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energie atomique • energies alternatives

FROM RESEARCH
TO INDUSTRY



17



Earthquakes



MEASUREMENT SENSORS
 PLANNING AHEAD
 MONITORING
 UNDERSTANDING



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Earthquakes

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The 1976 earthquake in Northern Italy.

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Special sensors are used to acquire data which are then analyzed. These data are combined with results from life size tests.

"An earthquake results from the abrupt release of the energy accumulated by movements and rubbing of different plates."

Earthquake signatures

The surface of the Earth is continually changing on a geological timescale. The tectonic plates, which make up this surface, are moving in relation to each other. On human timescale, these movements are the result of earthquakes, which suddenly, release energy accumulated over a period of time. The vibrations they produce propagate through the interior of the Earth: these are seismic waves. However, other phenomena can generate seismic waves, such as volcanoes, quarry blasts, etc. The surf of the ocean waves on the coasts, the wind in the trees and human activity (industry and road traffic) all contribute to the "seismic background noise". Sensors are able to detect signals from events which are then discriminated, analyzed and located.

Earthquakes and active volcanoes are not distributed randomly over the surface of the globe: they mainly coincide with mountain chains and ocean trenches and ridges. Study

of the propagation of seismic waves has allowed to determine the outline of the plates inside the Earth and has highlighted their movements. There are seven major plates which are colliding, diverging or sliding past each other. Each year the continents move several centimeters with respect to one another. This process, known as "continental drift", was finally explained by plate tectonics. The initial hypothesis for this science dates from the beginning of the 20th century, but it was not confirmed until the 1960s (see box on page 14). It explains that convection inside the Earth is the source of the forces required for these movements. This science, as well as explaining these great movements, has provided a coherent, unifying and quantitative framework, which unites the explanations for all the geophysic phenomena under one mechanism.

TODAY WE HAVE VERY PRECISE TOOLS TO MEASURE MOVEMENTS OF THE GROUND. MEASUREMENTS WHICH ARE FOLLOWED BY ANALYSIS AND ARCHIVING.

Measurement sensors



"Sensors are placed at isolated locations, sheltered from urban and/or other human noise."

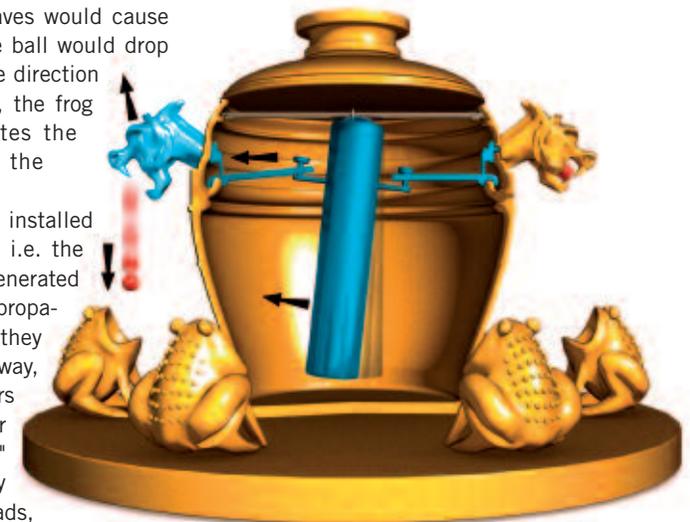
SENSOR DESIGN

Is the earth alive? In antiquity, "terrestrial palpitations" intrigued our ancestors who believed that the Earth was prey to the anger of the gods.

Sensors, known as seismometers or seismographs, have been designed and developed to improve our understanding and to detect even the smallest movements of the Earth.

The earliest known sensor dates from the year 130 B.C. This was a bronze vase with eight dragon heads fitted around the circumference at its top. Each dragon had a ball in its mouth. Eight frogs, with open mouths, were positioned on the ground. Seismic waves would cause the vase to vibrate and the ball would drop from the dragon head in the direction of the earthquake. Hence, the frog receiving the ball indicates the approximate direction of the earthquake.

Sensors are designed and installed to measure seismic waves, i.e. the movements of the ground generated by earthquakes, which can propagate over large distances. If they are very weak, or very far away, the movement of the sensors will also be weak, hardly larger than the "background noise" caused by human activity (vibrations from trains, roads, mines, etc.), or by nature (strong winds in the forest, waves on the beach or cliffs etc.).

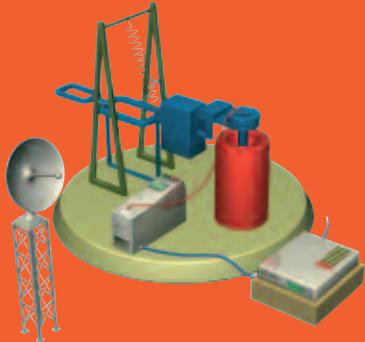


The first known seismograph was invented by the Chinese in the second century BC.



This seismic station in Mongolia operates autonomously using solar panels and a satellite relay.

OPERATION OF A SEISMIC SENSOR



A seismometer exploits the principle of inertia, having a rather heavy mass attached to an arm, suspended by a spring above a frame which is connected to the ground. The other end of the arm holds a conducting coil which can move inside a magnet resting on the frame. When the earth shakes, the mass remains fixe because of its inertia, whereas the frame follows the vibrations caused by the passage of the seismic waves. The magnet moves around the coil which detects variations in the magnetic field. These variations produce electrical impulses, which are electronically amplified and processed by a digitizer. The signals are then transmitted by satellite to the monitoring centers.

satellites are used for these transmissions. Development of this technology (mechanical, electronic, signal processing, etc.) has resulted in present-day high sensitivity detectors, i.e. sensors capable of measuring movements with amplitudes less than a nanometer (one billionth of a meter).

Modern seismometers measure the movement of the ground in three dimensions (along the vertical and two horizontal axes) and characterize the movement by its displacement, velocity or acceleration.

Sensors which are termed "short period" are intended to measure body waves, with periods which are mainly less than 2 seconds (frequencies greater than 0.5 **hertz**). Others, termed "long period", record slower movements and are aimed in particular at recording surface waves, with periods greater than 20 seconds (frequencies less than 0.05 Hz). They are also be used to study high magnitude earthquakes.

Number of oscillations per second.

SIGNAL ANALYSIS

Earthquakes, waves, wind, volcanic eruptions, quarry blasts, trains, road traffic and explosions each cause ground movements and seismic waves. The signals have different amplitudes and frequencies dependent on the energy of the event, its distance away and its nature. The geology of the intervening medium, traversed by the waves, also modifies their characteristics. When signals are received by the sensors and transmitted to the processing center located at CEA DAM-Ile de France, at Bruyères-le-Chatel (near Paris), they are automatically analyzed by data processing software which searches principally for the origin, location and magnitude of the earthquake which has generated them.

The priority is to alert the local authorities and population as rapidly as possible. If an event is sufficiently strong, the duty analyst is automatically called and applies his expertise to refining and validating these results. He then contacts the authorities. All of the analyses are stored in databases which are essential to increase our understanding of seismology and to study seismic hazards (see page 17). The first aim of the work of an analyst is to recognize the **seismograms** - useful signals -, in the continuous recordings.

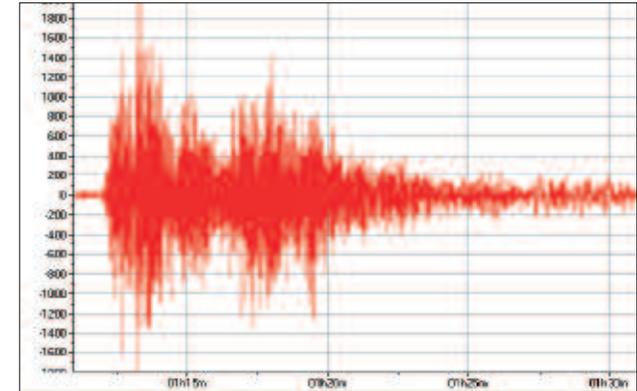
Graphical recording of measurements provided by a seismometer.

The second step is to recognize the various waves in this sequence of the recorded signal:

- P waves (primary) are compression waves.



© C. Dupont/CEA



This type of seismic sensor (left-hand photo) is particularly suitable for studying surface and body waves generated by earthquakes. This signal (right-hand photo) from an earthquake in Sumatra was recorded at the Flers station in the Department of Orne.

Propagation of these waves is parallel to the movement of the ground which is alternately stretched and compressed. These are the most rapid waves, of order 6 km/s in the ground layers near to the surface, and are the first to be detected by the seismograph.

- S waves (secondary) are shear waves. The rocks are sheared and distorted by these vibrations perpendicular to the direction of propagation of the wave. They are slower than P waves.
- L or R waves, called "surface waves", propagate across the surface of the Earth and are the most destructive.

If the selected waves are linked to an important event, an earthquake, explosion, etc, then its location, magnitude and nature need to be determined.

Location by seismic waves

In reality, simply recognizing the type of waves is not sufficient to locate the event. The path followed by the waves, between the epicenter and the seismic station, also needs to be identified.

The internal structure of the Earth is divided up into several successive layers, the main ones being the Earth's crust, the mantle and the core. At the beginning of the history of seismology, seismologists used seismic waves and a simple rule to label these layers: A rapid and abrupt change in the characteristics of a seismic wave is a strong indicator that it has changed environments, and hence changed layers.

DIFFERENT TYPES OF WAVES



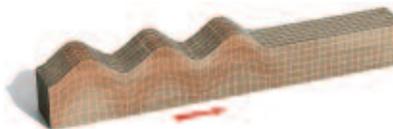
P waves : primary



S waves : secondary



L waves : Love



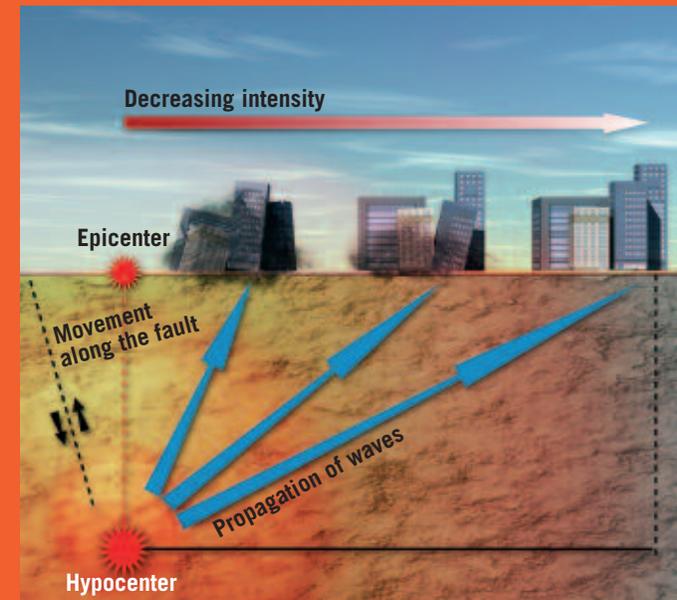
R waves : Rayleigh

This method was used to determine the state of matter at depths which cannot be reached by man, the deepest geological probe to date being 12 km. Hence, each layer could be modeled in terms of the speed and attenuation of seismic waves and so became part of a representation of the Earth, which

contributes to localization techniques. Each measurement station is assigned a GPS clock reference which enables high precision timing of the signals transmitted to analysts. The time of arrival of the waves is recorded in **universal time**.

The time used by astronomers in order to obtain precise data without time changes due to location.

PROPAGATION OF WAVES FROM THE HYPOCENTER TO THE EPICENTER



- Source or hypocenter: rupture point in the rock, origin of the earthquake, can lie between the surface and 700 km depth.
- Fault: a break caused by a sudden horizontal or vertical movement of plates. This break causes the vibrations, the seismic waves.
- Epicenter: point on the surface, vertically above the source.

Seismic waves leave the source and propagate in all directions. Their effects are attenuated with distance.

Then, knowing the position of the seismic sensors on the earth, the origin of the event can be calculated following one of several methods, such as triangulation (see box below). Artificial events, such as quarry blasting, take place on the surface of the globe (or not far away). In contrast, earthquakes can be extremely deep.

The following distinction is usually made:

- shallow earthquakes, known as surface earthquakes, are located at a depth of between 0 and 60 km;

- intermediate earthquakes occur at a depth of between 60 and 300 km;
- deep earthquakes are located at depths between 300 and 700 km.

The magnitude, energy measurement

The magnitude is a measure of the energy released during an earthquake or explosion. The Richter scale, which is the best-known and most used, reports the magnitude based on measurements of the amplitude of move-

ment of the ground, as determined from recordings obtained on a particular type of seismometer (Wood-Anderson), 100 km from the epicenter.

Created in 1935 by Charles Francis Richter and Beno Gutenberg, it is a logarithmic scale: seismic waves from an earthquake of magnitude 6 have an amplitude 10 times larger than those from an earthquake of magnitude 5, and an earthquake of magnitude 6 releases around 30 times more energy.

Contrary to common belief, the scale is open-

ended and has no upper limit. However, magnitude 9 earthquakes are exceptional; the strongest ever measured had a value of 9.5 and occurred on 22 May 1960 in Chile.

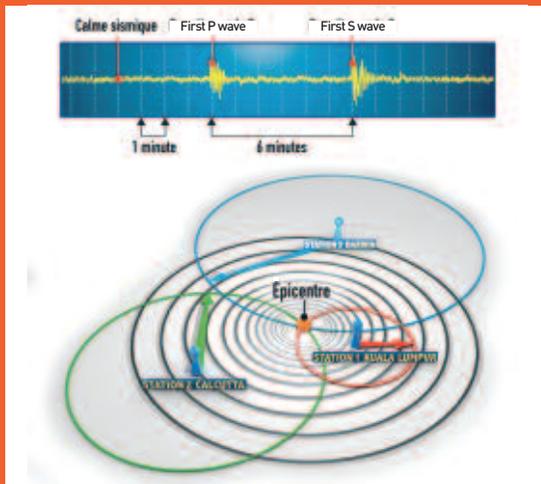
Magnitude 10 seems to be a reasonable limit, considering the solidity of rocks and the cracking of faults. The magnitude of explosions has traditionally been quoted in energy terms, expressed as tonnes of TNT (explosive).

An intensity scale is used to describe the damage caused by an earthquake, for example the de Mercalli scale or the MSK scale.

HOW TO LOCATE AN EARTHQUAKE

The triangulation method, described opposite, has long been used for shallow earthquakes.

The various seismic waves can be identified on a seismogram. The difference between the time of arrival of P and S waves, is used to deduce the distance from the sensor to the epicenter. Since several seismic stations will return a value for this distance, the position of the epicenter is located at the intersection of circles centered on the stations and with radii equivalent to the distance determined by each station. Currently, automatic calculation and data processing, which includes more accurate propagation models, can consider all classes of wave and a very large number of measurements.



THE DIFFERENT TYPES OF EARTHQUAKES AND THEIR CHARACTERISTICS

(ON THE RICHTER SCALE)			
MAGNITUDE	DESCRIPTION	EFFECTS RECORDED	FREQUENCY OF OCCURRENCE WORLDWIDE
less than 2.0	Micro	Microearthquakes, not felt.	8,000 per day
2.0 to 2.9	Very minor	Generally not felt, but detected by seismographs.	1,000 per day
3.0 to 3.9	Minor	Often felt, causing very little damage.	50,000 per year
4.0 to 4.9	Light	Shaking of indoor items, rattling noises, some damage.	6,000 per year
5.0 to 5.9	Moderate	Slight to major damage according to the buildings.	800 per year
6.0 to 6.9	Strong	Destructive in areas up to around 180 km from the epicenter.	120 per year
7.0 to 7.9	Major	Severe damage over larger areas.	18 per year
8.0 to 8.9	Great	Serious damage in areas up to several hundred kilometers from the epicentre.	1 per year
9.0 and greater	Epic	Devastating in areas several hundred kilometers from the epicenter.	1 to 5 per century

Intensity, from I to XII

The intensity describes the effects due to an earthquake on a scale which runs from I to XII. It depends on the distance from the epicenter. For intensity equal to I, the earthquake is not felt. At intensity VI, chimneys fall from houses. Beyond IX, the damage is very significant; this was the case for the Kobe earthquake in Japan, in January 1995. At XI, ruination is almost total, at XII all constructions are destroyed and the landscape is completely disrupted.

Earthquake, explosion or eruption?

Observation of seismic waves, location of the event and its magnitude, allow analysts to



Damage caused by an earthquake.



A seismic station set up in the Alps.

determine its nature. The following principles have been determined:

- An earthquake is the sudden release, by movement along a fault, of energy accumulated by the slow movement of tectonic plates. The seismic waves emitted are influenced by the orientation of these faults. Hence, at equal distances from the fault, different amplitudes will be observed as a function of the orientation of the station with respect to the fault. Note also that very high magnitude waves are always of seismic origin.
- An explosion produces energy over a very short time period, radiating in all directions. Moreover, the waves emitted in this case are mostly compressional waves.
- The majority of volcanic eruptions generate very weak seismic energy, although an eruption of the phreatomagmatic type, such as Mount St Helens (Washington State) in 1980, may register on remote devices several hundreds of kilometers away. However, monitoring volcanoes is generally carried out by a collection of sensors performing a variety of measurements (chemical composition of the gases,

pressure, etc.) which sometimes allows the precursor signs to be identified and hence enable evacuation of the population concerned. Depending on the case, particularly for extremely weak signals, in-depth analysis is required to arrive at a definitive determination.

DATA STORAGE

All analyses and signals are archived. The Earth Physics Institute in Strasbourg has collected instrumental intensity data from France, North Africa and several foreign countries, since the start of the 20th century. The Division of Analysis, Surveillance and Environment (DASE) of the CEA, has a database going back to the 1960s. It is growing by 200,000 measurements per year, corres-



THE TEN LARGEST EARTHQUAKES EVER RECORDED

Location	Date	Magnitude
Chile	22/05/1960	9.5
Sumatra	26/12/2004	9.2
Alaska	28/03/1964	9.2
Alaska	03/09/1957	9.1
Kamchatka	04/11/1952	9.0
Japan	11/03/2011	8.9
Equator	31/01/1906	8.8
Alaska	04/02/1965	8.7
Sumatra	28/03/2005	8.6
Assam-Tibet	15/08/1950	8.6

ponding to around 7,000 events of which 3,500 are located in France or in neighboring Europe, recorded by the network of 40 sensors distributed over French territory. By also studying data such as historical writings and testimonies, scientists can identify much older earthquakes. The information is not as precise as that recorded by a sensor. However, it enables evaluation of seismic risk in areas where earthquakes only occur once every hundred years or more. The most severe French seismic activity is found on Guadeloupe and Martinique. It is not as significant in metropolitan France as in other regions of the globe, such as Japan, California, Greece, Turkey, etc. This is a region of low seismicity. However, risks are still present: The earthquake at Lambesc (Provence) in 1909 destroyed several villages and killed 40 people. Other significant earthquakes have occurred at: Arette (Pyrénées-Atlantiques) in 1967,

FROM CONTINENTAL

Alfred Wegener, a German astronomer and meteorologist, was the founder of the theory of "continental drift" put forward in 1915. This theory was completed in the 1960s with the addition of the theory of "tectonic plates" which explained the origin of the movement of continents.

The idea arose from analyzing different types of data - topographic (the matching shapes of the coast of Africa and South America), geological (the same type of rocks, dating from 650 to 450 million years ago, are found in Africa and South America) and paleontological (the same fossils being found). This led to the idea that a single continent, Pangaea, had broken up leading to the existence of several new continents. For a long time this theory was regarded as controversial because it could not explain the origin of continental movement, i.e. the "engine" for these displacements. It was therefore rejected.

Many complementary observations were carried out thereafter; these studies enabled a more complete theory to be drawn up in the 1960s. Known as the tectonic plate theory, it explained all of the observed phenomena.

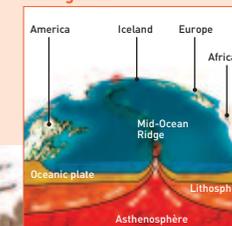
The lithosphere, the upper part of the mantle and the crust, is divided into plates with an average thickness of around 100 km. These are moving extremely slowly, several centimeters per year on average, on the more ductile Asthenosphere (which is malleable and can be stretched without breaking).

These movements are responsible for the creation of mountain chains (such as the Alps and Himalayas), submarine mountain chains (ocean ridges) and volcanoes. The forces induced by these movements produce considerable energy, which accumulates and is then abruptly released at seismic faults in the form of earthquakes. These movements cause ruptures in the Earth's surface. A fault is an identity card for an earthquake. Their shape, length and the disorder that they cause in the landscape, make it possible to distinguish three types of interaction between plates.

DRIFT TO TECTONIC PLATES

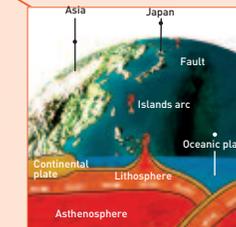
1 – Divergence: when two plates move away from each other, allowing the mantle to rise up between them. These are formation sites for the oceanic lithosphere and sites of intense, mainly sub-marine, volcanism.

Divergence



2 – Convergence: when two plates are moving towards each other, causing two different effects:

* a subduction zone; here the denser of the two plates (oceanic plate) "dives" under the other, less dense, plate (oceanic or continental), leading to terrestrial volcanism. For example, the creation of the ring of volcanic islands from Japan to the Kuril and Aleutian islands is caused by subduction of the Pacific plate under the Eurasian plate.



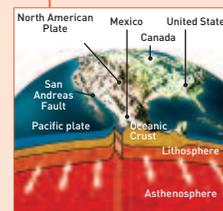
Subduction

* a continental collision zone, the site where two plates meet, overlapping and rising up, which lead to the formation of mountains: the Himalayas were formed as India moved towards the North and in the case of Italy it was the Alps.

* special case: an obduction zone, or "overthrusting" of a continental plate by an oceanic plate, such as the ophiolites in Oman.

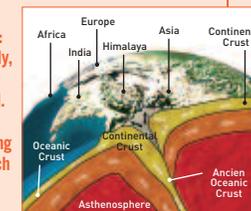


The upper part of the mantle and the Earth's crust is made up of rigid plates with an average thickness of around 100 km, which move several centimeters per year.



Transform fault

3 – A transform fault (or conservative plate boundary): when two plates slide horizontally, one beside and along the other, large transform faults are formed. An example of this is the Pacific Ocean plate which is sliding along the North American plate, on each side of the famous San Andreas fault, causing Californian earthquakes.



Collision



An analyst's workstation: between visualization of seismograms and computer processing of data.

It is impossible to forecast when an earthquake will occur. However, knowledge gained can be used to evaluate seismic risk.

Planning ahead

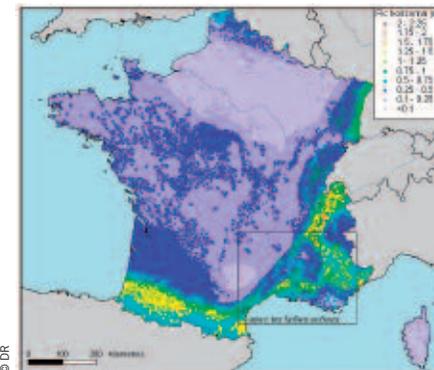


© C. Dupont/CEA

HAZARDS AND RISKS

Analysis of seismic hazard makes it possible to answer questions of the type: what is the acceleration of the ground expected at Lourdes in the event of an earthquake of magnitude 6 along such a fault? Or: What are the risks of exceeding the acceleration experienced in the ground at Nice in the next 50 years? The analysis is based on knowledge acquired from the history of seismicity, such as the occurrence of earthquakes and the large earth movements resulting from these. When the scenario is unpublished, numerical simulation is used. This analysis enables, by extension, production of a map of seismic hazard.

It is useful to distinguish between hazard and risk. Seismic risk is the impact of seismic hazard on human activity in general. Seismic hazard arises in regions having significant



© DR

A map of seismic hazards in France



© D.R. - Photofisc

Landscapes devastated by an earthquake

seismic activity. However, this seismic hazard does not strongly correlate to an increased risk if the region concerned is deserted or does not contain any buildings. By contrast, even a zone having only moderate seismicity can be considered as high risk because of the density of population, the importance of the buildings or the presence of sensitive infrastructure (chemical factories, nuclear plant, fuel depots, etc.). There is a risk when the hazard threatens vulnerable targets (population, infrastructure).

Determining the level of seismic risk requires calculation of the probability and degree of damage over a reference period in the region considered.

NO, IT IS NOT POSSIBLE TO PREDICT AN EARTHQUAKE

Since antiquity, a way of predict earthquakes has been sought... without success.

Seismologists try to identify the precursor signs. However, none of these seem to have universal value. Scientists cannot tell the date, place or magnitude of the next earthquake. They can only evaluate the seismic risk in the neighborhood of well identified faults in terms of probabilities and measurements of the degree of plausibility, taking into account the available information: past seismic activity, the recurrence interval (the time interval between two successive events in the same place), etc.

IMPORTANT CASES TO MONITOR: TSUNAMI

A tsunami is a series of waves originally caused by a sudden movement of the ocean floor, generally following an earthquake, volcanic eruption or submarine or terrestrial landslide (as in the 1958 Lituya Bay earthquake in Alaska) or, more rarely, after impact of an asteroid or comet.

Tsunami generated by earthquakes are imperceptible offshore: their amplitude rarely exceeds 10 to 50 cm away from the coast, and the waves do not survive for more than 20 to 40 minutes. Tsunami generated by landslides can be very much more devastating. However, their impact is only felt close to the source.

Tsunami only show significant effects when the wave train approaches the coast. Indeed, as the waters become shallower, the velocity of propagation decreases and, through conservation of energy, the waves increase greatly in ampli-



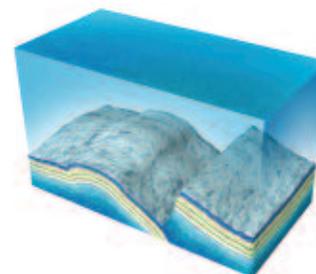
Coastal landscape following the passage of a tsunami.

“Many destructive waves can follow one after the other, over the course of several hours, with the most damaging not necessarily being those that arrive first.”

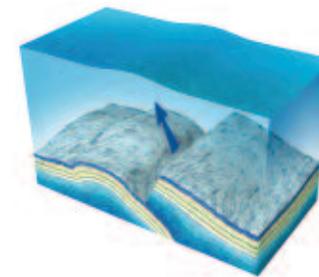
tude. Hence, waves which were formerly 10 to 50 cm high can grow to heights of between 3 and 5, or even 10 meters. Enormous damage can then be produced, particularly by the strong currents generated during the flow in and out and through their ability to drag people offshore. Victims can be struck by various objects carried by the wave or be violently projected. Material damage is often considerable: housing, infrastructure, fauna and flora (ecosystem) are destroyed. It should be remembered that many destructive waves can follow one after the other, over the course of several hours, with the most damaging not necessarily being those that arrive first. During the great tsunami of December 26, 2004 which took place off the coast of the Indonesian island of Sumatra, the waves attained a high of 30 meters on the coast and moved inland with a height of 5 to 10 meters for several kilometers.

Over the past few centuries, 75% of tsunami have been produced in the Pacific ocean, mostly due to the very strong seismic activity around the edge of this ocean.

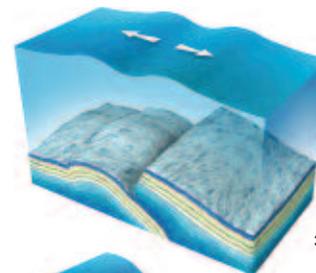
FORMATION OF A TSUNAMI



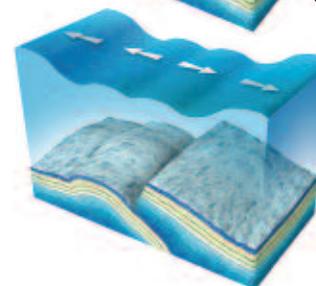
1 – The formation of tsunami is mostly linked to undersea earthquakes.



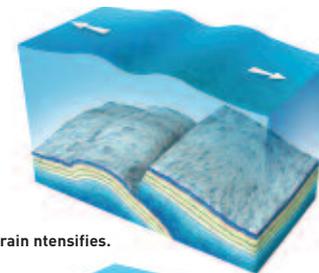
2 – Propagation of seismic waves, under the sea, triggers a wave train; this represents a tsunami.



3-4 – The wave train intensifies.



5 – Beyond the epicenter of the earthquake, in deep water, the tsunami generally attains a height of several tens of centimeters. However, the height of these waves will rapidly increase in shallower water.



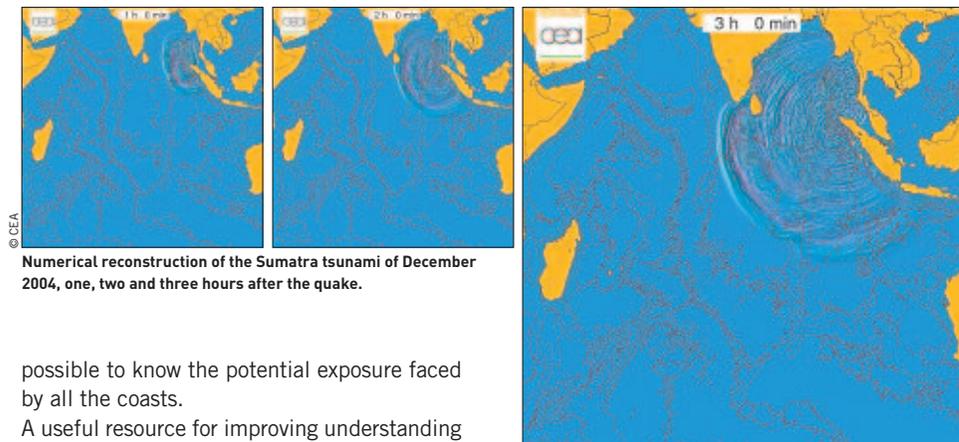
6 – When the seafloor rises, as the coast is approached, the waves slow down and amplify. The level of the sea increases from 1 to 20 meters, and the water flows inland.

The Sumatra tsunami reminded us that more than one ocean can be affected by a tsunami, even though this is very rare. This earthquake, which had a magnitude of 9.2, generated a tsunami which affected Indonesia, Sri Lanka, southern India and southern Thailand. It was

observed around the entire circumference of the Indian Ocean, on the East African coast of Somalia, on Réunion and on the northeast coast of Australia. In total 280,000 people disappeared.

The lack of historical data means it is not always

"Risk management is undertaken by considering many geological parameters."



© CEA
Numerical reconstruction of the Sumatra tsunami of December 2004, one, two and three hours after the quake.

possible to know the potential exposure faced by all the coasts.

A useful resource for improving understanding of tsunami hazard is numerical simulation, which allows us to study potential tsunami-generating earthquake scenarios and to study the expected impacts in detail. Hence, the work in progress on the 2004 tsunami shows that by having a good understanding of the local topography, and by using a source describing this exceptional earthquake, the level of flooding observed can be reproduced in a satisfactory manner. The challenge for tsunami prevention, is to be able to carry out this type of study for all exposed sites; and to do this before any more space great earthquakes occur.

RISK MANAGEMENT: WITH MULTIPLE PARAMETERS

Risk management is undertaken by consideration of a very large number of geological parameters (seismicity, earth movements,

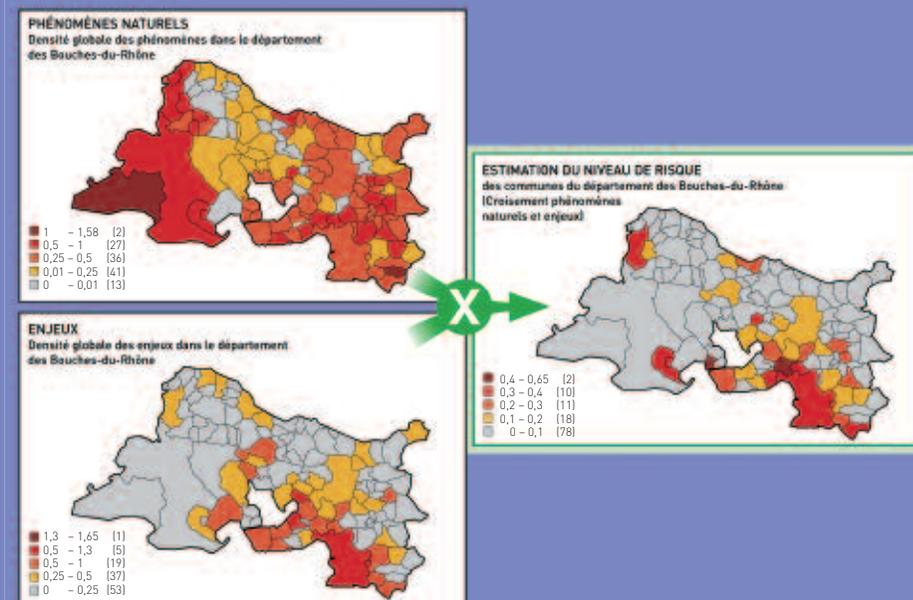
phenomena related to the swelling and shrinking of clays sensitive to drying, collapses related to underground quarries and abandoned mines and volcanic activity), climate, geography, demography and economics. It rests on understanding each of the phenomena and modeling them, and on evaluation of the corresponding dangers through monitoring, studying the vulnerability of exposed sites and risk evaluation. For example, the ISARD project is concerned with automatic regional seismic damage analysis, for seismic prevention in the Pyrenees.

Geological knowledge benefits from research and development programs on cartography (airborne magnetic surveys and spectrometry, work on physical and chemical characterization).

Aerial and satellite views are also analyzed to detect deformations of the landscape, such as convex ground, sudden ruptures of rock layers, Consideration of all these parameters highlights the necessity of building at good locations. For example, during an earthquake, ground that is

loaded with water will break up under the effect of vibrations. If this ground is supporting foundations, the buildings will sink into these "moving sands". Such "liquefiable" ground, on the edge of water, should be avoided and it makes sense to be wary of all soft ground. On clay, move-

THE BOUCHES-DU-RHÔNE CASE (SOURCE BRGM)



The combination of many parameters can be used to compile cartographic documents to guide decisions on installations according to which zones are at risk.

“Constructions, in particular, public buildings and at-risk facilities, are subject to strict regulation in seismic zones.”

ments can be up to 10 times as large as on solid rock, coupling the effects of distant Earth movements with factors on the site. This was the case in the 1985 Mexico earthquake, a city built on a dry lake, and in the case of the San Francisco Marina which was built on sediments on the edge of the Bay.

In this field, it is of prime importance to have an abundance of numerical data and sophisticated models. They enable detailed maps to be drawn up of seismic risks and hazards, of ground movements, subterranean cavities, and the setting up of databanks, such as SisFrance for earthquakes. This cartography is used to help manage natural resources, the environment and planning for the territory (putting in place prevention measures which restrict land usage in accordance with a Risk Prevention Plan).

Damage maps are often traced onto ground maps. Preventing natural risks, which are often amplified, or even created, by increasing industrialization or urbanization, is a major component of planning decisions in such areas.

THE TAMARIS LABORATORY

Seismic zones in France are subject to construction legislation, in particular for public buildings and at-risk facilities such as nuclear power plants (see the special legislation of July 22, 1987 and the Order of May 14, 1991).

Studies entrusted to the CEA's Tamaris laboratory have improved understanding and prediction of seismic behavior of structures. The objective is to verify that installations conform

to these rules and hence to reduce the consequences of earthquakes for the population. The laboratory possesses significant experimental and numerical simulation resources for this task. The experimental platform has four shaking tables, a pit and a reaction wall. Azalée is the largest of the shaking tables: six meters long and wide, two meters thick. It is able to simulate very powerful earthquakes and to carry structures up to 100 tonnes. This table has been used by a number of industrialists to judge the resistance of their buildings and structures. The pit is used to test very tall structures, such as control rods from a nuclear reactor. However, before starting the tests simulations



The Azalée shaking table was able to test this 1/3 scale, civil-engineering model with a mass of 35 tonnes.

© S. Poupin/CEA

are run. CAST3M is used to perform pre-sizing calculations and for interpreting tests and numerical simulations. Numerical models are constructed which define the shape of the building, its dimensions and its structure. Once this model has been optimized, a physical model is created and fitted with sensors. Then the researchers apply increasing levels of earthquakes. Between each test, experimental measurements are compared to the predictions of the numerical models. This approach helps us to understand the behavior of the structure, its local degradation and, for the last test at the strongest level, the ruination of the building. These studies also address questions such as: at what



These researchers are verifying the state of a structure, weighing approximately 20 tonnes, after testing.

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PARASEISMIC REGULATIONS

The majority of regulations currently in force around the world, whether for "normal" risk or for facilities of an industrial or nuclear character, are based on a probabilistic approach to the evaluation of seismic hazard. In France, the DASE has worked on this methodology for a number of years and today possesses a working tool for evaluating seismic hazard on a given site. Since the 1950s, French standards have been in place for the earthquake resistance of buildings. These have been progressively replaced by European standards, Euro code 8, which integrate the regulations specific to each country. These standards take account of international experience, particularly that of European countries such as Portugal, Italy and Greece, which are subject to strong seismicity.

Tests on the shaking tables at the Tamaris laboratory have contributed to the formulation of these regulations.

level of stress does the structure first show damage? What level of stress can it resist? Where and how does damage occur? Specialists from the paraseismic field consider all of the knowledge acquired from previous earthquakes. They develop computational methods based on observations, feedback and genuine consequences of earthquakes. The tests and calculations performed are used to strengthen existing facilities and to improve European seismic standards for future constructions, in collaboration with other CDA organizations or, for example, the BRGM (Bureau de recherches géologiques et minières - Office of geological and mining research).

SEISMIC EVENTS ARE DETECTED AUTOMATICALLY OVER THE ENTIRE SURFACE OF THE PLANET; A SYSTEM WHICH ENABLES VERY FAST REACTION.

Monitoring



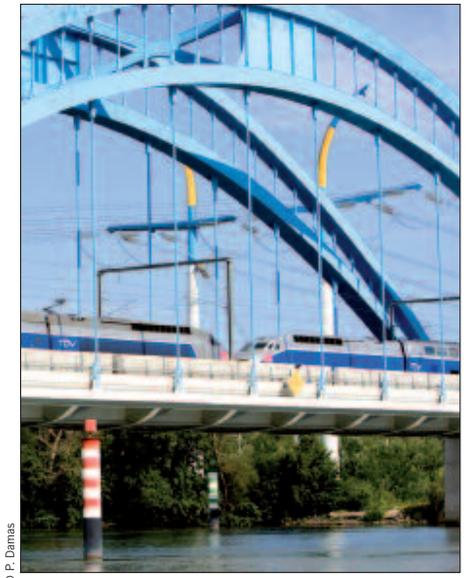
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CONTINUOUS MONITORING

At the CEA, analysts and seismologists from DASE continuously monitor seismic activity around the globe. For France and the surrounding regions, they are ready to alert the civil security services as soon as a magnitude 4 or higher earthquake is detected, which occurs around 30 times per year. This responsibility for warning requires the organization of a duty roster: around the clock scientists take turns to evaluate the seismic events automatically detected by the software. They determine the magnitude and location and, if necessary, take the initiative to alert the responsible authorities (civil security and responsible ministries) within one hour of the event.

When a seismic signal appears it is detected, filtered and measured. The signal processing algorithms developed by CEA are growing every day with the analysis of various significant signals (detection, location, magnitude), continually increasing the speed of reaction. The results of these analyses are posted in a weekly seismic bulletin which can be consulted on the Internet.

This expertise finds many other applications, such as monitoring the Méditerranée TGV since June 2001, to signal in real-time if too great a movement is detected and to slow down or stop the trains in the event of a risk arising. Over the 240 km of seismic risk zone that are crossed, the real-time detection stations, which consist of an accelerometer and data acquisition unit, have been installed next to the line at 10 km



© P. Demas

The Méditerranée TGV is monitored over 240 km of its path which is considered to be in a seismic risk area.

intervals. The data are transmitted via fiberoptic cable to the PC at Marseille Saint-Charles where they are recorded and analyzed. Exceeding a first threshold magnitude, automatically invokes an order to slow down the train from 300 to 170 km/h. Exceeding a second, higher, threshold, results in the trains being stopped. In both cases, the system interrogates seismologists from CEA who confirm or cancel the alert. The SNCF must then decide to return the traffic to normal, to restart at reduced speed and/or to inspect the tracks.

THE CTBT TREATY AND DETECTION OF NUCLEAR TESTS

In 1996 during the Conference on Disarmament, the UN proposed to the countries of the world that they enter into a comprehensive nuclear test ban treaty (CTBT). This was an essential element in the international fight against nuclear weapons proliferation and banned all nuclear tests whatever their power and whether in the atmosphere, underground or undersea.

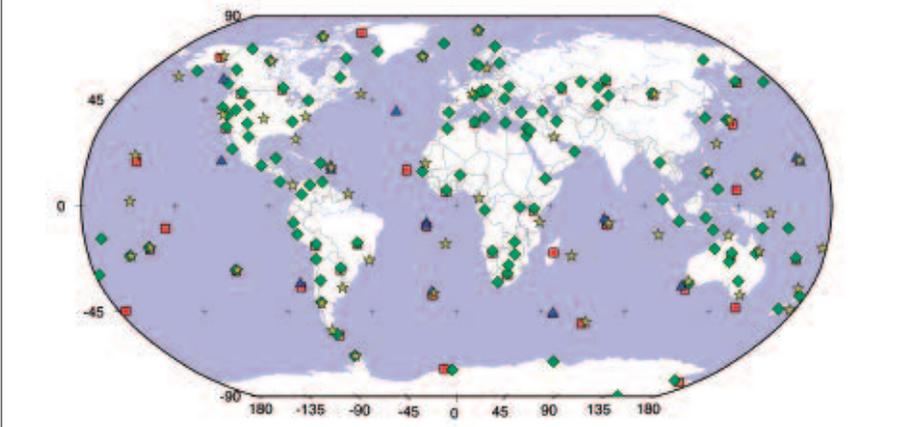
France signed this treaty on September 24, 1996 and ratified it on April 6, 1998.

As of March 1, 2008, the treaty has been signed by 178 States, of which 144 have ratified it. For it to enter into force, the governments of the 44 countries likely to detonate nuclear weapons must have signed it and then had it ratified by their respective parliaments.

To verify that this treaty is being observed, an International Monitoring System (IMS), made up of 321 detection stations and 16 radionuclide analysis laboratories, is currently being put in place. All data collected by the stations, whether they be seismic, radio nuclide, infrasound or hydroacoustic, are transmitted to the international data center located in Vienna.

As experts in the field of environmental monitoring, the Military Applications Division of the CEA has participated in the definition and development of the International Monitoring System. In France, the CEA are responsible for the installation and operation of resources dedicated to monitoring observance of the CTBT. Hence DASE (Department of Analysis, Surveillance and Environment)

IMS STATIONS (INTERNATIONAL MONITORING SYSTEM)



Map of the locations (at December 31, 2007) of the IMS stations (International Monitoring System) for the CTBT (Comprehensive Nuclear Test Ban Treaty Organisation).

◆ seismic stations ■ infrasound stations ▲ hydroacoustic stations ★ radioactive nuclide stations



© C. Dupont/CEA

Preparation of samples to identify possible nuclear tests. These analyses are part of the monitoring framework of the Non-Proliferation Treaty, NPT.

has a mission to operate the 16 monitoring stations which have been installed on French territory (Martinique, French Polynesia, Reunion, Guadeloupe...). It has also installed eight other stations around the world (Ivory Coast, Bolivia, Mongolia...) at the request of signatory countries which do not have the required technology.

Data coming from the stations are transmitted, under French authority, to the International Data Center and, in parallel, to the National data center on the CEA site at Bruyères-le-Châtel. The main mission for this center is to exploit the data and the signals provided from the entire network of accessible geophysical measurements and to ensure around-the-clock monitoring, 365 days a year, to be able to alert the authorities in the case of a potential nuclear test or earthquake.

The signal registered on October 9, 2006 originating in North Korea was characteristic of an explosion. But its magnitude was relatively weak, between 3.6 and 3.8, and hence an energy less than 1 kilotonne, which did not allow the physicists responsible for studying such signals to clearly determine whether this explosion had a nuclear or chemical origin.

Tsunami Alert Networks

One such warning system is designed to detect a tsunami when the wave is still far from shore and to provide early warning to the threatened population, in order to save lives. It is made up of seismic sensors and **marigraphs** coupled to a system for receiving, analysis, decision taking and transmission of warning messages. Response by this system must be very rapid, because of the speed of the waves (between 500 and 1,000 km/h offshore).

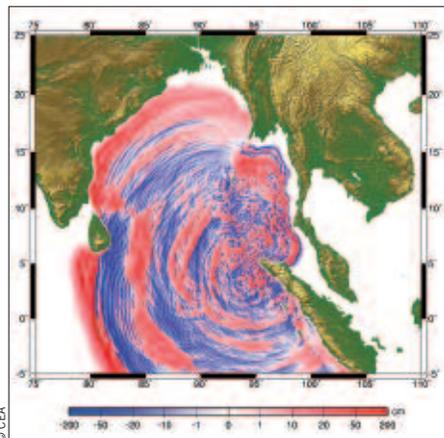
Instruments which measure sea level at a given location.

In 1946, following the destruction of Hilo Bay in Hawaii, the United States decided to create the first tsunami warning center in the Pacific, which continues forecasting on the Ring of Fire.

In 1965, this center became associated with an international measurement and warning network which is coordinated by UNESCO (The United Nations Educational, Scientific and Cultural Organisation). The CEA operates a warning center for France in Polynesia. Scientists from HQ based at Ewa Beach in Hawaii:

- collect signals;
- locate, analyze and compare with previous data;
- confirm or reject the tsunami;
- determine the bays which will be impacted in the United States;
- warn the country or countries concerned, who will decide if an evacuation of their coasts is necessary.

“Risk Prevention and Emergency Response Plans need to be added to these monitoring networks and warning centers.”



© CEA
Modeling the propagation of the 2004 tsunami in the Indian Ocean.

It takes between 10 and 20 hours for a tsunami to propagate from one Pacific Coast to the other which, apart from in the area close to the epicenter, leaves time to react.

The Sumatra earthquake unfortunately demonstrated the urgency for putting in place such a detection and warning network in the Indian Ocean. Since the end of 2005, all of the countries concerned have now nominated organizations responsible for receiving warning

messages and for preparing civil protection. In parallel, they need to initiate actions to raise awareness of the risks among coastal populations and of the actions required for survival and to make housing safe. The time factor is crucial: propagation to the nearest coast, outside of the epicenter area, took just two hours here.

Tsunami warning systems are also planned for the Mediterranean and for the North East Atlantic. All of the major exposed regions will then be monitored. Around the perimeter of the Mediterranean, one of the most dangerous faults is close to the Algerian coast. Researchers have calculated that the propagation time from the Algerian coast to the French coast would be little more than one hour. In addition to real time warning, it is also crucial to carry out a study of the at-risk zones. All of these monitoring networks and warning centers are useless if the authorities and population do not know how to react in the event of an alert. Therefore, it is necessary to have a Risk Prevention Plan (RPP) and an Emergency Response Plan and to organize regular alert and sheltering exercises, as is currently occurs in French Polynesia, Japan, the United States and Chile.

SEISMOTECTONICS, WHICH COMBINES TECTONICS, GEODESY AND SEISMOLOGY, IS ABLE TO PROVIDE AN OVERALL EXPLANATION OF EARTHQUAKE PHENOMENA.

Understanding



SEISMOTECTONICS: THREE DISCIPLINES IN ONE

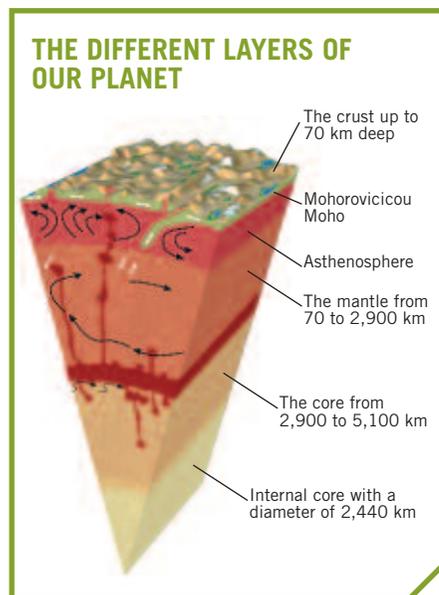
To obtain an overall understanding of how earthquakes are produced, seismotectonics combines three different but complementary scientific fields, namely: tectonics (mapping of active faults), geodesy (a science which measures and describes the Earth's surface) and seismology (recording and analyzing vibrations of the ground).

Geodesy includes global geodesy, which is concerned with determination of the shape and dimensions of the Earth, and regional geodesy, for which one of the main goals is to establish topographic maps on the national and regional scales.

Seismology improves our understanding of how our planet functions and several essential discoveries have been made through seismic tomography.

These combined studies have defined the different layers which make up the core of our planet:

- the crust, thin and rocky, has a thickness of 30 to 70 km (under the continents) and 5 km (under the oceans). The Mohorovicic, or Moho, discontinuity separates it from the mantle;
- the mantle is very thick (2,900 km) and consists of solid rock with a plastic behavior zone situated between 150 and 650 km deep and known as the asthenosphere;
- from the mantle to a depth 5,100 km, the core, formed of iron and nickel;



- the inner core, 2,440 km in diameter, is subject to such high pressures that it can melt.

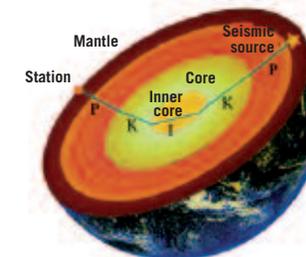
Analysis of seismograph recordings has updated models of the Earth over the course of the 20th century. The waves studied in seismic tomography are body waves, which cross the globe of the Earth in all directions (surface waves only propagate in the crust and provide no information on deeper layers). To identify their course, all of these waves are designated by different letters, progressively recording their path.

Hence, a PKP wave will be a P wave which returns to the surface having crossed the outer liquid core (path: mantle/outer core/mantle).

PROPAGATION OF WAVES

	P WAVE (PRIMARY)	S WAVE (SECONDARY)
Mantle	P	S
Core	K	
Inner core	I	J

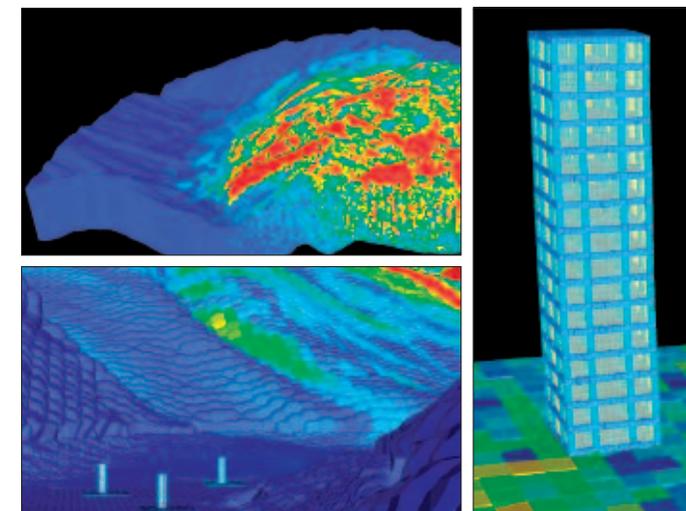
The different layers of th Earth



SIMULATION: OF A FAULT IN THE STRUCTURE

Numerical simulation can be used to verify and thoroughly check our understanding of seismic phenomena. It is based on a description of the rupture of a fault and on good knowledge of the medium of propagation. For the first time ever, a complete calculation including the effects of fault rupture, wave propagation and even building resonances was performed at the end of 2007 on the CEA's Tera-10 super-computer. The area which was simulated had sides of 10 km length and contained a sedimentary valley and a precise description of the topography of the terrain was available. Moreover, it was an area where the

mechanical properties were special and could be set in motion if stressed by the passage of seismic waves. The simulation took account of all these phenomena.



Numerical simulation carried out on Tera-10 and displayed on a video wall. Above: start of the wave propagation (the color moves increasingly towards the red corresponding to stronger and stronger waves), from a fault situated at the bottom right of the image. Local variations in attitude are mostly due to variations in topography. Below: The same point in time, viewed from the floor of the valley, where the buildings are located. On the right: A snapshot of a building at the moment when the seismic waves pass; note the deformation of the tower.