SEISMOLOGY

Earthquakes in the Sky

The best early warnings of a big disaster may appear 180 miles above the ground, a controversial new theory says

By Erik Vance

Illustration by María Corte

Science writer Erik Vance wrote about vaquitas, threatened porpoises in the Sea of Cortez, in the August 2017 issue. He lives in Baltimore, Md.

On Friday afternoon, March 11, 2011, Kosuke Heki was in his office in Hokkaido University in northern Japan when the ground began to shake. The pulses were far apart, and each one lasted a few seconds. Heki, a geophysicist who studies an arcane phenomenon involving odd patterns formed by electrons in the sky after quakes, was interested but not unduly alarmed. It seemed like a large earthquake but far away. As the shaking continued, he thought perhaps data from the event might help his research. Then someone flipped on the news, and Heki's curiosity turned to horror.

The waves he felt had come from the biggest temblor in modern Japanese history—the devastating magnitude 9.0 Tōhoku earthquake, which cost the country hundreds of billions of dollars and claimed more than 15,000 of his compatriots' lives. The tsunami after the quake crippled the Fukushima Daiichi Nuclear Power Plant and triggered the worse nuclear disaster in a quarter of a century.

While emergency personnel worked to evacuate people and save lives in another part of the country, Heki could only wait for spotty phone and Internet service to come back online. By Sunday, the Internet was working, and he quickly downloaded satellite observations of the air over the region of Tōhoku and hungrily combed through them. As he expected, electrons in the ionosphere showed a disturbance 10 minutes after the quake. But he could not get his model to fit the data by just looking at the minutes after the quake. So he tried expanding the time frame, including the hour before. That is when he saw something that stopped him in his tracks.

Forty minutes before the earthquake struck, there was a subtle rise in electron density above the temblor's epicenter. Maybe it was an anomaly, a one-off or an instrument malfunction. Or maybe it was something more. Scientists have yet to find a reliable earthquake precursor—a telltale sign that could alert people before the onset of a large quake. If electron changes were such a warning, they could save thousands of lives a year.

Heki, whom colleagues describe as unassuming, quiet and cautious, was immediately skeptical of his own data, so he pulled up information from two other earthquakes. He saw the density change again and decided to keep digging. To date, he has found the electron signal before 18 big quakes, and over the past seven years he has come to believe it is real.

Other experts are now starting to take a close look at the idea. "Years ago people didn't think we could predict the weather, but we do now," says Yuhe Song, an expert in remote sensing at NASA's Jet Propulsion Laboratory. "We probably can see something earlier than when we feel it on the ground. There is something there … I think this warrants a discussion."

Not everyone agrees. Many scientists see Heki's work as the latest in a long line of false prediction promises. "These things are like the common cold: they're always going around," says seismologist Robert J. Geller, an emeritus professor at the University of Tokyo, who has spent years debunking various earthquake forecasting ideas. "If you ignore them, they go away."

Heki's idea seems to be sticking around, however, and may be getting stronger. The electron signal has shown up in medium-sized quakes as well as the largest ones. Other scientists have formed a theory that connects faults in the ground to activity in the sky. Heki has published his findings in reputable journals such as Geophysical Research Letters and been invited to lecture about the results at the American Geophysical Union's annual meeting. This past spring Japan's Chiba University hosted an entire meeting to

IN BRIEF

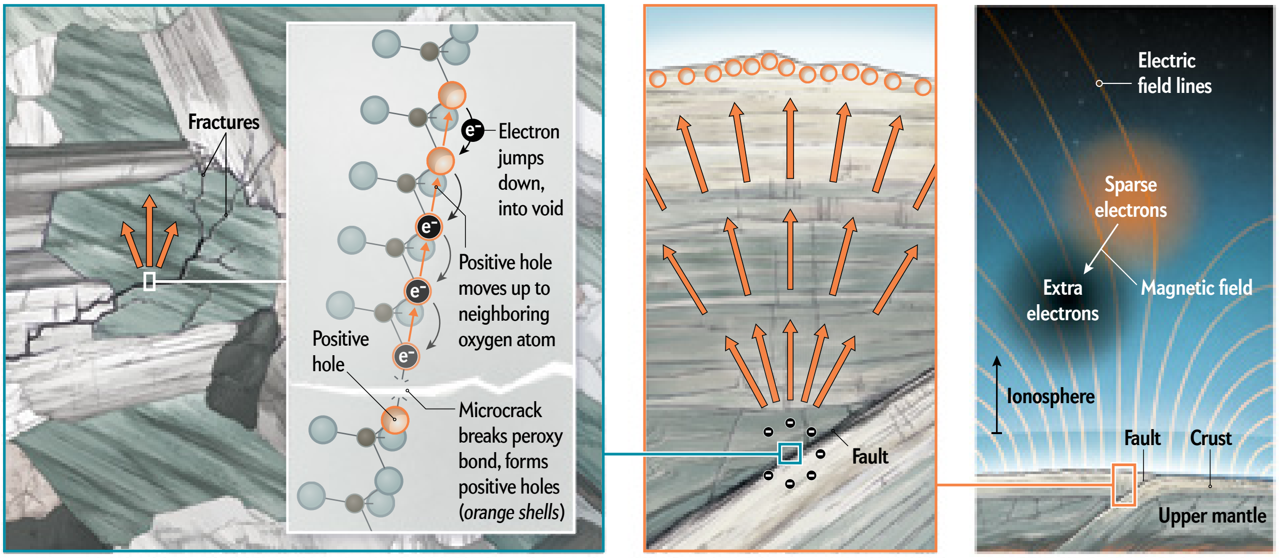
Tens of thousands of people can be killed by a single earthquake, so scientists have struggled to predict quakes well enough to sound an alarm.

New observations suggest that clumps of electrons form in the ionosphere, sometimes 30 minutes or more before a temblor, giving an early warning.

There have been false promises of prediction in the past, so this notion is drawing skeptics—but the data are beginning to convince more scientists.

From the Ground Up

Electrical disturbances miles above the planet's surface may occur at least half an hour before major earthquakes, new research indicates. These could be early warnings of disasters. And there is a theory about the way cracks in rocks might create activity high in the sky.



1. A Fracture Begins
Within the ground, parts of the earth's crust slide slowly across one another. Sometimes at a fault line they jerk suddenly, and the strain of the movement begins to tear the rock apart, creating small breaks called microfractures.

2. Electrons Jump
The microfractures generate enough force to break peroxy bonds, which hold together oxygen atoms within molecules in rock grains. This force alters the energy of negatively charged electrons in these grains, making the electrons move. They leave behind positively charged spaces called holes. As more electrons move, the holes move in the opposite direction, creating a tiny electric current in the rock grain.

3. To the Surface
This process continues across adjoining grains of rocks, like chains of falling dominos. Electrons move, leaving room for holes and their positive charges to propagate up from the original fracture, jumping from grain to grain up to the surface. Behind them, the strain created by grinding rocks grows.

4. Up in the Air
When positive holes accumulate at the surface, they can pull electrons from molecules there, generating an electromagnetic field. These fields can form lines that extend miles upward. They alter patterns of electrons in the ionosphere, making dense clumps in certain spots and sparse concentrations in others. Such anomalies can be detected by satellites.

debate quake prediction, including his idea. If Heki is right, the implications for public safety are enormous, but there are difficult questions about how to use such a precursor. How accurate must a warning system be to sound an alarm, and what kind of emergency response should ensue?

PREDICTING THE WORST

Charles F. Richter—creator of the quake magnitude scale that carries his name—is said to have remarked that "only fools and charlatans predict earthquakes." But that hasn't stopped people from trying. In 373 B.C., animals reportedly ran for shelter five days before an estimated 6.0 to 6.7 magnitude temblor rocked Greece and destroyed the city of Helike. The Japanese once thought that twitching or thrashing catfish could predict earthquakes. Dogs, sheep, centipedes, cow's milk and a Sumatran pheasant called the great argus have all been said to change their behavior before a quake.

Others have looked at wells that suddenly go dry, temperature changes, radon gas emissions and, of course, groups of smaller foreshocks as possible precursors. In 1975, using a combination of these signs (including animal behavior), the Chinese even managed to predict a 7.3 quake early enough to begin evacuating the city of Haicheng. It raised hopes. "In the 1970s American and Japanese seismologists became pretty optimistic about short-term earthquake prediction," says Masao Nakatani, an expert in rock mechanics at the University of Tokyo. "We tended to believe that earthquakes must be predictable." By the 1980s both the U.S. and Japan had created research groups to pursue the challenge.

Reliable signals proved elusive, however. One year after the Chinese success the same techniques failed to spot another, larger quake that killed hundreds of thousands of people. Japan, sitting on the tectonically restless Ring of Fire around the Pacific, put in a fair amount of effort only to find that a precursor would work once and not again. Nature seemed to keep changing the rules. The U.S. abandoned forecasting efforts in the late 1990s after a predicted quake—based on the pattern of previous earthquakes—failed to appear near Parkfield, Calif. (It eventually hit in 2004 but with none of the expected warning signs.)

The year of the Tōhoku quake, an international commission on prediction, set up by the Italian government, essentially closed the book on the field. "In spite of continuous research efforts in Japan, little evidence has been found for precursors that are diagnostic of impending large earthquakes," the members wrote in May 2011.

Four months later Heki reopened the book. What he saw were bizarre pockets of ionized particles not at or on the earth's surface but 186 miles above it. The idea of a connection between ground and sky is not out of this world. In the 1970s scientists first found that rocks under extra pressure create an electric current, like a very weak battery. The theory goes that as a rock is pressurized, its oxygen atoms give up electrons, leaving deficits that physicists describe as positive holes. Electrons from other nearby atoms move into those holes, leaving yet more holes behind them, creating a chain reaction of moving charges.

TOLL OF A QUAKE: With little warning, the deadly Tōhoku earthquake and tsunami destroyed the Japanese city of Rikuzentakata; afterward, residents walked among the ruins.

NICOLAS ASFOURI Getty Images

The holes "have the ability to move around over long distances—miles, tens of miles, hundreds of miles," says Friedemann Freund, a researcher at NASA and the SETI Institute, who discovered the phenomenon. "It's like a bucket of water in a fire line. It's being handed from person to person to person."

Freund says that the holes then roam through rocks, eventually reaching the earth's surface, where they attract negatively charged electrons from molecules in the air, like a magnet attracting iron shavings. The electrical charges then travel to the upper atmosphere. The mechanism is just theory because it is hard to measure directly, but it seems to fit with hints of electron clumps seen after an earthquake. But no one had clearly seen the effect before a quake.

For his research, Heki brought in a new method that used sophisticated GPS satellite networks, which can detect subtle changes in atmospheric electrons when their radio signals bend across the atmosphere. Japan has a particularly dense GPS receiver network, which allowed Heki to spot a subtle electron surge in the sky far above Tōhoku's epicenter, about 40 minutes before seismometers in the ground detected any movement.

But the geophysicist says he was reluctant to present his findings. "I had to worry about how to publish it," he says. "Earthquake prediction is something special. Everybody becomes very emotional."

He did not, in fact, publish right away. After Tōhoku, Heki looked back at two giant earthquakes where detailed GPS data were available. In each, he found a telltale rise in electron concentration more than 30 minutes beforehand. The larger the quake, the longer the advance time, it seemed. A magnitude 8.2 quake in 2014 in Chile had a 25-minute lead time, whereas 9.0 Tōhoku gave the 40 minutes. So the signals not only hinted that the faults were about to slip; they also indicated the relative size of the ensuing temblor. "I have never seen such a clear phenomenon occurring just before an earthquake," he says.

CHAOTIC DEBATE

Armed with these data, Heki finally published a paper in September 2011, announcing what he found. Other scientists quickly started pointing out problems. Some said the result came from a misreading of the data and that disturbances during and after the quake muddied the picture. Heki responded by using a different analytical method to highlight the prequake effects. He also converted measurements taken at an angle to a bird's-eye view, thinking this would make the effects easier to spot. But critics argued this was just reorganizing the same flawed data. Another Japanese team said the effect was caused by geomagnetic storms. Heki performed another analysis to account for storm effects and found that storms could not explain all the changes he saw.

Soon some doubters began to agree with him. "This is by far the best precursor ever reported," says Nakatani, who says he stopped believing in earthquake forecasting after the failures of the 1990s. But Heki has rekindled his faith, so much so that he now says the work could very well be "the most important discovery in the history of earthquake science." NASA's Song is less hyperbolic but agrees the electron clouds have been hard to explain away as errors and seem to signify a real event. Freund says Tōhoku followed months of pressure buildup and changes in electron density. And although that pressure might have found other outlets—such as invisible "silent" earthquakes—the charged particle release is still a predictable phenomenon that, in theory, could be detected in other quakes.

Critics, however, insist Heki is seeing things in a computer that do not exist in the real world. "He is trying to confirm his initial thought without providing a valid support," says Fabrizio Masci of the National Institute of Geophysics and Volcanology in Italy. He has published papers refuting not just Heki but other earthquake prediction ideas and says Heki's responses are "a skillful way to distract the reader." Many of the criticisms focus on Heki's reading of baseline electron levels. The tiny particles permeate our planet and fluctuate as much as the weather. Heki says that just before an earthquake, electrons clump a little more than average. Critics say that the change is caused by the daily ebb and flow of electrons. In other words, Heki may be chasing a statistical ghost.

Masci goes even further and says seismic precursors might be impossible if earthquakes themselves are fundamentally chaotic. If the initial conditions of an event are not precisely determined, it is impossible to know how the effects will play out. And with quakes, it is devilishly hard to nail down all the initial conditions.

Giovanni Occhipinti of the Institute of Earth Physics of Paris is not so pessimistic, although he agrees it is a daunting problem to understand all the factors at play—the rock type, the pressure, the faults nearby—well enough that you can make a prediction. Occhipinti, like Heki, studies how earthquakes affect atmospheric ions. He says that, given how chaotic ions are in the atmosphere, you simply cannot pull a signal from all the noise. It is like trying to predict a hurricane based on a single cloud a day beforehand. "The problem is there are tons of clouds that are coming and moving around," he says. "It's not simple to deduce a way to discriminate that specific cloud that you want to see as a precursor."

Until recently, Occhipinti was on the side of skeptics and felt that Heki's discovery was merely a statistical hiccup. Heki's latest work,

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> —Giovanni Occhipinti Institute of Earth Physics of Paris

however, which takes into account the complex 3-D space in which the effects happen, caught his interest. Rather than a limited satellite snapshot, 3-D modeling shows multidimensional effects that point to a consistent physical process underlying the anomalies, making them hard to write off as ghosts. Occhipinti wants to see more 3-D analyses, along with comparisons of those results with other models to see how well they fit. So he is not, as yet, a complete believer. But he calls the idea "intriguing" and is now looking into it more closely. "It's pushing science forward," Occhipinti says, but "you have to be really, really, really precise. You are playing with the lives of people."

SOUNDING ALARMS

The numbers of those lives can reach into the hundreds of thousands. The U.S. Geological Survey examined worldwide earthquake fatalities for a 16-year period beginning in 2000. The death counts fluctuate because there are not giant quakes every year. But the toll is daunting. In seven of those years there were more than 20,000 deaths, and for another two years the totals exceeded 200,000. In the countries hardest hit, people are desperate for any kind of warning, even just a few seconds. Take Mexico City, one of the most lethal and well-studied earthquake zones on the planet. After a devastating 1985 quake that killed as many as 10,000 people, the government took advantage of the fact that quake waves travel over unusually long distances in the region and built a monitoring system that can give a couple of minutes warning if the waves are detected far enough away.

Carlos Valdés, a geophysical engineer and director of Mexico's National Center for Prevention of Disasters, says a 40-minute warning might sound good, but the reality is not so simple. First, false alarms can ruin any emergency response. Some Mexican quakes triggered warnings but were too weak or in the wrong position to actually shake the city, for instance. People became annoyed and stopped responding to those alerts. But he worries more about the opposite problem: panic. "Somebody is going to say, 'I have 40 minutes, I'm going to leave the city,'" he says. "It takes only one person to start screaming or start running, and everyone follows." Roads clog, and no one gets to safety [see "This Way Out," on page 74].

Still, other emergency planners note that even short warning times create the opportunity to shut down gas lines or stop subways, reducing risks. And greater accuracy would solve the false alert problem. British and Russian scientists have proposed a satellite that could better track atmospheric anomalies such as the ones Heki studies, and China is moving forward with a space-based prediction program that relies on electromagnetic disturbances in the ionosphere. But given the complex nature of the ionosphere, coupled with the confusing nature of earthquakes, it may be decades until atmospheric data become actual earthquake warnings.

Geller does not think that day will ever come. "The precursor hunters throughout the past 130 years have a childlike belief that, one, there must be precursors and that, two, the bigger the quake, the bigger the precursors must be. But there's no particular reason these beliefs should be correct," he says.

Still, Heki is moving forward. He recently published a paper that analyzes the precursor of a 2015 Chilean quake in detailed 3-D, which he says may make his ideas harder to refute. He is also trying to fill in some data gaps between the electrical charges and the actual earthquake locations themselves. The goal is to better understand what it is in the crust that creates the effects high above. "There is something before an earthquake in the ionosphere. I don't know about a physical mechanism," Heki says, "but the observation itself is so clear." SA

MORE TO EXPLORE

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