3, Compass, Quakesat, and Demeter). Those missions used magnetometers with high sensitivity, in order to measure the low frequency pre earthquake EM signals.

### 2.3 Enhanced infrared emission or thermal IR anomalies

During the monitoring of the daily and seasonal variations of the earth surface temperature, excess thermal infrared emissions were detected before some of the quakes. These thermal infrared anomalies in satellite remote sensing images before an earthquake were reported worldwide for approximately 25 years since 1988 (Gorny et. al, 1988); (Qiang et. al, 1991); (Xu et. al, 1991); (Tronin, 1996). The large rapidly changing areas of enhanced mid-IR emission were linked to impending earthquake activity. The areas were sometimes as large as 500 km and sometimes elongated along the fault areas. They were recognized at night time using meteorological satellite images from NASAs MODIS on TERRA and AQUA, by NOAAs AVHRR and GEOS, by Europe’s METEOSAT satellites.

The anomalies seemed to be characteristically unstable fluctuating at periods of hours or tens of minutes. The satellites measured an apparent increase in temperature. Scientists call them thermal anomalies because of the mismatch (2-5°C, up to 10°C) between the IR-based estimation and the actual *in-situ* measured temperature.

The continuous inspection for similar phenomena revealed that these anomalies seemed to evolve in five different phases: normal phase, continuous growth, rapid increase, transient dropping and final silence before the shock.

Several theories tried to explain the physics behind these TIR anomalies. Tronin (2004) suggested the hydrogeological causes (local greenhouse effect). Geng (1998) explained it through the stress thermal effect caused by tectonic stress. Freund (2003) suggested the source of the excess TIR photons were due to de-excitation (p-hole recombination).

None of the presented mechanisms was able to give satisfactory answers by itself, but rather they paved the way towards a more convenient understanding of the observations. Nevertheless, the experimental studies identified the initial factor of the TIR disturbances before seismic shocks to be stress-thermal effect accompanied by other effects: *p*-hole, hydrogeological, and greenhouse. Moreover, the spatial-temporal evolution of TIR anomaly seems to be stage-related to the fracturing process of the stressed crust (Wu et. al, 2007).

The Initial observation of these anomalies obtained using sensors collecting earth observation on a wide range of the electromagnetic spectrum, including TIR channels. Even space agencies were not aware that one day the TIR data collected by their meteorological satellites would be a database for continuous researches about potential earthquake precursors.

Unlike the visible light that is a reflection of the sunlight and restricted to day time, thermal infrared remote sensing is available day and night. During the night, the sensor captures only the earth's TIR radiation. At day time, TIR images would also include sun's reflected radiation (1/10$^{th}$ -1/100$^{th}$ of ground surface radiation). The main drawback connected with depending only on satellite TIR sensor is its difficulties to penetrate clouds and fog, so some information will always be lost in this case.

### 2.3.1 Positive-hole Theory

The hypothesis is based on an idea of microscopic process of solid-state defect from oxygen atoms in minerals, igneous and high grade metamorphic rocks. The point is that oxygen anions exist in the valence 1- instead of the usual 2- (Freund, 2003).

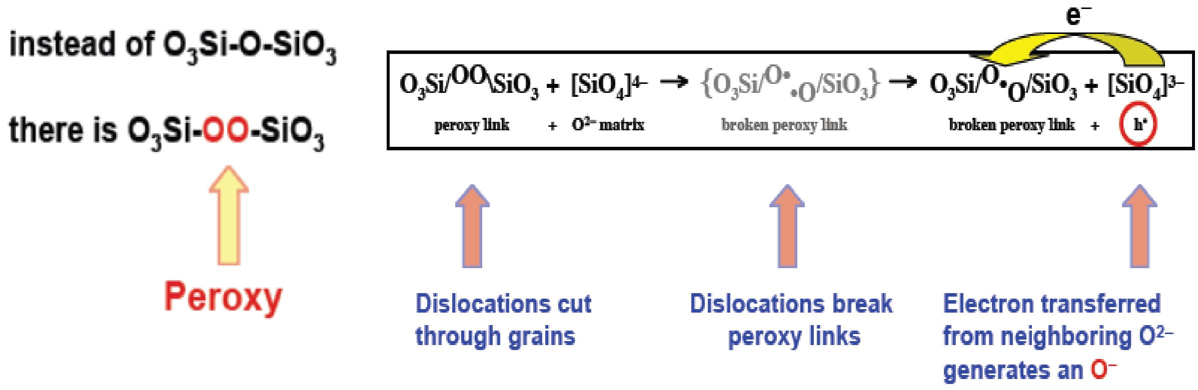



Figure 9. The defect state of oxygen anions, peroxy, in minerals and igeous rocks, (Freund, 2009).

Peroxy is effectively a diamagnetic point defect found at a rate of about 100 -1000 ppm in igneous and high-grade metamorphic rocks (Freund, 2009).

The peroxy thus forms a dormant self-trapped positive-hole pair. When stress is applied, the positive holes can then move forming a current flow out of stressed rock volume. Consequently, stress somehow turns a rock into a battery.

Freund's hypothesis was supported by several experiments showing the effect of the *p*-hole recombination at rock surface, where the energy released was as much as 2.4 eV as expected. The recombination energy is radiated in distinct IR bond around 8-11 µm. Note that this is not thermal IR emission (temperature-based), but distinct IR photons due to de-excitation, bound to material strain rather than to temperature.

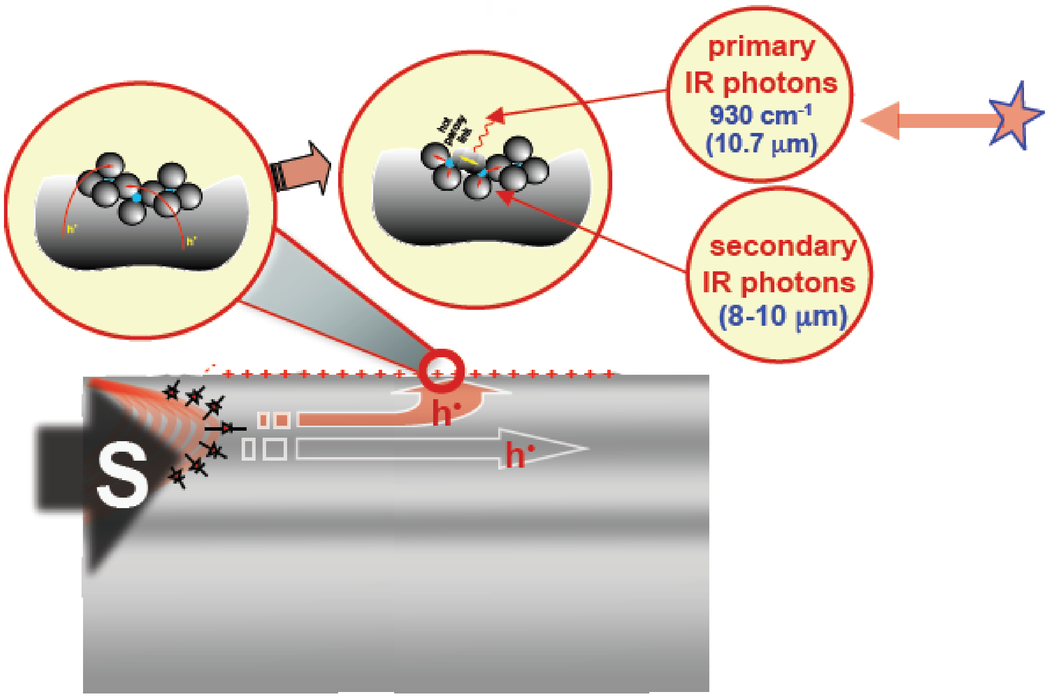



Figure 10. The micro process of surface TIR emission, (Freund, 2009).

Positive-hole theory provided a possible physical basis for many types of reported pre-earthquake signals like earthquake light (corona discharges), air ionization/conductivity, radio noise, and haze fog. These signals were interpreted as a consequence of the massive injection of ions into Earth surface that affects the atmosphere at the ground level. In fact, recently there was an attempt in this field to present a unified theory for pre-earthquake signal by Freund from the NASA Research Centre Ames (Freund, 2009). It suggests that once the positive holes are generated, currents propagate through the rocks leading to electromagnetic emission, positive surface potentials, corona discharges, positive ion emission, and mid-infrared radiation.

### 2.3.2 Supporting experiments

Lots of experiments on loaded rocks detected regularity in the observed TIR anomalies. It seems that the positive IR anomaly accompany the high-stress points and follow its movement.

1. **The first experiment** shows results of a typical evolution curve for average IR radiation temperature (AIRT) of a uniaxial loaded rock Fig(11). The curve is divided into 5 stages: normal loading - AIRT drops slightly, elastic deformation- AIRT rises stably, stress locking- AIRT rises rapidly, stress de locking- AIRT drops suddenly and changes to rise again, then fracturing failure where AIRT drops quickly (Wu et. al, 2007).

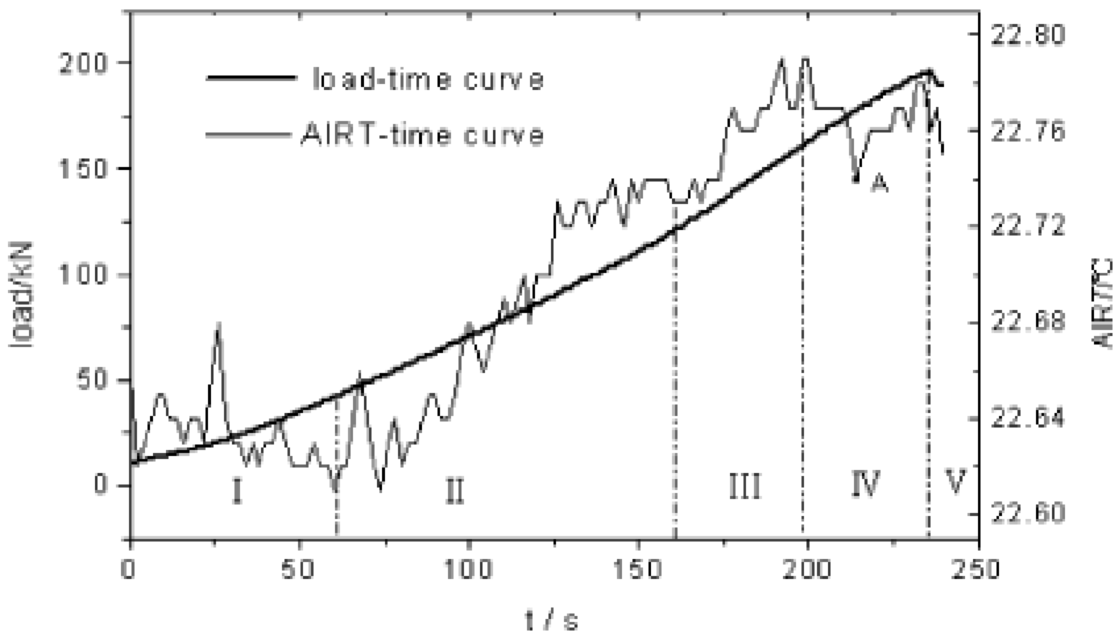



Figure 11. the staged features of the evolution of AIRT with loading, (Wu et. al, 2007).

2. **The second experiment** was performed using a bi-axial load on granite blocks to mimic satellite monitoring for TIR emissions. The blocks were used with different angles of intersection to simulate the faults joining geo-blocks in the crust (Wu et. al, 2007).

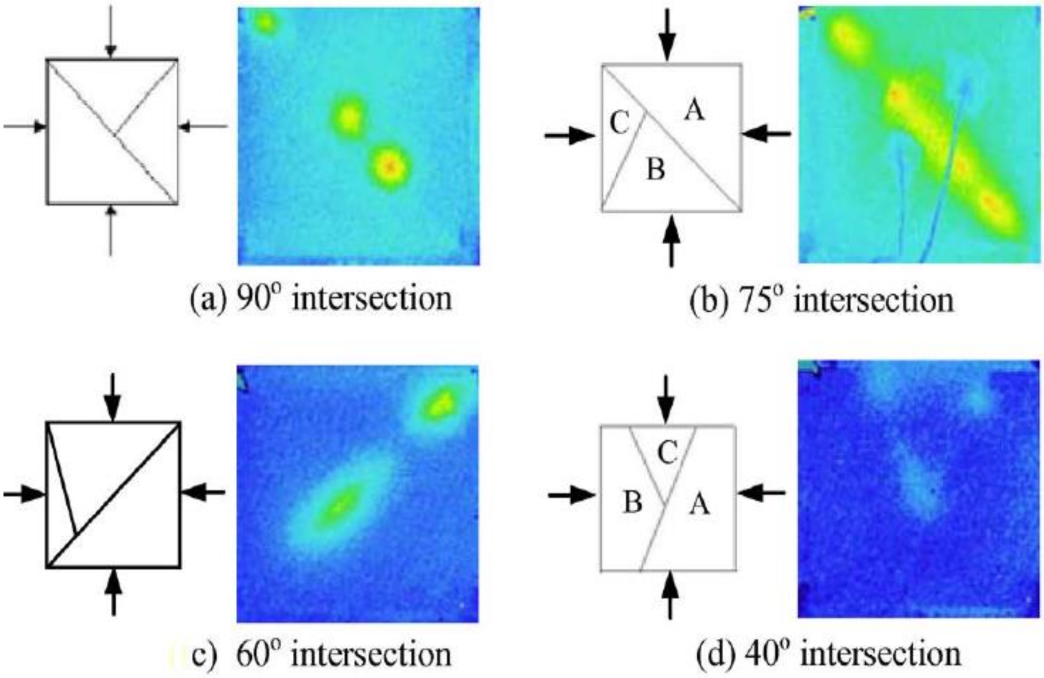



Figure 12. TIR anomaly of simulated tectonic activities due to bi-axially load, (Wu et. al, 2007).

An increase in the positive TIR anomaly in remote sensing data was noticed along the primary intersections and on the secondary intersections for acute angles (Wu et. al, 2007). In the satellite observations, common appearance of positive TIR anomaly along the active fault have been observed 1 to 2 weeks before the shock and its disappearance preceded the earthquake in hours.

The brightest spot of TIR anomaly was expected to be the possible future epicentre, which was not the case in some satellite data. This experiment showed with no doubt that the geometric characteristics of the faults net is in direct relation with the features of the observed TIR anomaly.

3. **The Third experiment** is a laboratory test for *p*-hole hypothesis, which was introduced by Freund 2002. The *p*-hole theory was verified by tests using loaded blocks of igneous rocks fig (13). Upon loading, varying potential differences on the rock surface were

measured. Moreover, using an IR spectro-radiometer, excess IR emissions were noticed after starting the loading (see fig. (14, 15)).

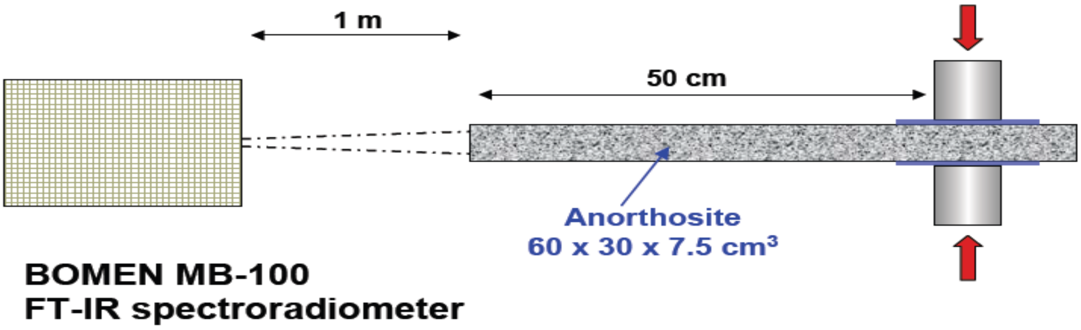



Figure 13. 60 cm long slab of Anorthosite to be squeezed at one end, (Freund, 2009).

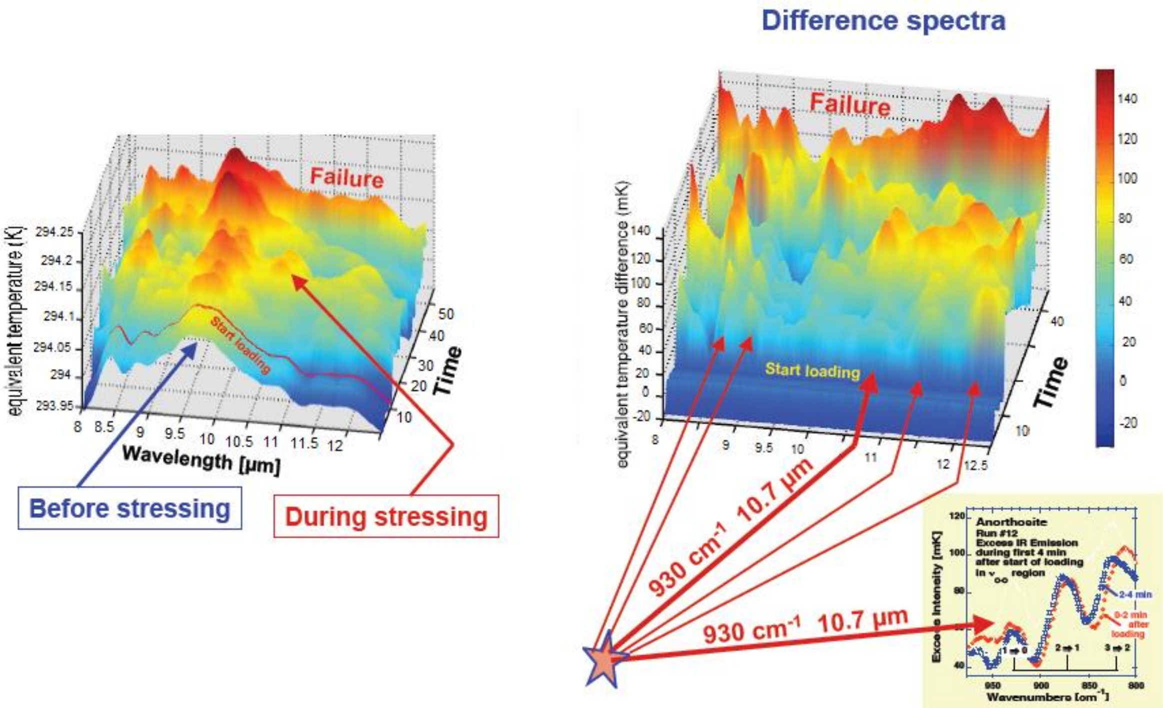



Figure 14. Observations from the IR spectro radiometer from the Anorthosite slab stressing experiment (Paccioni et. Al 2001), (Freund, 2009).

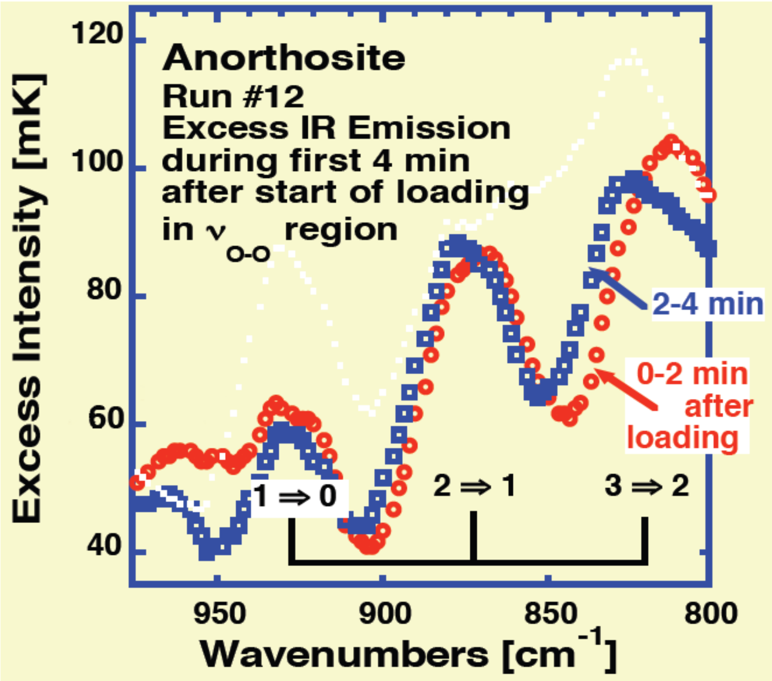



Figure 15. Excess Infra Red emission after loading due to p holes recombination, (Freund, 2009).

The curves obtained for the excess IR emission were different depending on the loading time. The results obtained provide a proof for the recombination theory which explains the decline in the excess intensity for the different time curves in (fig. 15).

Although the idea of strain-induced IR emission appears fascinating, one should not forget that the involved uncertainty when using IR space borne sensing in quake prediction is high for a number of reasons. Even if one does not consider the issue of false positives, IR anomalies appear over large areas and this makes it difficult to estimate the location of the possible epicentre. Also, the epicentre is the vertical projection of the place where the first rupture occurred, without considering the geometric properties of the fault; a strongly non-vertical fault may cause the detectable IR emission to appear definitely far from the actual epicentre of the quake.

A group of researchers inspected infrared satellite imagery from NOAA, AVHRR for TIR anomalies after Iran earthquake on 22 Feb 2005 (Choudhury, 2005) and (Choudhury et. al, 2006). The primary diagnosis of these pictures showed that the epicentre was on the borders of the red region and this weakened the thermal IR anomaly theory.

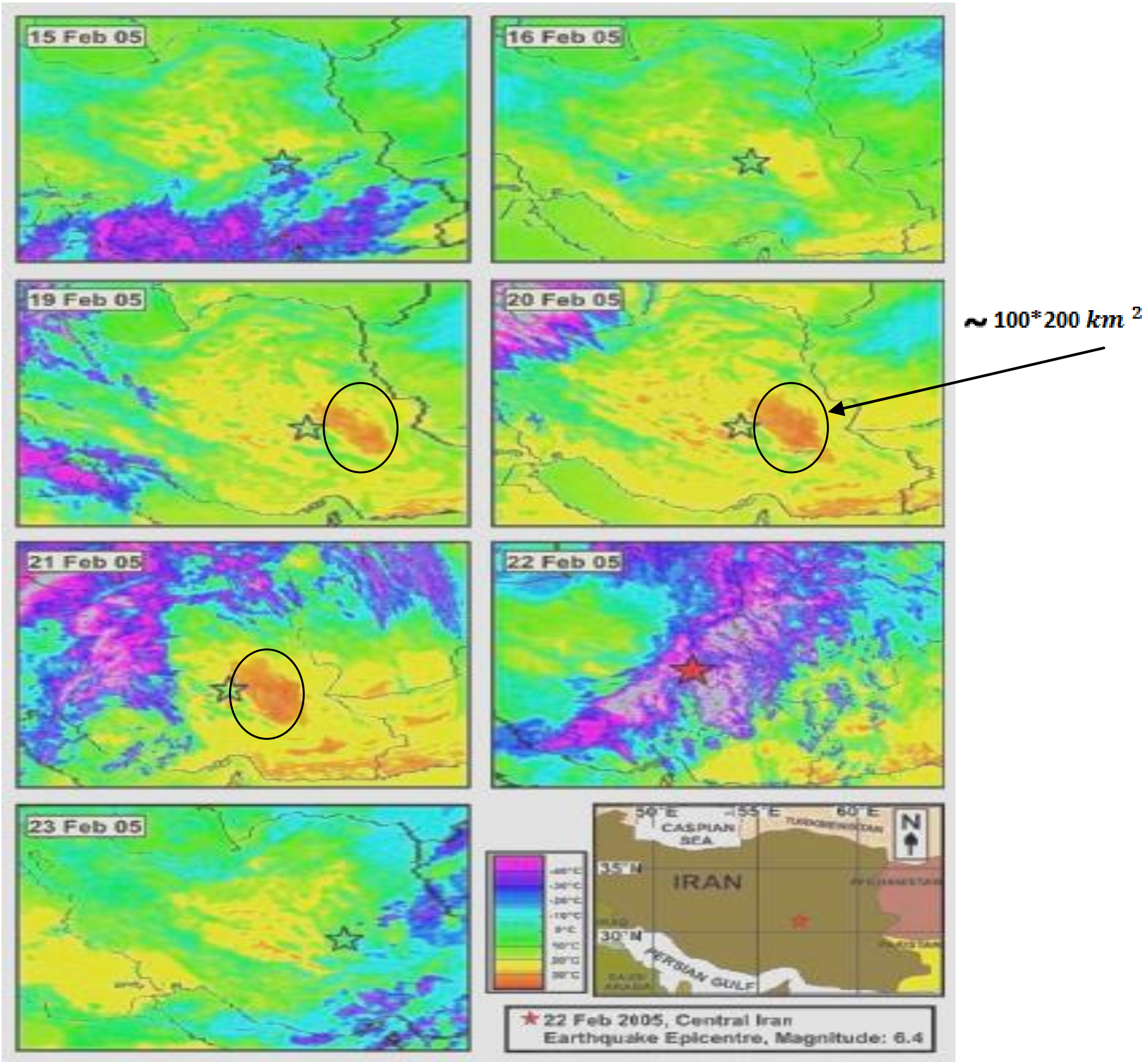



Figure 16. The graph shows an application study on the day time IR anomalies using NOAA AVHRR satellite for Zarand earthquake (M=6.4), Iran, on 22 Feb 2005 (Choudhury, 2005). Note the star is the epicentre location, and the red star indicates the earthquake day.

Then another group from Oxford, (Parsons, 2005), analysed the vertical displacement before and after the earthquake using InSAR (Saraf & Choudhury, 2005). They measured the displacement of the surface comparing a post-earthquake to a pre-earthquake image.

The most interesting point is that combining the two studies (INSAR and TIR) showed that the maximum infrared emission came from the area with the maximum crust displacement fig. (17), where 25cm uplift is shown with red colour and 25 cm subsidence with blue colour.

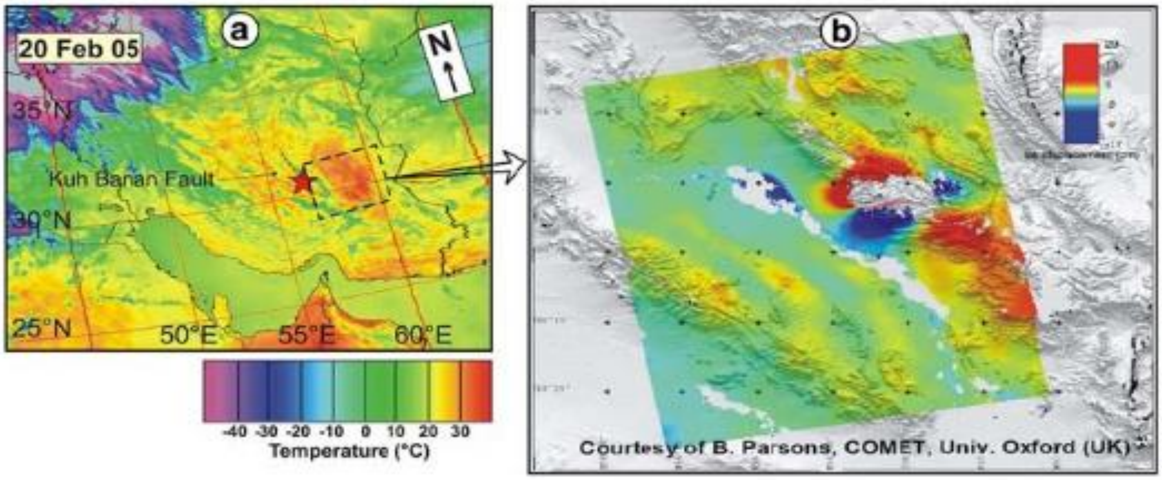



Figure 17. Comparison of thermal anomaly field from the daytime NOAA-AVHRR image (a) (Choudhury, 2005), with crust displacement field derived from InSAR image (b) (Parsons, 2005). (Saraf et. al, 2008).

This worthy notification requires intensified monitoring and might lead towards a better understanding of the studied physical phenomenon of earthquakes. Moreover, it shows the importance of data fusion in accelerating the development of ideas and increasing research work efficiency.

## 3 Conclusions

Although highly desirable, precise earthquake prediction as defined in (Allen et. al, 1976) is currently still technically unfeasible (Kossobokov, 2012). Currently, the various methods that rely on precursors suffer from large uncertainty margins. This does not imply that the tiny perturbations to the environment generated by an impending earthquake cannot be caught by sensing systems in some cases.

Cooperation between different scientific fields (geology, seismology, meteorology, remote sensing…) in the establishment of information model for short-term earthquake prediction is the foreseen necessity. The research attempts should emphasis learning more about correlation of the measurements from various fields. However, this should not mean dropping the detection for any further possible earthquakes precursory signatures. The recent progress is expected to accelerate analysis integration on earthquake precursors using massive data fusion by combining space and ground networks. In conclusion, our inadequate knowledge of the bases mechanism of earthquakes preserves the high uncertainty of our prediction. Therefore, triggering a costly evacuation based on very uncertain probabilistic predictions is still highly risky for any decision maker.

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