Changing the Landscape of Geology: Forecasting Earthquakes

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Scientia

CHANGING THE LANDSCAPE OF GEOLOGY: FORECASTING EARTHQUAKES

Imagine a world where we knew about earthquakes before they strike – days before a potentially lethal event. A world with an early warning system that would give us time to evacuate vulnerable buildings, to activate civil defence organisations, to minimise the loss of life and reduce recovery costs. Although the dream of earthquake prediction has been on people's minds for centuries, it is dismissed by most seismologists and geophysicists as a pipedream. However, all that could change dramatically, thanks to **Professor Friedemann Freund** at the NASA's Ames Research Center.

Between the years 2000 and 2016, there were nearly 30,000 earthquakes recorded worldwide with a magnitude of 5 or greater. These earthquakes caused hundreds of thousand fatalities and trillions of dollars in economic damage, some with long-lasting effects that will linger on for years, decades and even centuries, such as the radioactive contamination from the preventable Fukushima Nuclear Power Plant disaster.

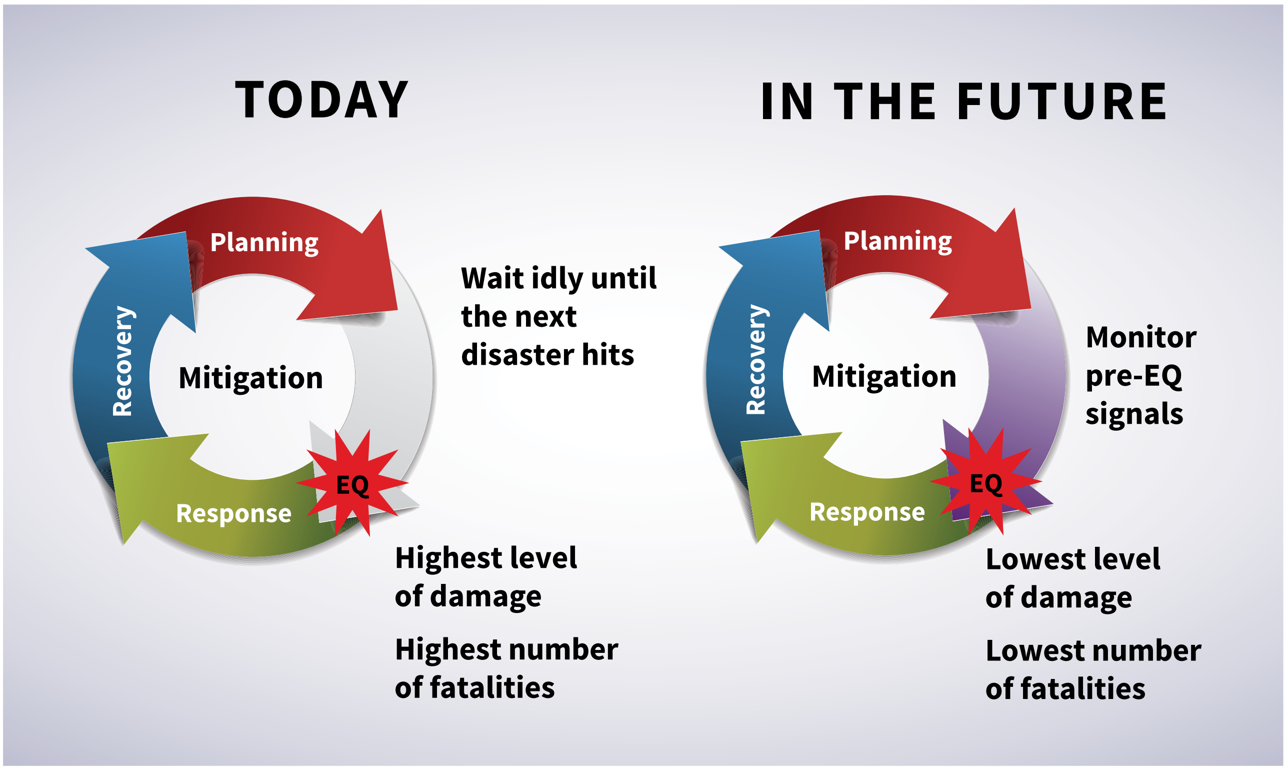
The famous San Francisco earthquake of 1906 led to the destruction of more than 80% of the city, more than 3,000 deaths and an estimated $400 million in damage – approximately $10.7 billion in today's money. More recently, the 2011 Tōhoku earthquake in Japan left more than 15,000 people dead and caused over $360 billion in direct damage in Japan and around the Pacific rim. These costs continue to accumulate due to the need to manage the Fukushima Nuclear Power Plant site. With so much at stake, it's no wonder that efforts to forecast earthquakes have been underway since the very beginning of seismology.

What Causes Earthquakes?

The Earth's outer shell, the 'crust', is made up of tectonic plates, about 150 km thick, that fit together like pieces of a giant puzzle. These rigid plates move around over timescales of millions of years, changing the face of our planet slowly but inextricably. As these plates slide past each other or collide, stresses build up. When these stresses reach a critical range, rocks rupture catastrophically, sending out powerful seismic waves that can be highly destructive at the Earth's surface.

Large earthquakes are monstrous mechanical events, with ruptures that can run over tens, sometimes hundreds of kilometres. Because they are mechanical events, those who wanted to develop the means to predict them, the seismologists, started out by focusing on mechanical precursors. Despite a concerted effort spanning more than a century and ample public funding, the seismology community has failed in its effort to develop tools for actionable prediction.

There is, however, a collection of seemingly unrelated, non-seismic pre-earthquake signatures that have largely gone ignored due to their disparate nature. These signatures include subtle, often fleeting phenomena, mostly electrical or electromagnetic in nature, such as transient electric currents in the ground, emission of electromagnetic radiation from within the Earth, lights near the ground or in the sky, and even abnormal animal behaviour. Science has never been able to offer sound, testable explanations for the origins of such precursory signals. As a result, the mainstream geoscience community has come to view them with suspicion, more as folklore than anything else.



Over the years, Professor Friedemann Freund, in collaboration with his son Mino, has developed a deeper understanding of the processes that give rise to a bewildering multitude of non-seismic signals before major earthquakes. He and his research team at the NASA's Ames Research Center in California have shown that there is a single physical process, occurring deep in the crust, that could explain all of these unconventional precursory effects. Thus, a unifying picture emerges, which is likely to change the course of earthquake prediction for ever. In a forthcoming volume of the *European Physical Journal*, a number of papers will be published supporting the contention that all non-seismic pre-earthquake phenomena can be traced back to one fundamental physical process: the activation of electronic charges in rocks in response to the ever-increasing tectonic stresses prior to any major seismic event, namely the rupture of peroxy bonds.

Peroxy Bonds: Shaking Up the Science of Earthquake Prediction

Professor Freund's journey started decades ago with work that was published back in 1976 with the discovery of a previously unknown chemical reaction that leads to the formation of so-called 'peroxy bonds'. Although quite familiar to chemists, peroxy bonds are totally alien to geoscientists.

At its most basic level, the reaction leading to the formation of peroxy bonds involves a rearrangement of electrons between two atoms in the structure of a mineral. An oxygen atom with two extra electrons, O^{2-}, donates one of its extra electrons to a suitable acceptor, such as a proton, H^+. This proton thereby turns into a hydrogen atom, H, and combines with another H to form a hydrogen molecule, H_2. Meanwhile, O^{2-} turns into an oxygen atom with just one extra electron, O^-, and combines with another O^- to form a peroxy bond, $O^-–O^-$.

This process happens deep within the Earth's crust and along the boundaries between mineral grains. The peroxy bonds not only exist inside the mineral grains but also along grain boundaries and even across grain boundaries, linking adjacent grains together like a 'glue'.

This last aspect is important for understanding what happens when rocks are stressed. Professor Freund has been able to show that when very slight stresses are applied to a rock and its grains start to shift relative to each other, peroxy bonds break. In that moment, the rocks change from an insulator to a semiconductor state: the rocks become laced with mobile electrons (e') and holes (h$^\bullet$), similar to semiconductors that are used in electronic devices. The stress-activated electrons are mobile inside the stressed rock but lack the ability to flow out. The holes, by contrast, have the remarkable ability to spread into the surrounding less stressed or unstressed rocks. They can travel at up to 100 metres per second and over distances of tens of kilometres – even hundreds of kilometres in the case of large earthquakes getting ready to strike.

The situation is very dynamic. As electrons and holes are activated inside a stressed rock volume, these charge carriers start to flow out but also instantly begin to recombine, returning to the inactive peroxy state. By measuring in the laboratory the speeds at which electrons and holes are activated and holes flow out, Professor Freund has been able to shed light on these processes that happen deep in the Earth's crust way beyond direct observability. This has led to a conceptual picture of the balance between production of electrons and holes and their return to the inactive state, coupled to the outflow holes from the rock.

The situation is further complicated by the fact that, once the holes have flowed out of the stressed rock, they spread, travelling ever more slowly as the distance increases. When the positive holes arrive at the Earth's surface, they become trapped and initiate secondary processes. One important secondary process is recombination, which leads to the emission of infrared light. This infrared light is widely interpreted as temperature increase, while in fact it is due to a non-thermal infrared emission process. Another follow-on process is air ionisation, first producing positive airborne ions, followed by negative ions alongside ozone production and a rise in radiofrequency noise.

Although this multitude of reactions holds the key to a potential paradigm shift in the Earth sciences, the omnipresence of peroxy bonds in the constituent minerals of crustal rocks has been largely overlooked by the geoscience community. Convinced of the significance of his discovery, Professor Freund continued to pursue this line of research throughout the 1980s and 1990s with little, or sometimes no, external funding. Due to his sheer determination and persistence, he made a breakthrough in the early 2000s, when he began looking more closely at the electron density distribution in the so-called 'oxygen anion sublattice' – the collection of negatively charged oxygen ions within a material – from the perspective of a semiconductor physicist. He made two ground-breaking observations: (i) that stresses applied to a rock cause it to turn into a new form of semiconductor, and (ii) that the charges flowing out of the stressed rock volume are positive. Never had such a behaviour been reported in the scientific literature.

Based on these observations and his broad interdisciplinary knowledge, he began to develop a new approach for forecasting earthquakes. He postulated that the outflow of these positive electric currents is responsible for the wide range of widely reported but never properly understood phenomena that occur before and sometimes during earthquakes – phenomena that range from electric and magnetic field anomalies in the Earth's surface, light flashes rising out of the ground or appearing high up in the skies, and – most puzzling – abnormal animal behaviour.

What is the Impact on Our Current Understanding?

Indeed, throughout history, there have been countless reports of pre-earthquake phenomena that science has been unable to explain due to a lack of understanding of the physical processes occurring deep in the Earth's crust. Today, with a global network of observation satellites, ground-based observation stations and even the video-capable smartphones, there is a growing body of evidence that helps us to understand why electromagnetic radiation, electric and magnetic field anomalies, radon gas, ionospheric disturbances, and many more precursory signals are *bona fide* signs of an approaching major seismic event. Although there are still no properly funded efforts to collect such pre-earthquake data systematically, the scientific community is beginning to take notice.

This theory is an important step forward in humanity's quest to be able to forecast major earthquakes days or even weeks in advance, and to understand the multitude of seemingly unrelated pre-earthquake signals. In the forthcoming *European Physical Journal* issue mentioned previously, Professor Freund and a team of collaborators put the theory to the test: 'We review a credible, unifying theory for a solid-state mechanism, which is based on decades of research bridging semiconductor physics, chemistry and rock physics. This theory, which we refer to as the "peroxy defect theory", is capable of providing explanations for the multitude of reported pre-earthquake phenomena.'

This *European Physical Journal* issue examines a wide range of independent studies into previously disregarded phenomena that occur before – or during – earthquakes, and many of them provide results that are consistent with Professor Freund's theory. Although his work is far from complete, Professor Freund has opened the door to an area of Earth Science that was previously thought to be replete with nothing but wishful thinking.

Perseverance in the Face of Controversy

The story of how Professor Freund developed his paradigm-shifting theory is not one that is merely about science, it's a tale about tenacity, determination and perseverance in the face of controversy – about pursuing the evidence and working towards a goal, even when others cast doubt on the value of this work.

Professor Freund is inspiring and, when asked about his journey, he is happy to provide some words of wisdom. 'As we make progress in demonstrating the validity of my semiconductor approach to pre-earthquake signals, the resistance in the seismology community starts to erode,' he says. 'I view my academic career as setting an example for the younger generation that a paradigm-shifting discovery may require an enormous amount of patience and the willingness to pursue an idea with dogged persistence.' It is this attitude that has allowed him to change the landscape of the science of changing landscapes.

Meet the researcher

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Professor Friedemann Freund completed his PhD in Mineralogy and Crystallography in Marburg University, Germany, in 1959. His career has spanned over fifty years and he has worked with NASA at the Ames Research Center since 1985. His research interests include organic chemistry, astrobiology, the study of defects and impurities in crystalline solids and semiconductor aspects of mineral and rock physics in relation to earthquake and pre-earthquake phenomena. Throughout his career, he has demonstrated an absolute determination to pursue his scientific goals in the face of controversy and, as a result, he is on the cusp of ushering in a paradigm shift in the geosciences.

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W: https://geo.arc.nasa.gov/sg/cv/esddir3cv-freund.html

FUNDING

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FURTHER READING

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