CEA/DAM

As a region host to the collision between the Indian and Eurasian tectonic plates, the Himalayas are an area subject to deformation, its motions being measured by way of GPS, and a DORIS station.

III. THE MOVING EARTH

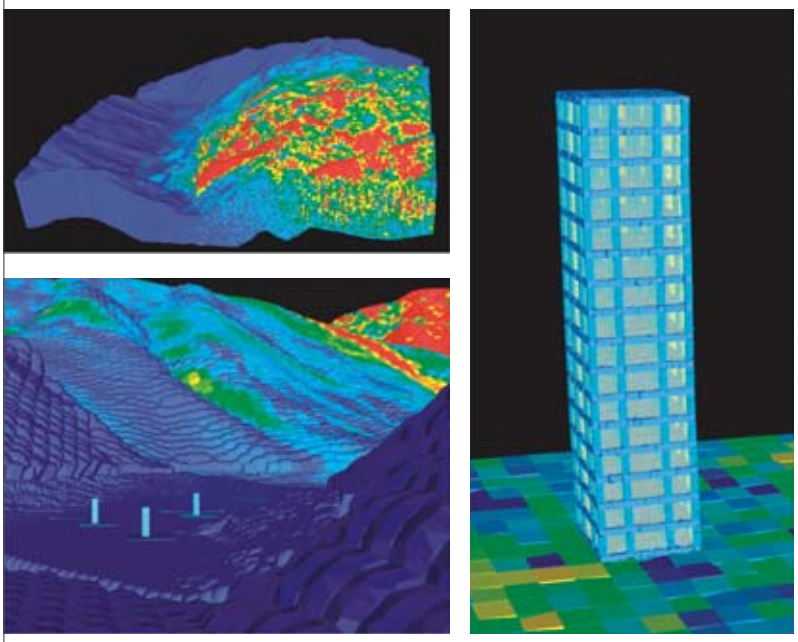
Whether at the scale of geological eras, or over shorter timescales, or even by abrupt surges, the Earth is moving, and changing. The manifestations of this unceasing travail of our planet may prove violent, and destructive to a greater or lesser extent, as e.g. earthquakes, tsunamis and volcanic eruptions. They may also be almost imperceptible, as the evolution of receding coastlines, or estuaries silting up. All the more so as regards the motions of tectonic plates, which are in turn the deep, underlying causes of the violent phenomena mentioned above.

Researchers at CEA have long since been addressing such phenomena, for a number of distinct purposes. Those in charge of nuclear tests needed to gain better knowledge of the environments in which these were carried out, if they were to control their effects, and arrive at estimates of their results. This remit led them to avail themselves of the resources to detect tests by other nuclear powers, whether avowed or otherwise – resources that took on their full significance under the aegis of international nuclear proliferation controls. Underground nuclear tests generate seismic waves, similar to those due to earthquakes, and it was a natural step for that monitoring activity to extend to seismology as a whole. Thus, the aim is to detect, and identify, in real time, any seismic event, regardless of its origin, to evaluate whether that event may have caused a tsunami, and, should this be the case, to have the ability to warn exposed coastal areas, while advancing ever further our knowledge of the Earth's motions. In these various areas, the scientist involved have been at the same time deploying conventional instruments, and developing novel techniques, even as they were putting to use techniques initially developed for other purposes, e.g. satellite positioning. Thus, permanent GPS stations are measuring, with millimeter precision, the motions, and deformations of tectonic plates.

For other research workers in the organization, the focus is on implementing the many practical applications of nucleonic methods, for the purposes of investigating sediment dynamics in fluvial, and coastal environments. These methods involve three types of radionuclides. Some are introduced artificially, remaining active however over very short timespans, to preclude effects on the environment. Other radionuclides, standing as traces of past events, e.g. atmospheric nuclear tests, are ultimately pressed into service, to make a positive contribution to Earth, and environmental sciences. Others, finally, of altogether natural origin, as e.g. radon produced in the Earth's crust, play an irreplaceable part in atmospheric tracing techniques. For the purposes, in particular, of gaining a better understanding of greenhouse gas transport, with regard, more particularly, to carbon dioxide – which brings us right back to the concerns of the first chapter in this issue.

From seismological **observation** to seismic **risk assessment**

While it would be a vain hope to expect a reliable method may soon be available, to predict the imminent occurrence of an earthquake, assessment of the risk of an earthquake occurring is making very real advances, to which CEA's seismic hazard center has been contributing.



Simulations CEA

Grand Challenge numerical simulation, carried out on CEA's Tera–10 supercomputer. Top, onset of wave propagation, from the fault located at lower right in the picture. Red color corresponds to the strongest waves. Local variations in amplitude are due, in particular, to variations in topography. Bottom, the same point in time, viewed from the bottom of the valley, where the buildings are located. At right, snapshot of a tall building, as seismic waves pass through: the tower block deforms.

Plate tectonics stands as the theory which, at the present time, best accounts for the various observations regarding the mechanical phenomena affecting the superficial layers of our planet. This emerged as a fully-fledged theory in the 1960s, as the outcome of a synthesis of observations, and measurements systematically carried out by numerous observatories. The two main areas covered by these observations relate, on the one hand, to the exploration of ocean floors – allowing an ordered pattern of rocks to be uncovered, thus evidencing **seafloor spreading** – and, on the other hand, the systematic, and increasingly detailed analysis of **seismic waves** – leading to the unraveling of the plate structure of the Earth's surface, and to determining the relative motions of these plates (see Focus A, ***Journey to the center of the Earth, and the outer reaches of the atmosphere***, p. 21; and Focus D, ***Plate tectonics and earthquakes***, p. 90).

Finescale detection, and analysis of seismic events

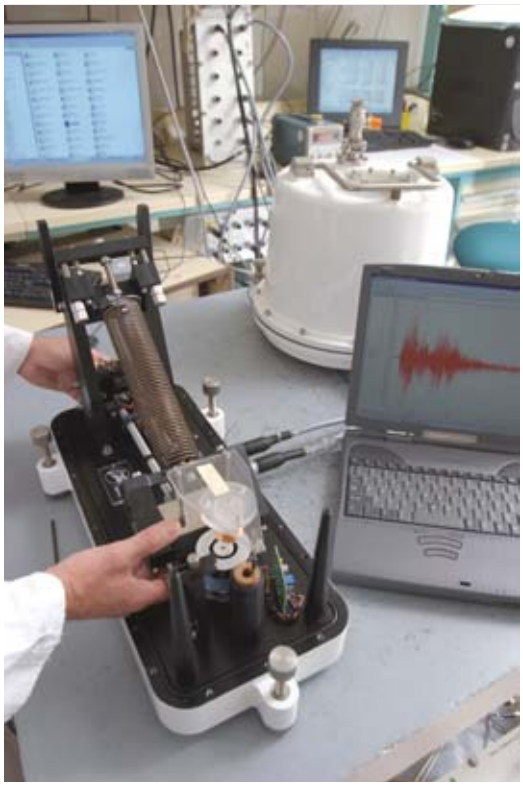
From the late 1950s, CEA has been involved in these issues, particularly by way of its remit, of detecting nuclear tests. Indeed, an explosion of this kind, if set off underground, also produces seismic waves. Owing to the diversity of the media traversed by these waves, it is, in many cases, at the outcome of a complex analysis that a diagnosis may be made, as to the origin – natural (**earthquake**), or artificial (explosion) – of such waves. This is the reason why, from the time the first **seismic stations** were set up in mainland France, the Detection and Geophysics Laboratory (LDG: Laboratoire de détection et de géophysique), coming under CEA's Environmental Assessment and Monitoring Department (DASE: Département analyse, surveillance, environnement),[1] decided to look into all of the **events** it detected across that network, and thus to publish a bulletin of seismic activity (see Figure 1). That work has gone on unabated since that time, and the stations at Lormes (Nièvre *département*, central–southeastern France), or Flers (Orne *département*, western France) stand among those turning in the best performance, in statistical terms, on the basis of the number of measurements referenced in the worldwide *Regional Catalogue of Earthquakes*, published by the **International Seismological Center**. The database built up at LDG, holding more than 140,000 events, and growing at a rate of some 7,000 new events per year, has made it possible to ascertain precisely seismicity levels for mainland France, a crucial component when determining seismic risk.

The work involved in analyzing seismic records chiefly involves measurement of two characteristic parameters of seismic waves: time of arrival, and amplitude. These pieces of information, as obtained at a number of stations, when combined, and complemented by a **model** of wave propagation inside the **Earth**, then make it possible to locate the event that gave rise to them, and give an estimate of its **magnitude** (see Focus D, ***Plate tectonics and earthquakes***, p. 90).

This monitoring activity has led LDG to be put in charge of issuing strong earthquake alerts, for the French Civil Defense organization (Protection civile). For the purposes of that alert remit, the duty seismologist must provide initial characteristics (location, magnitude) for any seismic event liable to have been felt in mainland France, within one hour of the event.

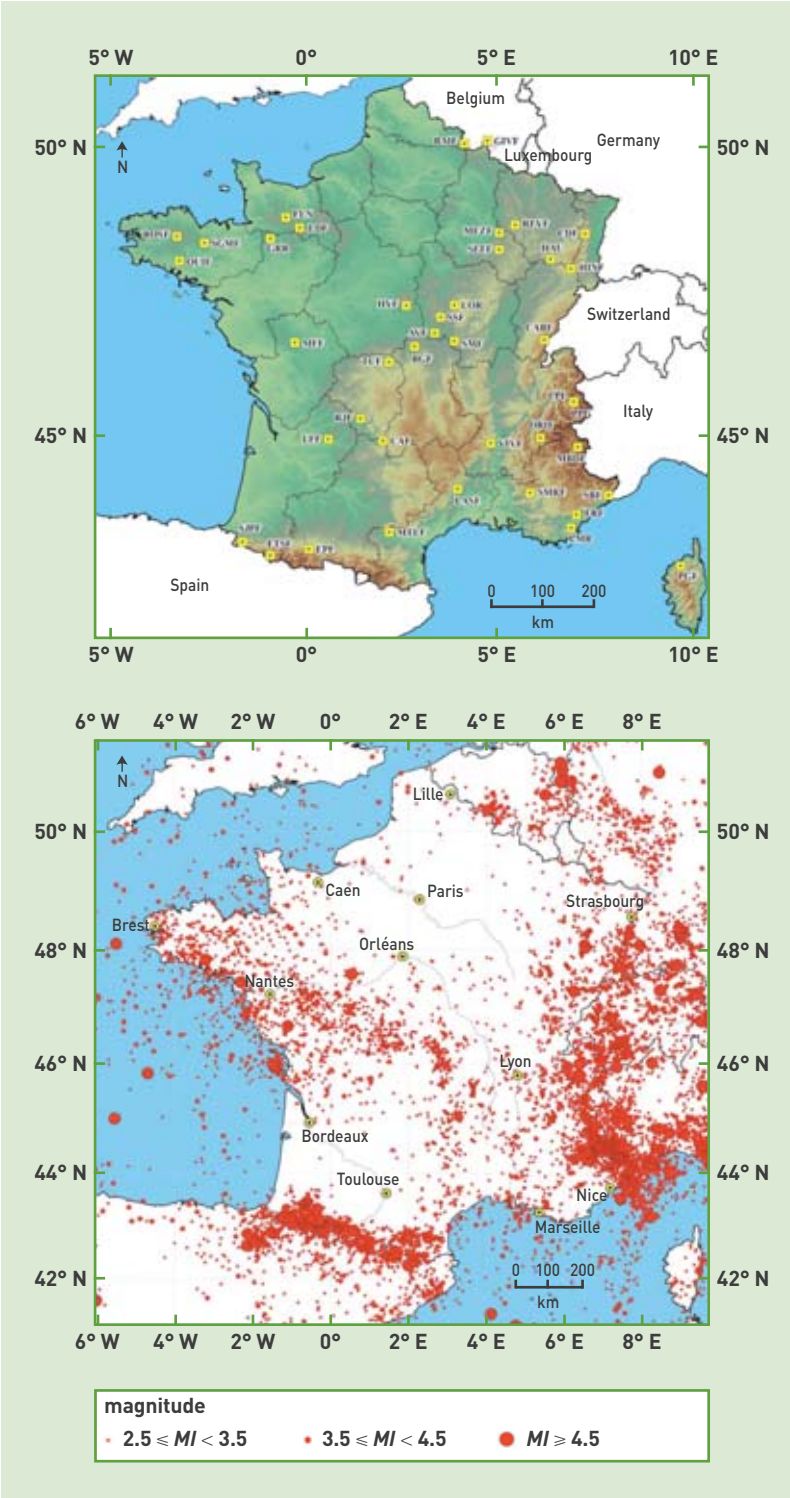
With respect to major earthquakes, such a description, in the form of coordinates, and magnitude, is inadequate. To assess the effects of such earthquakes – particularly in order to assess the risk of a **tsunami** (see *How may tsunami prevention, and prediction be achieved?* p. 101; and Focus E, ***How does a tsunami arise, and propagate?*** p. 105) – it is indispensable that the characteristics be ascertained, of the fracture invol-

(1) Website: http://www-dase.cea.fr/



C. Dupont/CEA

The long-period seismic sensor allows measurement of ground motions involving periods longer than 1 second. It is particularly suitable for the purposes of studying surface, and body waves generated by earthquakes, Earth tides, and the Earth's free oscillations.



CEA/DAM

Figure 1.
Top, DASE's seismic monitoring network (yellow squares) across mainland France. The 40 sensors, distributed across the country, make it possible to record close to 200,000 measurements every year. Bottom, seismicity, as measured by that network since 1962 (restricted to events of magnitude greater than 2.5).

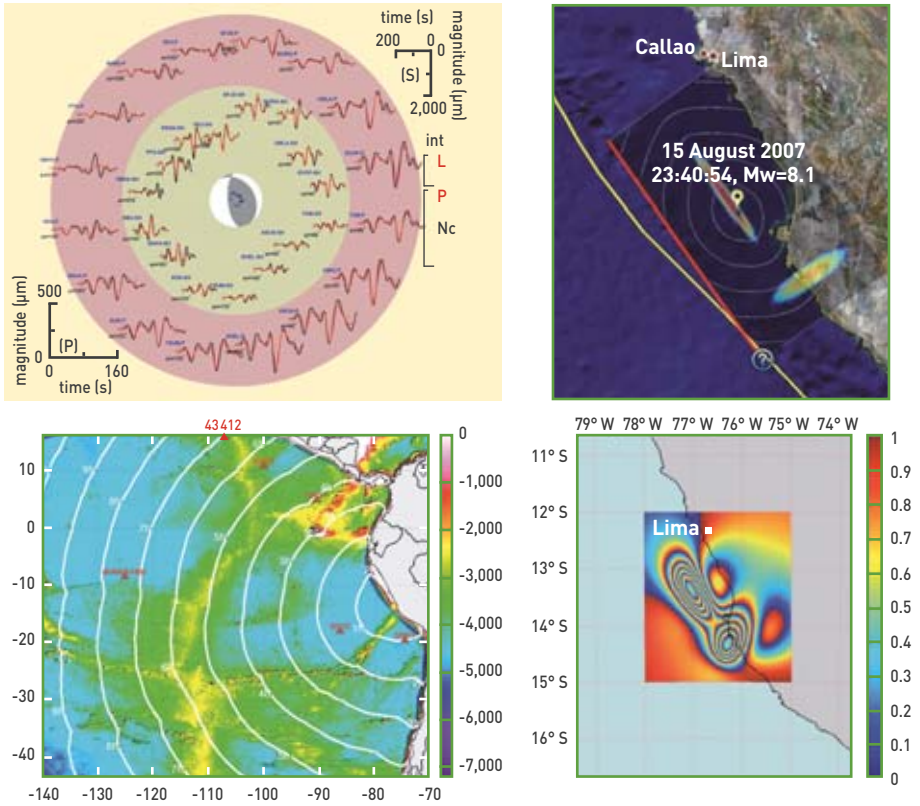
ved, such as the location, and length of the **fault** that has ruptured, rupture velocity, and duration, and the strain reduction brought about by the earthquake. Likewise, when the event detected is liable to be a nuclear test, its analysis must be taken further. Seismologists then look for specific features, e.g. evidence of a depth of a few hundred meters only (earthquakes may arise at depths of up to 700 km), or an **isotropic** distribution of **P-wave** (compressional wave) amplitudes, and low **S-wave** (shear wave) amplitudes, features that are typical for an explosive source. Such detailed analytical work involves a variety of techniques, providing the analyst with tools affording the highest performance, for the purposes of assisting in interpretation (see Box 1). Signal processing is used, to seek out certain characteristic features, in the recordings. **Numerical simulation** provides the means to test a hypothesis (explosive, or seismic source, for instance), through comparison of results from simulations with the seismic records. Finally, modern data analysis techniques, e.g. nonlinear **inversion techniques**, neural networks, fuzzy logic, are used for the purposes of comparing the ensemble of parameters obtained, for a given event, with the same parameters, as characterizing similar events in the database.

Seismicity and seismic hazard

It would still prove a vain hope to imagine a reliable method is at hand, such as would allow the imminent occurrence of an earthquake to be predicted; consequently, the assessment of the risk of an earthquake occurring, in any given location, may only be made in statistical terms. The method used is based on the notion of reference seismic event, for a particular region, this providing the basis for seismic risk assessment studies. In France, seismic regulations require that installations be constructed so as to be able to withstand the strongest seismic motions they are liable to be subjected to. Consequently, the definition, for each site, of the reference event is

The detailed analysis of a strong earthquake

1



CEA/DAM

This detailed summary presentation of the analysis of the earthquake of magnitude 8.1, which occurred off Peru on 15 August 2007, shows the various processing stages, from waveform analysis, through description of the rupture, as obtained by inversion of the waveforms, and the anticipated consequences of this event, in terms of tsunami, and ground surface displacement.
Top left, the picture shows the records (black), and synthetic signals (red), as computed for the seismic source yielded by inversion, and appearing on the map at top right. The fault extends over a distance of 200 km, and comprises two "patches" (colored ellipses), over which the largest motion involved a slip of 8 m, for a total rupture duration of about 100 s. From these inversion results, the effects caused by the earthquake may be computed. The picture at bottom left shows tsunami propagation times (white lines), while that at bottom right shows ground displacement, in the form of the simulated interferogram, as it might be obtained by processing satellite pictures, taken before, and after the earthquake.

complemented by an investigation of site effects, which may, depending on the nature of the soil involved, considerably amplify, or damp down the amplitude of the seismic waves generated.
The definition of reference events relies, first and foremost, on a detailed analysis of seismicity catalogs. On the other hand, these record but a small fraction of the cycle governing, at a large scale, plate motions. They must thus be complemented, by researching events that have affected a particular region within a human timescale (historical seismicity), but equally in more remote times (paleoseismicity). In France, such effects are difficult to identify, owing to low seismicity levels. It thus proves indispensable to study more active regions, such as Nepal, or Mongolia (see *GPS measurement of deformation: a method for the investigation of large-scale tectonic motions*, p. 95).
Site effects, as evidenced by many instances of highly destructive earthquakes, e.g. the earthquake that occurred in China in May 2008, are investigated both from a theoretical standpoint – in particular by way of numerical simulations (see Box 2) – and field experiments. For that purpose, DASE operates a network of accelerometers, located either close to sensitive sites, or near seismically active areas, in order to obtain detailed records of strong motions. Through this initiative, DASE is also a participant,

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This seismic station, sited in Madagascar, operates in self-standing mode, by means of solar panels, and a parabolic VSAT antenna.

at the national scale, in the French Permanent Accelerometer Network (**RAP**: **Réseau accélérométrique permanent**).
All of these activities enable LDG – acting as CEA's seismic hazard expertise center, since 1996 – to carry out, on behalf of safety authorities, mandatory site studies, as required by current legislation.

The contribution of numerical simulation

As soon as the main wave types were identified, seismologists sought to arrive at a theoretical formulation for these waves, this subsequently serving for the computation of waveforms. From the 1960s through to the 1980s, many **algorithms** were published, making it possible, for the various types of seismic wave, to produce increasingly realistic, synthetic **seismograms**, by integrating models of the Earth's internal structure, of ever greater precision. However, all these methods work on the assumption of a regular, stratified structure of soil horizons. In order to arrive at a more realistic approach, integrating e.g. a three-dimensional model of propagation, discrete methods – i.e. methods resolving space and time into a cell grid – must be used, for the purposes of computing the stepwise evolution of seismic waves, from one cell to the next, for every point in the grid. Of late, a new **computation code**, developed at DASE, and dubbed Mka3D, has made it possible to implement such a formalization, for the purposes of processing, simultaneously, rupture problems – e.g. along the fault, or around unstable blocks, falling under stress from the propagation of seismic waves – and problems of elastic mechanics – e.g. wave propagation through the ground, or in building structures (see Box 2).

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Entrance to a seismic cave in Mongolia.

A synergy of competences

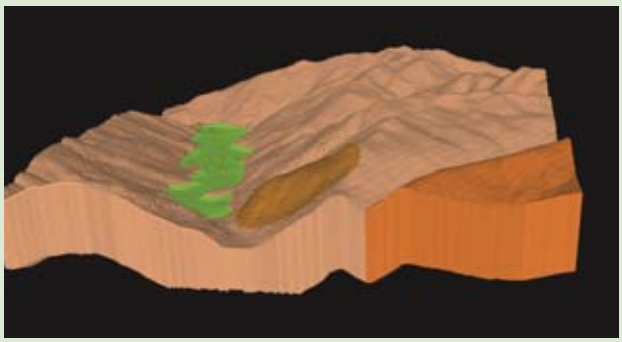
The remits assigned to CEA mean DASE is able to be involved in a wide gamut of activities, related to the area of Earth sciences. These activities involve expertise in a variety of domains, going beyond the strict confines of Earth sciences. Such synergy of competences, brought together within a single unit, provides each research scientist or engineer with the ability to draw on the tools best suited for the issues at hand, or, in any event, to be involved in developing such tools, with a high assurance of effectiveness in the process.

> **Yves Cansi, Jocelyn Guilbert** and **Marc Nicolas**
Environmental Assessment
and Monitoring Department (DASE)
Military Applications Division
CEA DAM–Île-de-France Center

Grand Challenge: highly realistic simulations

2

The propagation of elastic motions, the rupture of continuous media, motions of blocks... all of these processes are covered by the mechanics of continuous media. However, depending on these various domains of application, further theoretical developments, and the solutions of the associated equations do vary, ultimately not coming under one and the same formalization. With regard to **seismic risk**, all of these processes must be taken on board, from rupture to the stressing of buildings, through elastic **wave** propagation across a complex geological environment. This was achieved in the Mka3D **code**, based on a finescale **modeling** approach, covering all of these processes, thus allowing their implementation in a realistic environment.
In the example shown here, which required use of 500 processors, over 40 hours, in CEA's Tera supercomputers (i.e. a total 20,000 hours' computing time), a **fault** causes an **earthquake** of **magnitude** 5.5 on the **Richter scale**. Seismic waves then propagate across a three-dimensional environment, complex both in terms of its shape (topography), and composition (nature of the various geological media). The domain investigated here is at the scale of a town (11 × 11 km^2, over a depth of 2 km). Seismic waves reach the foot of the buildings, likewise modeled, as part of the same computation, this allowing direct interaction between ground, and structure. One of the original features of this software precisely involves its ability to cater for quite a major switch in scale, from the scale of the buildings to that of the seismic wave propagation domain. The numerical approach used in the Mka3D code further makes it possible to take on board complex physics, for the purposes, e.g., of predicting possible ruptures, and monitoring the collapse of a particular structure, or the buildup, and onset of a landslide.



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Grand Challenge simulation. The picture shows a simple depiction of the propagation environment, including the fault (separating the orange, and light brown areas, at lower right), detailed topography, the presence of a sedimentary basin (in green), and a superficial region (brown, at center), involving mechanical characteristics such that stressing by elastic waves is liable to result in a landslide. Finally, buildings are positioned in the distance, on the sedimentary area.

FOCUS D

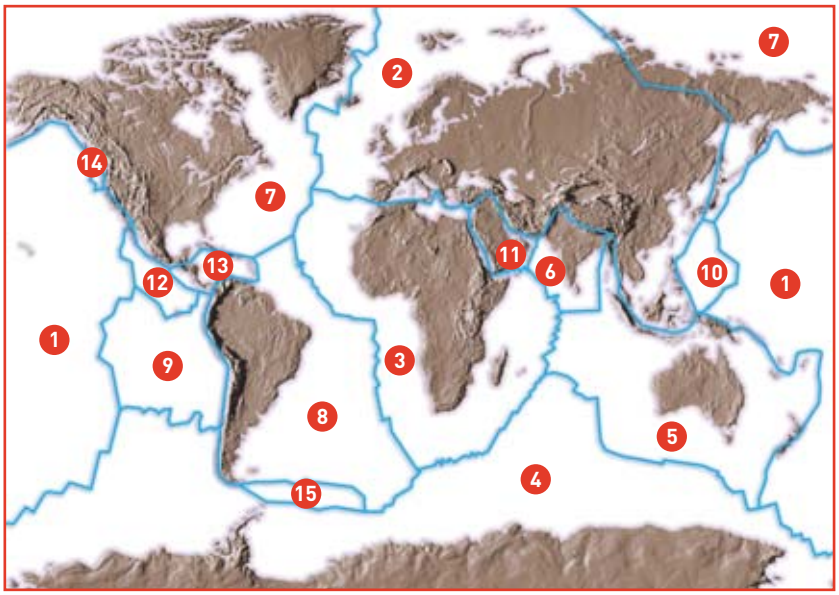
Plate tectonics and earthquakes

The Earth's crust, i.e. the superficial, outermost portion of our planet, envelops the deeper layers, namely the mantle, and the core (see Focus A, *Journey to the center of the Earth, and the outer reaches of the atmosphere*, p. 21). Its thickness is augmented by that of the uppermost part of the mantle, together with which it forms the lithosphere, a mosaic comprising a dozen rigid plates (the so-called lithospheric plates), including 7 major plates, and 5 minor plates (see Figure 1). With a thickness varying from about 10 to 100 kilometers, these plates move across the underlying, more plastic part of the mantle, the asthenosphere.

In 1915, German meteorologist and astronomer Alfred Wegener published his hypothesis of continental drift. It was not before 1967, however, that this took on a formalized form. The theory was initially known as seafloor spreading, subsequently as plate tectonics. This describes the motions of these plates, moving as they do – either drawing apart (Arabia is thus moving away from Africa), or coming together – at a rate of a few centimeters per year. The source of the force setting the plates in motion is still a matter for debate: is this due to a subduction movement, initiated at the (cold) edge of a plate, resulting in a (hot) upwelling of the mantle at the opposite edge? Or is this due, conversely, to a hot upwelling of the mantle, "thrusting" against the surface, and causing the opposite, cold edge of the plate to go under? Or to the effect of a stress of a more mechanical nature, such as the weight of the subducting crust slab, pulling the plate with it, or the weight of the young crust pushing it along?

Be that as it may, these motions form the counterpart, at the surface, of the process of convection taking place within the mantle. This process is powered by heat (temperature stands at some 1,300 °C, at a depth of 100 km), coming from radioactive decay of rocks in the Earth's core, to wit potassium, uranium, and thorium. Convection is one of the three mechanisms through which cooling of the Earth takes place, by removing heat at its surface – along with heat conduction, and radiative transfer. Some regions in the mantle thus become hotter, and consequently less dense, and rise through buoyancy. The material cools at the surface (thus removing the heat generated inside the planet), becoming cooler, and consequently denser (and at the same time more "brittle"), causing it to sink again. This "conveyor belt" process leads to the emergence of relatively stable regions, in areas where matter is rising (ridges), or sinking (subduction zones), matter being displaced across the surface of the mantle, from the former to the latter areas. The Earth produces magma both along the rising, and sinking currents.

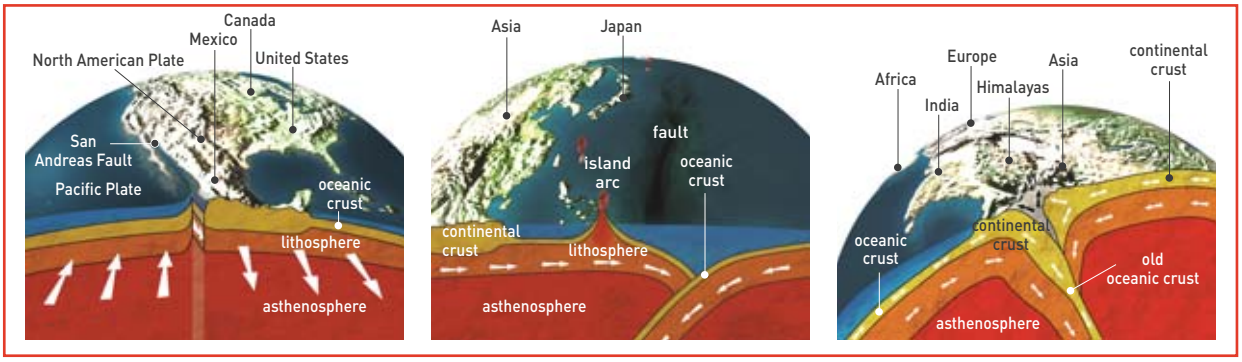
The motions driving the displacement of tectonic plates are found to be of several types. Divergence (spreading), whereby two plates move apart, allows the mantle welling up between them to replenish the oceanic lithosphere. The divergent interplate boundary corresponds to a ridge, which at the same time is a region of intense volcanic activity. Convergence involves two plates drawing together, resulting in three types of boundary. In subduction, one of the plates (as a rule the denser one, in most cases oceanic crust) dips under the continental crust. The area around the island of Sumatra, for instance, is thus a subduction zone, where the dense Indian–Australian Plate plunges under the less dense Eurasian Plate, at an average rate of about 5 cm per year. The collision of continental plates, on the other hand, is the cause of mountain range formation,



Yuvanoé/CEA

Figure 1.
The Earth's outermost layer is subdivided into a number of rigid plates, slowly moving across the underlying viscous material in the asthenosphere, while rubbing one against the other. Certain plates may in turn be subdivided into several plates, involving smaller relative motions.

	plate	average velocity
1	Pacific Plate	10 cm/year northwestward
2	Eurasian Plate	1 cm/year eastward
3	African Plate	2 cm/year northward
4	Antarctic Plate	rotating about itself
5	Australian Plate	6 cm/year northeastward
6	Indian Plate	6 cm/year northward
7	North American Plate	1 cm/year westward
8	South American Plate	1 cm/year northward
9	Nazca Plate	7 cm/year eastward
10	Philippine Plate	8 cm/year westward
11	Arabian Plate	3 cm/year northeastward
12	Cocos Plate	5 cm/year northeastward
13	Caribbean Plate	1 cm/year northeastward
14	Juan de Fuca Plate	2.8 cm/year northeastward
15	Scotia Plate	3.6 cm/year westward



Yuvanoé/CEA

Figure 2.
At left, an instance of transform boundary. The Pacific Plate and the North American Plate are slipping past each other, on either side of the San Andreas Fault, which is the source of Californian earthquakes. Middle, an instance of subduction. The formation of volcanic island arcs, extending from Japan to the Kuril Islands, and the Aleutians, is due to the fact that the Pacific Plate is plunging under the Eurasian Plate. At right, an instance of collision. The formation of the Himalayas is the result of the contest between the Indian Plate, and the Eurasian Plate, which overlap and undergo uplift.

e.g. the uplift of the Himalayas, at the boundary between the Indian, and Eurasian Plates (see Figure 2). Finally, **obduction**, or overthrusting, involves the transport of a section of oceanic lithosphere on top of a continent (no convergence process of this type is currently active). Another kind of interaction involves friction between plates: **transcurrence**, or **transform boundaries**, where two plates slip horizontally past each other (see Figure 2).

In effect, the three main families of **faults** are associated, respectively, to these interaction types: normal faults (divergent, extensional); reverse faults (convergent, compressional); and strike–slip faults (transcurrent: both the extension, and compression axes lie in the horizontal plane). Plate motions, classically monitored by means of conventional instruments (theodolites, distance meters), are increasingly tracked by way of satellite resources, namely the Global Positioning System (GPS), which proves particularly well suited to the requirements of deformation measurements, across a given region (see *GPS measurement of deformation: a method for the investigation of large-scale tectonic motions*, p. 95).

It is along interplate boundaries that most **earthquakes**, and **volcanoes** arise, as a consequence of the selfsame deep phenomena. A certain number of volcanoes are found to arise, however, right at the center of plates (these locations are known as **hotspots**). These hotspots are thought to be the surface manifestation of convecting blobs of material, less dense than the mantle as a whole, rising straight through the latter. Such hotspots – the largest ones are located under the islands of Hawaii (USA) and La Réunion (France) – scarcely move relative to one another, while plates "ride past" above them.

Volcanoes and earthquakes as markers of deep motions inside the planet

Volcanoes may be of the *effusive*, or *explosive* type, or a combination of the two. The former let molten rock stream out of their crater(s), and often occur as chains of

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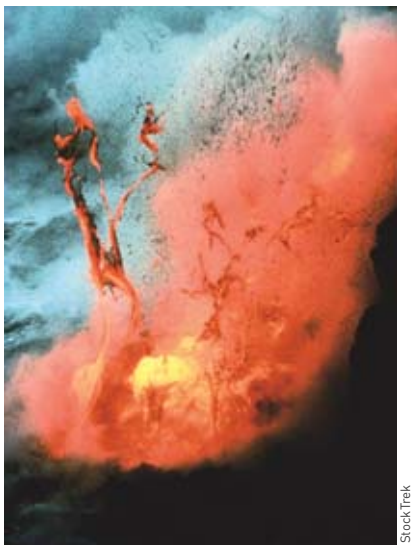

Stock Trek

The Pacific Plate is dotted with volcanic islands, such as Hawaii, where volcanoes numbered among the most active, the world over, are to be found.

CNRS Photothèque/Hervé Philip

Damage caused by the earthquake occurring in Spitak (Armenia), on 7 December 1988. This earthquake, of magnitude 6.2, resulted in a death toll of about 25,000. The violent release of strains, accumulating as plates move, scraping against one another, induces a concomitant, more or less abrupt, ground motion.

FOCUS D

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volcanoes, especially under the sea. The second type involves volcanoes that hold in the rising pressure of imprisoned gases, until they "spring the plug;" these form alignments, and occur on islands, and continents. High-frequency, low-amplitude seismic noise (**tremors**) arises as a precursor of eruptions. Some 3,500 volcanoes have been active over the past 10,000 years.

Plate motions, as they edge one against the other, cause deformations in the Earth's crust, and a buildup of strains. When such strains exceed the crust's mechanical strength, weaker, more brittle zones fail. An earthquake is the violent release of such accumulated strains, involving more or less abrupt ground motion (from a few millimeters, to several tens of meters) along the faults.

Most earthquakes are of natural origin – the Earth experiences more than one million seismic shocks every year, some 140,000 being of a **magnitude** greater than 3,[1] while some may be due to motions of volcanic origin – however **seismic events** may also be induced by human activities, e.g. dam reservoir impounding, or **hydrocarbon** extraction from oil fields. Further, events such as mining or quarrying blasts, or nuclear tests, particularly underground tests, likewise set off seismic waves, very similar to those generated by natural events.

Regions involving intense seismic activity include *mid-ocean ridges*, subduction zones, areas around faults along which plates are slipping past each other (e.g. the San Andreas Fault, in California [USA]), and regions where collisions between continents are taking place.

The release of strains, as the earthquake occurs, gives rise to elastic vibrations, known as **seismic waves**, propagating in all directions, across the Earth and through water, from the point of initial rupture of the Earth's crust – the **focus** (or **hypocenter**) – lying somewhere between the surface and a depth of around 700 km. The **epicenter** is the point on the surface lying vertically above the earthquake focus: this, as a rule, is the point where the shock experienced at the surface is strongest. Seismic waves propagate at velocities ranging from 2 km/s to 14 km/s, with a longitudinal motion (**P waves**, this standing for pressure, or **primary** waves), or transverse motion (**S waves**, standing for shear, or **secondary** waves). P waves (6–14 km/s) act by *compression*, as in a coil spring, particles being displaced along the direction of wave propagation, whether in solids, liquids, or gases. S waves (3–7 km/s) are *shear* waves, displacing particles perpendicularly to the direction of propagation: these waves only travel through solids (see Figure 3).

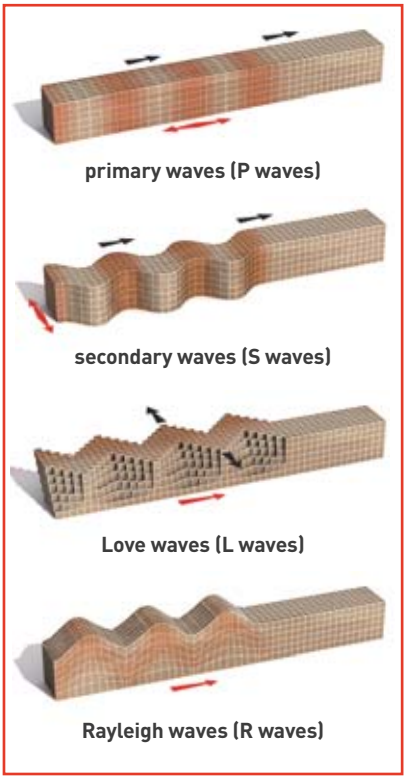
Velocity, for both types of waves, varies as a function of the density of the medium they travel through. The "softer" that medium is, the slower waves travel. Such wave phenomena are subject to physical laws, e.g. reflection, or refraction. It should be added that these waves do not all travel at the same velocity, depending on the medium they are traveling through. Further, as a P wave reaches a transition zone, e.g. the mantle–core interface, a small part of its energy is converted into S waves, making for more complicated interpretation of seismograph records. Seismologists therefore label waves by different letters, according to their provenance (see Table).

	P wave	S wave
mantle	P	S
outer core	K	
inner core	I	J

Table.
A PKP wave, for instance, is a P wave reemerging at the surface, where it is detected after it has passed through the liquid **outer core**.

Complementing these so-called body waves, surface waves – L waves (*Love waves*, causing a horizontal displacement), and R waves (*Rayleigh waves*, which are slower, and induce both horizontal and vertical displacement) – involving much larger amplitudes, propagate only through the crust, which is a less homogeneous medium than the mantle (see Figure 3).

It is through the painstaking effort initiated in the last century in seismological observatories, that tables could be drawn up, relating propagation time and distance traveled. That work thus contributed to enhancing knowledge of the **Earth's internal structure**, making it possible, presently, to **model** correctly the wave paths involved. Nowadays, methods such as **seismic tomography** further assist in improving models, in particular by taking on board three-dimensional structures.



Yuvanoé/CEA

Figure 3.
The various types of seismic wave. P wave propagation is parallel to the ground displacement induced, the ground being alternately dilated, and compressed.
In the case of S waves, rocks undergo shearing, and evidence distortion, due to vibrations perpendicular to wave propagation.
L waves and R waves propagate along the Earth's surface, and prove the most highly destructive types.

Seismic monitoring: location, magnitude, intensity, seismic moment...

Detecting a seismic event involves detecting the waves generated by it, by means of two types of facilities, appropriate for the propagation medium. Ground motions, even low-amplitude motions, are detected, both at close, and long distances, by **seismic stations**, fitted with **seismographs**, i.e. devices allowing the measurement of even the most minute ground motions, in all three dimensions, and yielding their characte-

(1) Currently, seismologists use magnitudes such as **moment magnitude**, for the purposes of estimating the size of very strong earthquakes. This magnitude, noted **Mw**, introduced in 1977 by Hiroo Kanamori, from the California Institute of Technology, is defined by the relation $\log Mo = 1.5\ Mw + 9.1$ (where Mo stands for the seismic moment, expressed in newton–meters). Information directed to the public at large usually refers to the **Richter magnitude** (open-scale magnitude), as established by Charles Francis Richter, in California, in 1935, initially defined for the purposes of quantifying the size of local earthquakes.

ristics, in terms of displacement, velocity, or acceleration.

Hydroacoustic waves, generated by undersea explosions, or explosions set off underground close to a sea, or ocean, are detected by **hydroacoustic stations**, comprising submerged receptors, and coastal seismic stations. Networking such stations around the globe (in particular in and around a region that needs to be monitored) makes it possible to determine precisely the geographic location of the earthquake focus, and to issue an alert call, if required. Indeed, while precursor signs do exist (variations in the local magnetic field, heightened groundwater circulation, reductions in rock **resistivity**, slight ground surface deformations), it is not feasible to predict earthquakes.

The first methods used for the purposes of locating seismic events, on the basis of the arrival times of the various wave trains, were based on geometric principles. For distances lower than 1,200 km, propagation times, for P waves and for S waves, are proportional, as a first approximation, to the distances traveled by these waves. The difference between the two times of arrival is thus itself, in turn, proportional to distance, this allowing the source to be located on a circle, centered on the station. By repeating this analysis, across several stations, the site of the epicenter may be geometrically located, at the intersection of the corresponding circles (see Figure 4). Current numerical methods deal with the problem globally, by treating it as an inverse problem, involving unknowns that are brought together into a 4-dimensional vector $\boldsymbol{x}$ (latitude, longitude, depth, event origin time), and data subsumed under a vector $\boldsymbol{t}$ covering the various measurements (e.g. wave arrival times). The direct problem, as noted by vector $\boldsymbol{t(x)}$, involves computing, from $\boldsymbol{x}$, the theoretical values associated to the data involved. Solving the **inverse problem** involves finding the vector $\boldsymbol{x_0}$ that minimizes the differences between $\boldsymbol{t}$, and $\boldsymbol{t(x_0)}$.

The characterization of an earthquake does not end with its geographical location. Describing the source poses a more complex problem.

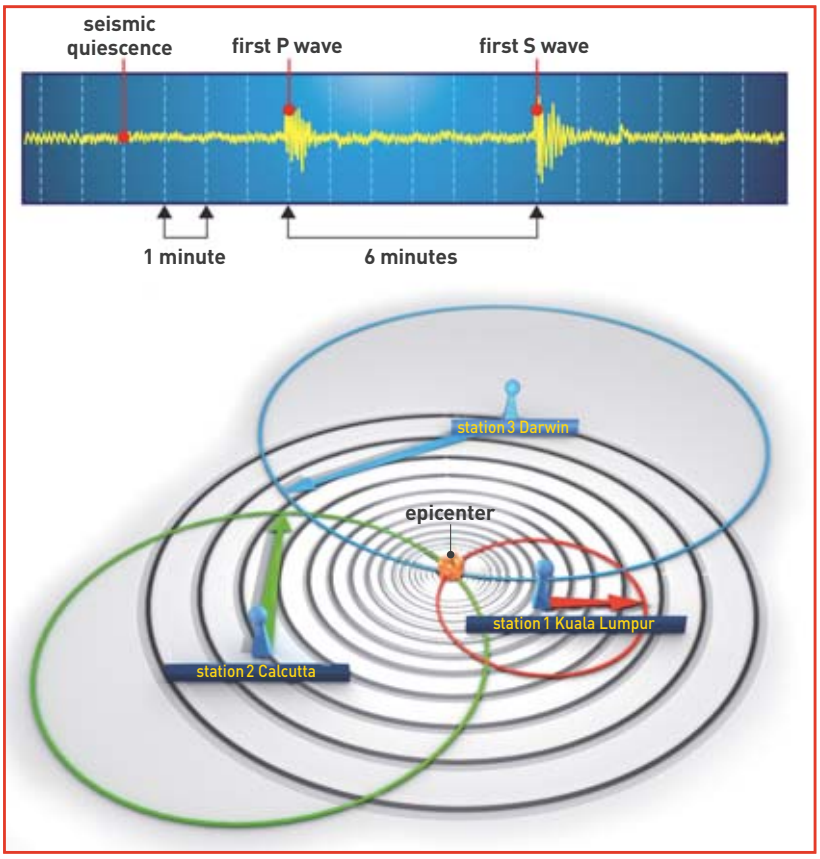
Magnitude is a representation of the elastic energy released by the earthquake. Historically, this was based on the measurement – in well-defined conditions – of wave amplitudes, corrected for attenuation effects from the soils traversed. This is a logarithmic scale, energy being multiplied by a factor 30 for every increase by one unit! Over time, this definition was found to be incomplete, leading to a number of other definitions being put forward.[1] Magnitude should not be confused with earthquake **intensity**, this characterizing, on the other hand, the *effects felt* by human beings, and the *amount of damage observed* at a particular location, subsequent to the event.[2] The largest earthquake to have occurred since 1900 took place in Chile, in 1960, with a magnitude of 9.5. However, the earthquake taking the lar-

Skip to page 94

(2) In France, as in most European countries, the intensity scale adopted is the EMS–98 scale (European Macroseismic Scale, as established in 1998), which features 12 degrees.

C. Dupont/CEA

The short-period seismic detector allows measurement of ground motions involving periods shorter than 2 seconds. It is particularly suitable for the purposes of studying body waves generated by nearby earthquakes.



Yuvanoé/CEA

Figure 4.
The triangulation method has long been used for the purposes of locating a seismic event. The time difference between arrivals of P waves, and S waves allows the distance of the detector from the epicenter to be derived. On the basis of a number of seismic stations, each yielding a value for distance, the epicenter is located at the intersection of the circles centered on each station, of radius equal to the distance found at that station.

FOCUS D

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gest toll in lives (some 250,000 casualties) was the Tangshan earthquake, in China, in 1976, with a magnitude of 7.5. The earthquake that affected Sichuan Province (southwestern China) on 12 May 2008, with a magnitude of 7.9, caused at least 90,000 casualties. One and the same earthquake, of a given magnitude, as defined by the energy released at its focus, will be experienced at varying intensity levels, depending on focus depth, distance from the epicenter, and the local characteristics of the observation location.

The concept of **seismic moment** was introduced, fairly recently, in an endeavor to provide a description of an earthquake in mechanical terms: the value of the seismic moment is obtained by multiplying an elastic constant by the average slip generated at a fault, and the area of that fault. This is complemented by the description of the rupture mechanism involved, specifying the parameters of the fault along which the rupture propagated (direction, length, depth...), the sections that have failed, their displacement, and rupture velocity, on the basis of wave recordings made by a number of detectors.

Nowadays, data from stations are directly transmitted via satellite to an analysis center, where every event is studied. Networks with a global coverage, such as the US World-Wide Standardized Seismograph Network (**WWSSN**), or Incorporated Research Institutions for Seismology (**IRIS**), or France's **Géoscope**, chiefly bring together equipment recording all the components of ground motion, across a wide band of frequencies. At the European level, the European–Mediterranean Seismological Center (**EMSC**) gathers all the findings from more than 80 institutions, in some 60 countries (from Iceland to the Arabian Peninsula, and from Morocco to Russia). In France, alongside the National Seismic Monitoring Network (**RéNaSS**: Réseau national de surveillance sismique), headquarted in Strasbourg, which covers all of mainland France, the global monitoring remit is entrusted to CEA, more precisely to the Detection and Geophysics Laboratory (LDG: Laboratoire de détection et de géophysique), coming under the Environmental Assessment and Monitoring Department (DASE: Département analyse, surveillance, environnement), part of CEA's Military Applications Division (DAM). LDG, based at Bruyères-le-Châtel (Essonne *département*, near Paris), seeks to detect, and identify, in real time, every seismic event, while advancing knowledge of the Earth's motions. The ensemble of data collected makes it possible to draw up a catalog of seismicity, a reference serving as the basis for the seismic zoning of mainland France, which was revised in 2007, for the implementation of the European Eurocode 8 (EC 8) seismic design standard, due to supplant existing French seismic design regulations (PS92, PS–MI) from 2010.

Finally, the French Permanent Accelerometer Network (**RAP**: **Réseau accélérométrique permanent**) – comprising more than one hundred stations, run on behalf of a scientific interest group, bringing together **CNRS**/**INSU**, CEA, **BRGM**, **IRSN**, **IPGP**, the Civil Engineers Central Laboratory (LCPC: Laboratoire central des Ponts et chaussées), and a number of universities – has the remit of providing the scientific, and technological community with data, allowing an understanding to be gained of phenomena related to ground motion during earthquakes, and arrive at estimates of such motion, in future earthquakes. The high sensitivity achieved makes it possible to investigate scaling laws, and nonlinearity phenomena. RAP should thus assist in the determination of reference spectra, allowing structural dimensioning to be carried out.

C. Dupont/CEA

DASE's geophysical signals analysis room. In this room, all signals are centralized, as they are detected by monitoring stations set up all around the world. Analysis of these signals makes it possible to alert instantly government agencies, in the event of a strong earthquake, a nuclear test, or exceptional events.

S. Poupin/CEA

Tests carried out on vibrating tables, in CEA's Tamaris laboratory – shown here, a test involving a structure of about 20 tonnes – have contributed to the drawing up of European seismic engineering standards for buildings.

GPS measurement of **deformation**: a method for the investigation of large-scale **tectonic motions**

The Global Positioning System (GPS) satellite system has made its mark, over ten years, for the purposes of monitoring, with millimeter precision, large-scale tectonic plate motions, and deformations. CEA is participating in the acquisition of new data, under the aegis of an international collaboration.

L. Bollinger-CEA/DAM

The Langtang Lirung (elevation: 7,227 m), a summit rising at the fore of the high Himalayan range, in central Nepal. As a region host to the collision between the Indian, and Eurasian Plates, the Himalayas provide a widely studied deformation region.

For its work under its site monitoring remit, CEA's Environmental Assessment and Monitoring Department (DASE: Département analyse, surveillance, environnement) has used the Global Positioning System (GPS) satellite system ever since it was put into service (see Box). Allowing as it does – as has been the case for the past ten years or so – millimeter precision to be achieved, the GPS system has become, nowadays, an indispensable tool, whether it be for the measurement of large-scale **tectonic plate** motions, or the detection of possibly smaller motions, across intraplate deformation zones.
In the context of investigations carried out by the Detection and Geophysics Laboratory (DASE/LDG: Laboratoire de détection et de géophysique) – acting as CEA's seismic hazard expertise center – the aim is to assess the seismogenic potential of the region considered, in particular with regard to active **faults** (see Focus D, ***Plate tectonics and earthquakes***, p. 90).

However, across mainland France, deformations are small, and not readily measured. DASE is therefore conducting fundamental work, as regards investigation of the seismic cycle. One of the regions lending themselves to such investigations is the continental **collision** region between the Indian, and Eurasian Plates, where motions take place at rates four times faster than is the case in the Alps Mountains. A GPS network has been set up in Nepal. In mainland France, DASE is also a participant, at the same time, in the RENAG[1] national GPS network

(1) RENAG (Réseau national GPS permanent - National Permanent GPS Network): an array of permanent GPS stations, run by French research laboratories, for the purposes of scientific research, and Earth observation, with regard to internal, and external geophysics, and geodesy. For that purpose, RENAG receives financial support from **CNRS/INSU**, and the French Ministry of Higher Education, and material assistance from a number of state organizations, e.g. **IGN**, CEA, **IRSN**, **CNES**. The data gathered are public-access, free of charge.

What is the operating principle of GPS?

The GPS system was initially devised by the US Department of Defense (DOD), to provide US armed forces with a radionavigation system having global coverage. The system has been fully operational since April 1995, and has been made available to the civilian community. It allows anyone equipped with the system to access their position, in any weather, by day or by night, at any point on the globe, whether on the ground, at sea, or in space. The GPS constellation comprises more than 24 satellites, on quasi-circular orbits, at an altitude of about 20,200 km. These satellites are deployed over 6 planes, inclined relative to the equator, with 4 satellites per plane. Their orbiting time around the Earth is about 11 hours 58 minutes.

National Executive Committee for Space-Based PNT

NAVSTAR GPS satellite constellation, and picture of a satellite.

The GPS system comprises three segments: the space segment (the satellites), the user segment (the ensemble of receivers), and the control segment. The latter involves 5 tracking stations, constantly monitoring the satellites, and sending on their data to a master control station, which recomputes precise orbital data for each satellite.

The signals transmitted

Each satellite carries several rubidium, or cesium atomic clocks.[1] The satellites broadcast simultaneously, in the L radiofrequency band,[2] over two frequencies, of respective wavelengths 19 cm, and 24 cm, signals modulated by two codes, the C/A (coarse acquisition) and P (precise, about 10 times more precise than the former one) codes, along with a navigation message, containing a variety of data, e.g. orbital parameters, clock parameters, time, and health information.

Operating mode, and data processing

The GPS antenna must be set on a stable support (pillar, tripod, building), and anchored to the ground, so as to fully follow the motions of the Earth's crust. The antenna is connected to an ultra-precise receiver (allowing, in particular, measurements related to signal phase). The receivers carry out measurements of the electromagnetic signal's satellite–receiver propagation times, converted into pseudoranges (range measurements, allowing for clock errors), together with measurements involving counting the number of cycle fractions on the sinewave (carrier) signal. It is these latter, highly precise measurements that are used for the purposes of geodesy. Initial processing has the purpose of eliminating a major part of the errors involved (in particular clock, and modeling errors), by means of a differential technique, combining, at any given time, the ensemble of satellites,

(1) Atomic clock: this uses as a reference (analogously to the pendulum motion used in a conventional clock) the frequency of radiation emitted in the atomic transition between two specific energy levels of a cesium-133, or rubidium-87 **atom**.

(2) Radiofrequency L band: the segment of the electromagnetic spectrum defined by the (approximate) frequency range 1.4–1.5 **GHz**. Parts of this band are assigned to radioastronomy activities, for the purposes of space, and scientific research. It is used in France, in particular, for terrestrial digital radio broadcasting, in Digital Multimedia Broadcasting (DMB) format.

CEA/DAM

Data acquisition and transmission system at the permanent GPS station DAMAN set up in Nepal.

and receivers available. Subsequently, a so-called least-squares inversion technique – involving adjusting the initially obtained coordinates, to minimize in optimal fashion the discrepancies between the differences obtained, between observed, and theoretical paths, while taking into account various correction parameters (ionosphere, troposphere, horizontal gradients, Earth and Moon tides, solar radiation pressure, relativistic correction), and the precise orbital data – allows very precise relative coordinates to be determined, between stations. Owing to the many possible sources of error, data redundancy, for data provided by permanent stations, results in a notable gain in precision, compared to campaign data (errors due to repositioning, aberrant points, seasonal variations). In order to relate the absolute coordinates for the network to the worldwide geodetic system, the computation must take in data from International Global Navigation Satellite System Service (IGS) stations, positions which are known with a very high precision. The forthcoming European Galileo system, which is due to be operational from 2010–2013, should bring further enhancements in performance, with the extra number of satellites that will be available. GPS receivers will then have to be replaced, to be able to receive data from this new system, along with data from the Russian GLONASS system (Global Satellite Navigation System).

project, one purpose of which is to measure the deformation of the Earth's crust over France, and across border areas (see Focus A, ***Journey to the center of the Earth, and the outer reaches of the atmosphere***, p. 21).

Dense arrays of permanent stations

The development of **space geodesy** techniques has brought about a veritable revolution, as regards measurement of deformations of the Earth's crust, not only owing to their precision, but equally due to their ability to provide unified reference systems, at the scale of the planet, an achievement that had proved virtually unfeasible previously. Owing to its relative ease of deployment, combined with steadily falling costs, the GPS system, which has been fully operational since 1995, is widely used by the scientific community, as a rule in association with multidisciplinary, complementary approaches (seismology, tectonics, **terrestrial geodesy**, **radar interferometry**,

DORIS).[2] This has enabled, over the past ten years or so, many scientific advances to be achieved, as regards knowledge of crust deformation modes, at all spatial scales, and at every stage in the seismic cycle, i.e. before, during, and after an earthquake. One of the most active regions around the world, the San Andreas Fault, in California (USA), was one of the first to be equipped with the relevant instrumentation. Motions arising during the Landers earthquake (1992; **magnitude** 7.4) were thus measured directly. The development of permanent stations, with the setting up, in particular, of the International Global Navigation Satellite System Service (IGS) – a worldwide academic consortium, comprising some 350 stations – now allows millimeter precisions to be achieved. The data thus obtained contribute, in conjunction with other data, to defining the International Terrestrial Reference Frame (ITRF),[3] and serve for velocity computations by member stations. The trend to denser permanent networks is constantly speeding up, at regional level, first and foremost in high-deformation zones, which arise, as a rule, at plate boundaries (California, Japan, Taiwan, Sumatra, Chile, Mexico… to mention but a few of them), and in intraplate deformation zones, some of which involve smaller amplitudes (Mongolia, the Alps Mountains, Jura Mountains in eastern France…). Phenomena that would go completely undetected previously are now being highlighted. Transient deformations, interpreted as possible aseismic slips (slow earthquakes) – e.g. in the Cascades (Canada), and Guerrero (southern Mexico) regions – or again as possible earthquake precursors – e.g. in Chile – are thus being observed.

Large-scale investigation methods

Among the more spectacular corroborations of plate tectonics – a theory initially known as **seafloor spreading** (see Focus D, ***Plate tectonics and earthquakes***, p. 90) – magnetic anomalies yielded the first quantitative estimates, as to plate motions. **Basaltic** materials, rising up from the **mantle** at a **mid-ocean ridge**, and spilling on either side of its axis become magnetized, as they cool, magnetization orienting itself along the direction of the Earth's magnetic field, at the time, thus "freezing" the memory of that field as they solidify. Now, the direction of that field undergoes reversals, over time, at more or less regular intervals. As they spread away from the ridge, rocks on the ocean floor preserve this imprint, resulting in a pattern of alternating anomalies, of varying width, either positive, or negative, depending on whether the Earth's field was normal, or reversed, compared with present orientation. The phenomenon proves symmetrical, on either side of the ridge. Such barcode patterns – so to speak – thus stand as a dated scale, making it possible to determine the spread rate of ocean floors.
A large number of observations are also yielded by **geomorphology**, and seismicity. Horizontal tectonic plate displacements were, for a long time, described by way of **models** drawn up solely on the basis of geological, and geophysical observations made at plate boundaries. One such reference kinematic model is the NUVEL–1 model. This works on the assumption of rigid tectonic plates, involving displacement velocities that remain constant over 3–4 million years. Among other methods employed, very-long-baseline interferometry (**VLBI**) geodetic measurements have made it possible, e.g., to measure the opening rate of the Atlantic Ocean, at 2 cm/year. New geodetic models are now available, combining space geodesy data that are not dependent on geologic models.

Investigation of deformation across the Himalayas in Nepal

Pursuing as they have, over many years, their scientific collaboration in Nepal, DASE and Nepal's Department of Mines and Geology (DMG) laboratory set up, in 1997, an array of 3 permanent, telemetered GPS stations,[4] to complement the extant seismic network. This array was further backed up with point measurement campaigns, to provide measurements involving a higher spatial density. The interseismic **convergence** rate across the Himalayas in Nepal, an essential parameter for the purposes of seismic cycle investigations, is an issue that has been a subject for

(2) DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite): a system proposed, in 1982, by **CNES**, the French Space Geodesy Research Group (GRGS: Groupe de recherches en géodésie spatiale), and **IGN**, to support the POSEIDON oceanographic altimetry experiment. Such a system is known as an "ascending" system. The signal is emitted by ground stations, comprising a transmitting beacon, and an antenna, and received by satellites, by contrast to GPS, for which the transmitters are mounted on the satellites. The embarked receiver carries out **Doppler shift** measurements, at the two frequencies – around 400 **MHz**, and 2 **GHz** – beamed by ground stations.

(3) International Terrestrial Reference Frame (ITRF): a system allowing positioning on Earth, but equally the positioning of any celestial object relative to the Earth (a star, the Moon, a planet, or an artificial satellite orbiting the Earth).

(4) M. Flouzat, J.-P. Avouac, B. Durette, L. Bollinger, T. Héritier, F. Jouanne, M. R. Pandey, "Interseismic deformation across the Himalaya of Central Nepal from GPS measurements, 1997–2001", American Geophysical Union Fall Meeting, 2002.

CEA/DAM

The DAMAN permanent GPS station, set up in 1997 in Nepal, at an elevation of 2,150 m.

debate for years. Analysis of the combined geodetic data obtained made it possible to set constraints as regards the shortening rate across central Nepal, and the velocity of the motion sustained by India. The study of GPS time series evidenced, at the same time, significant seasonal variations.

Subsequent to the closure of the **Tethys Ocean**, India entered into collision with Eurasia, at a time estimated at 60–45 million years (Ma) ago, a collision that is still ongoing at the present time. Over that time, India has penetrated into Asia over more than 2,500 km, generating the highest topographies found on Earth, while the Indochina block has been squeezed out to the east. The respective contributions from these two global deformation mechanisms remains an issue subject to debate, and a crucial one with regard to seismic risk, which stands particularly high in Nepal. A number of destructive **earthquakes** have hit Nepal, since the end of the 19th century, the last one, in 1934, having a magnitude (**Mw**) of 8.4. Knowledge of the deformation mode involved, and its relation with seismicity, is thus indispensable, for the purposes of seismic risk assessment.

(5) F. Jouanne, J.-L. Mugnier, J.-F. Gamond, P. Le Fort, M. R. Pandey, L. Bollinger, M. Flouzat and J.-P. Avouac, "Current shortening across the Himalayas of Nepal", *Geophysical Journal International* 157, 2004, pp. 1–14, DOI: 10.1111/j.1365-246X.2004.02180.x.

(6) J.-P. Avouac, L. Bollinger, J. Lavé, R. Cattin and M. Flouzat, *Comptes rendus de l'Académie des sciences* Paris (section Sciences de la Terre et des planètes/Earth and Planetary sciences) 333, 2001, pp. 513–529.

L. Bollinger, J.-P. Avouac, R. Cattin and M. R. Pandey, "Stress buildup in the Himalaya", *Journal of Geophysical Research–Solid Earth*, 109, 2004, B11405, DOI: 10.1029/2003JB002911.

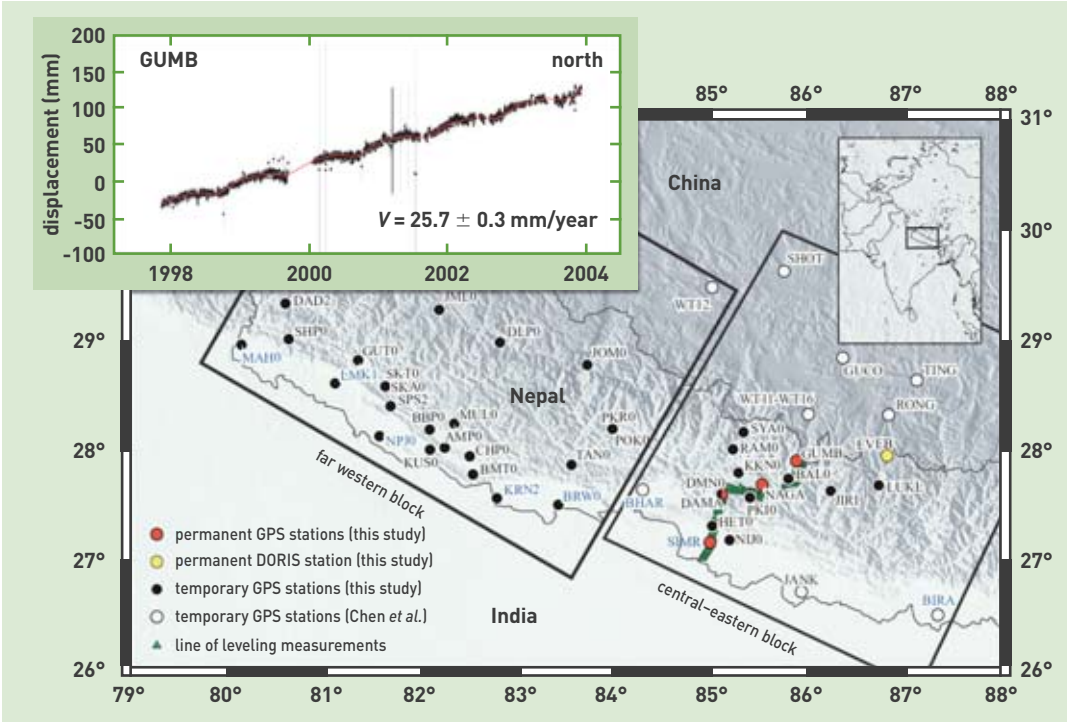
(7) P. Bettinelli, J.-P. Avouac, M. Flouzat, F. Jouanne, L. Bollinger, P. Willis and G. R. Chitrakar, "Plate motion of India and interseismic strain in the Nepal Himalaya from GPS and DORIS measurements", *Journal of Geodesy* 80, 2006, pp. 567–589, DOI: 10.1007/s00190-006-0030-3.

Consistent with the collaborations,[5] and investigations pursued at DASE on the seismic cycle,[6] by way of geomorphological, geological, and **seismotectonic** approaches, a study using combined geodetic data was recently carried out. This analysis included data on vertical displacements, data from the DORIS system's Everest station, data from GPS campaigns from 1995 to 2001, and, finally, from the continuous GPS stations deployed by DMG and DASE, across a north–south section, along the longitude of Kathmandu[7] (see Figure 1).

GPS data were processed at DASE/LDG within the ITRF 2000 reference frame, taking in data from 20 stations from the worldwide IGS network. This showed that India is moving at a rate of about 35 mm/year[7] (see Figure 2), i.e. at a significantly less rapid rate than that derived from global plate tectonics models (48 mm/year). This discrepancy is probably related to the difficulty involved, with global geological models, in resolving the respective motions of the Indian, Arabian, and Eurasian Plates. Internal deformation across India, on the other hand, is quite small (less than 1.8 mm/year).

Shortening across the Himalayas in central Nepal is absorbed along a major overthrust fault, the Main Himalayan Thrust Fault (MHT), while deformation remains aseismic at depth. The slip surface is blocked during the interseismic period, and the elastic energy accumulated during compression is released violently, in earthquakes of large magnitude. The study made it possible to set constraints on the blocked zone, over a distance of 115 km, from the surface to a depth of 20 km under the high range, and on the shortening rate, across the central–eastern region of Nepal, at 19 ± 2.5 mm/year[7] (see Figure 3).

GPS time series evidence, at the same time, seasonal variations, particularly as regards the horizontal component, perpendicular to the Himalayan range (see Figure 1). It was shown that these variations are



(Taken from Bettinelli *et al.*[7])

Figure 1. The set of geodetic data used in processing, as provided by permanent GPS stations (red dots), DORIS (yellow dot), and GPS campaigns (black, and white dots). The names of the stations used for the purposes of determining the motion of the Indian Plate appear in blue. Inset, top left, the northward shift in the position of the GUMBA permanent station, and its velocity, referred to the ITRF 2000 worldwide reference frame. Seasonal variations may be seen. The continuous line represents the best theoretical adjustment for data, taking into account two periodic – annual, and bi-annual – variations.

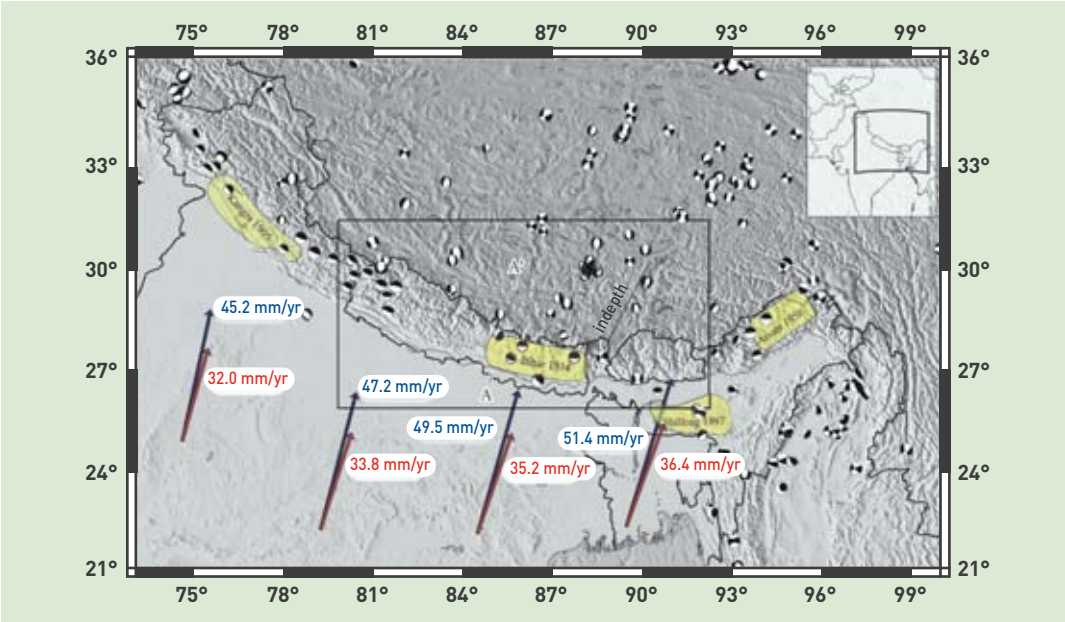
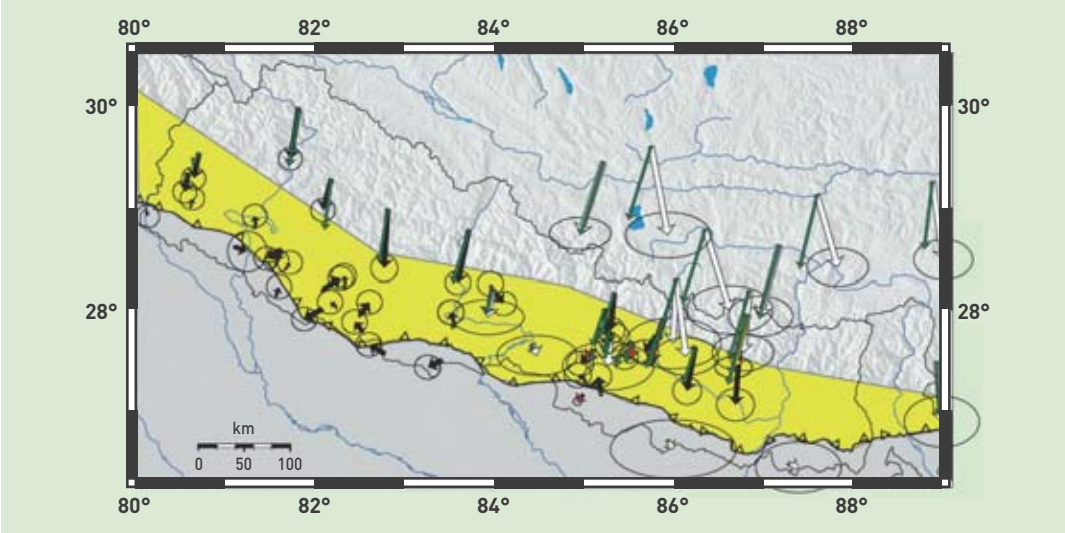


Figure 2.
Seismotectonic map centered on Nepal. The rupture zones for major historical earthquakes are shown in yellow. Blue arrows indicate the motion of India, relative to Eurasia, as derived from the NUVEL–1A global model. Red arrows show the motion of India, relative to Eurasia, as determined by Bettinelli *et al.*[7]



[Taken from Bettinelli *et al.*[7]]

Figure 3.
Observed velocities of GPS stations, relative to India. Red arrows correspond to the permanent GPS array, the yellow arrow corresponds to the DORIS system, black arrows stand for GPS campaigns, white arrows for other networks, and green arrows for modeled velocities. The yellow area shows the geometry of the blocked zone of the MHT.

related to surface loading due to water storage in the Gangetic Plain.[8]

Investigation of the Africa–Europe motion

Seismic risk assessment entails taking into account active, seismogenic faults in the region being investigated. Across mainland France, such faults are still inadequately known, while their velocity, lower than, or equal to 1 mm/year, is not readily evaluated, owing to lack of data, and the weakness of the signals involved. Nevertheless, a low deformation rate, accumulating over many years, may result in an ensemble of elastic strains sufficient to cause moderate-to-strong earthquakes, along active faults involving a long recurrence period.
Seismicity, across France, is attributed, as a rule, to the convergence of the African, and Eurasian Plates, which

(8) P. Bettinelli, J.-P. Avouac, M. Flouzat, L. Bollinger, G. Ramillien, S. Rajaure and S. Sapkota, "Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology", *Earth and Planetary Science Letters*, vol. 266, issues 3–4, 2008, pp. 332–344, DOI: 10.1016/J.epsl.2007.11.021.

CNRS Photothèque/Michel Faure

General view of the French–Italian Alps. Convergence of the African, and Eurasian Plates is driving deformations that have resulted in the formation of the Alps Mountain Range. Measurement of present deformation, and understanding the mechanisms it involves, and its relationships with major, large-scale geological structures: such is the purpose of investigations relying, in particular, on GPS measurements obtained by the RENAG network.

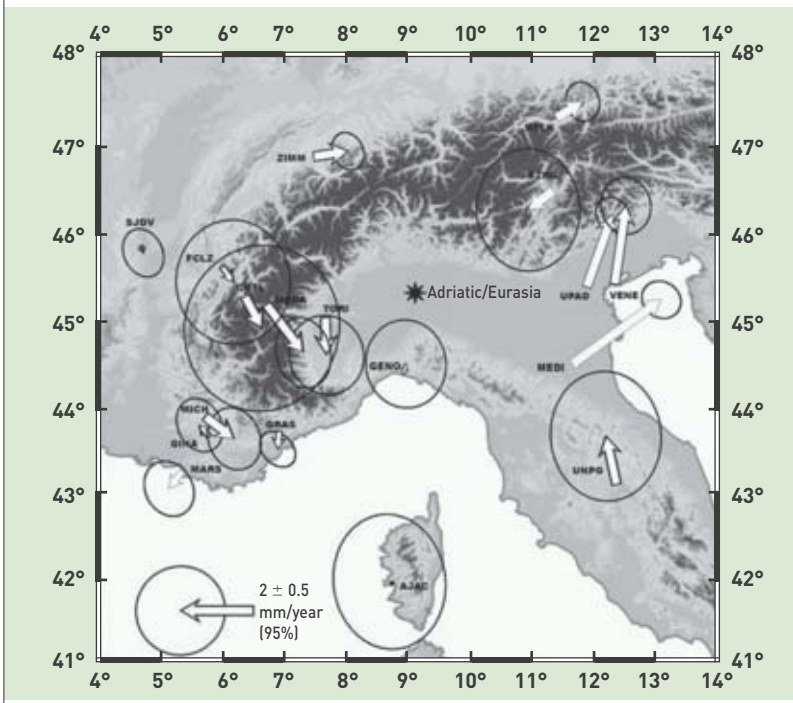
TENC permanent GPS station (Tence, Auvergne *département*, central France), set up by DASE for the purposes of monitoring the Cévennes Fault.

CEA/DAM

are coming together at a rate of about 5 mm/year, along the relevant longitudes for France. However, the shortening mode, between these two plates, does remain inadequately ascertained. In the context of seismic hazard investigations at the scale of mainland France, CEA has been collaborating, since 2000, in the REGAL (Réseau GPS dans les Alpes) Alpine GPS Network project, set up in 1997, this subsequently becoming RENAG [see note (1), p. 95]. One of the prime aims of that project was to investigate tectonic deformation in the Alps. Two permanent GPS stations were set up by DASE in the Provence region (southern France), to monitor the Nîmes (CHRN) and Cévennes (TENC) faults. Initial findings from GPS campaigns, carried out in the Alps by members of the French scientific community, and from the REGAL network,[9, 10] have already yielded new evidence. The deformation field, in the western Alps, evidences a combination of east–west extension, and dextral **strike–slip** faulting. The hypothesis of an independent Adriatic microplate, rotating anticlockwise relative to Europe, is thus corroborated (see Figure 4). This would control the deformation regime, along its boundaries in Friuli (northern Italy), the Alps, and the Apennine Mountains in central Italy. The relative motion of the African, and European Plates, in the western Mediterranean, would be some 40–50% slower than predicted by geological models, and along an oblique direction (20–30°, measured anticlockwise). Most of the Africa–Europe convergence thus appears to be absorbed, at the present time, across North Africa, and the southern Iberian Peninsula, with very little by way of deformation being transferred to the Alps.

(9) C. Vigny *et al.*, "GPS network monitors the western Alps' deformation over a five-year period: 1993–1998", *Journal of Geodesy* 76, 2002, pp. 63–76, DOI: 10.1007/s00190-001-0231-8. J.-M. Nocquet and E. Calais, "Crustal velocity field of western Europe from permanent GPS array solutions, 1996–2001", *Geophysical Journal International* 154, 2003, pp. 72–88, DOI: 10.1046/j.1365-246X.2003.01935.x.

(10) J.-M. Nocquet and E. Calais, "Geodetic measurements of crustal deformation in the western Mediterranean and Europe", *Pure and Applied Geophysics* 161, 2004, pp. 661–681, DOI: 10.1007/s00024-003-2468-z.



(Taken from J.-M. Nocquet and E. Calais[10])

Figure 4.
Deformation velocity vectors over the Alps, and the northern section of the Apennines, and velocity vector for the Adriatic Plate, relative to Eurasia, as derived from the French RENAG, and European permanent GPS networks. Owing to uncertainties, the point of every arrow is located within a black ellipse, showing a 95% confidence interval.

Fruitful collaborations

Direct GPS measurements prove to be indispensable, and informative, for the purposes of investigating deformations of the Earth's crust, in the context of seismic risk assessment, and understanding the relationships between deformation, and seismicity. The acquisition of new data is ongoing in Nepal, through a tripartite collaboration between DASE, DMG, and California Institute of Technology (Caltech), along with collaborations at the national level in mainland France, a region involving lower deformation. The results obtained, from GPS short-term space geodesy data, over some 20 years, and from geodynamic models built up on the basis of long-term data, do still call for discussion.

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How may **tsunami prevention**, and **prediction** be achieved?

The disaster that occurred on 26 December 2004, in the Indian Ocean, gave a new dimension to tsunami investigation, and prevention programs. With the contribution made by CEA, France stands, in this area, as a leading player on the international scene.

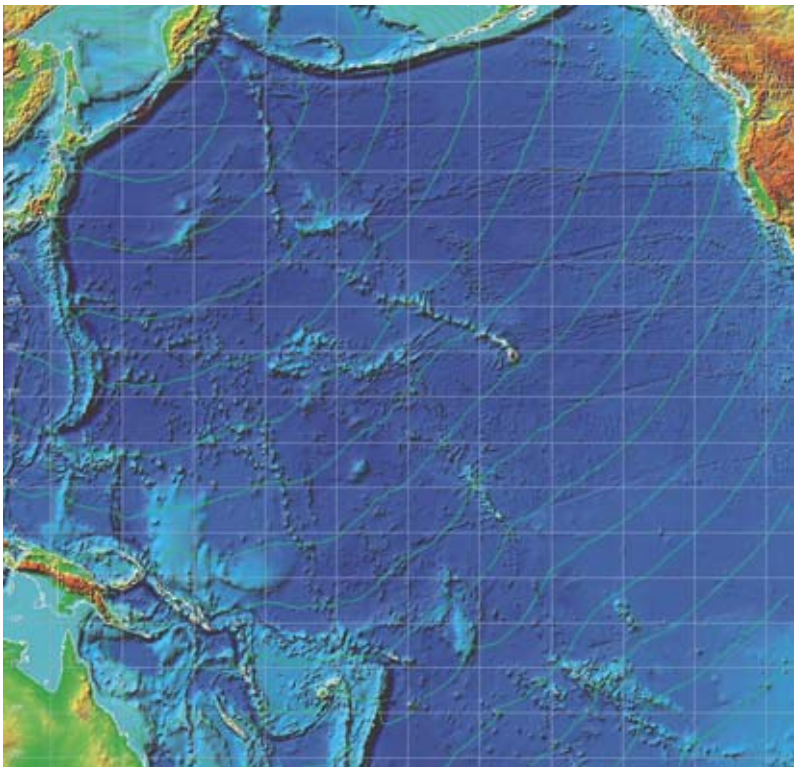
Since 26 December 2004, awareness of the **tsunami** phenomenon has greatly increased. CEA has been a participant in a number of research projects, launched following that event, thus giving a further impulse to the organization's activities in the area of **numerical simulation**, and tsunami alert. These various areas were already well to the fore, owing to CEA's participation in the **Pacific Tsunami Warning System**, with specialists gaining from that experience, to meet the new challenges set, in terms of prevention, and prediction.

Did tsunamis exist before 2004?

The disaster that took place on 26 December 2004, in the Indian Ocean, shocked the entire world, an emotion amplified by unprecedented media coverage, and accompanied, for many people in this part of the world, by the discovery of that extraordinary phenomenon, a major ocean-wide tsunami. Geophysicists had long since ascertained the characteristics of tsunamis (see Focus E, ***How does a tsunami arise, and propagate?*** p. 105), thus recording recent events, that had proved liable to cause large-scale destruction, and hundreds of casualties, subsequent to an **earthquake**, or a submarine landslide (1998, Papua New Guinea: about 2,000 casualties in fishing villages), but equally liable to have a moderate impact across a sea that seemed relatively immune from such concerns, within a human timescale at any rate (2003, following the Boumerdès earthquake, in Algeria: causing much damage in ports, and some point flooding in the Balearic Islands, along with a degree of swell in some harbors along the French Côte d'Azur).

That event in the Indian Ocean altogether altered the perception of the phenomenon, and jolted into awareness an entire population of scientists, and policymakers. Large numbers of research scientists, and institutions started focusing on the hitherto largely ignored phenomenon.

At CEA, the issue had been a matter of interest since the 1960s. At that time, under the aegis, internationally, of the Intergovernmental Oceanographic Commission (IOC) of UNESCO (the United Nations Educational, Scientific, and Cultural Organization), the first tsunami warning system was being deployed in the Pacific Ocean, with its operational center based in Hawaii, which had been heavily affected by a number of major ocean-wide tsunamis across the years, from the 1940s through to the 1960s. The French presence, and CEA involvement, in the Pacific resulted in CEA's laboratory on Tahiti Island (one of the Society Islands, French Polynesia) becoming a participant in this warning system, from the very first years of its deployment – and the legacy of that contribution, at the present time, is the only operational tsunami warning center to be run by France: the Polynesian Tsunami Prevention Center (Centre polynésien de prévention des tsunamis), based in Tahiti.



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Computation of arrival times, in the Pacific Ocean, for the tsunami triggered subsequent to the strong earthquake, of magnitude 8.3, that occurred in the Kuril Islands, in the North Pacific, on 15 November 2006. This shows French Polynesia was affected some 11 hours after the earthquake, each line being 1 hour apart.

Understanding, and preventing the tsunami risk

From the 1960s on, CEA has made a strong contribution to the understanding of tsunamis, and tsunami prevention, and warning, along two complementary directions. The first area concerns the use of numerical simulation techniques, for risk assessment purposes, through the validation of **computation codes**, on the basis of observations of recent events, and the simulation of possible scenarios, to suggest lines of action

CNRS Photothèque/Franck Lavigne

The beach at Lhok Nga, in January 2005, showing the devastation caused during the Sumatra tsunami of 26 December 2004; in the background, to the right, the 15 m-high traces left by breakers on the hill slopes.

CEA/DAM

The effects of tsunamis in Tahauku Bay, near Atuona, on Hiva Oa Island (Marquesas Islands). These tsunamis originated in Chile (30 July 1995, magnitude 8.0: photographs at left, and center), or Peru (21 February 1996, magnitude 7.5: photograph at right), and only caused material damage.
On the other hand, there was considerable disruption of shipping, and on nearby shores; fairly major inundations occurred close to this small harbor. Numerous eddies, and strong currents thus carried boats outside the harbor, such phenomena being liable to last several hours.

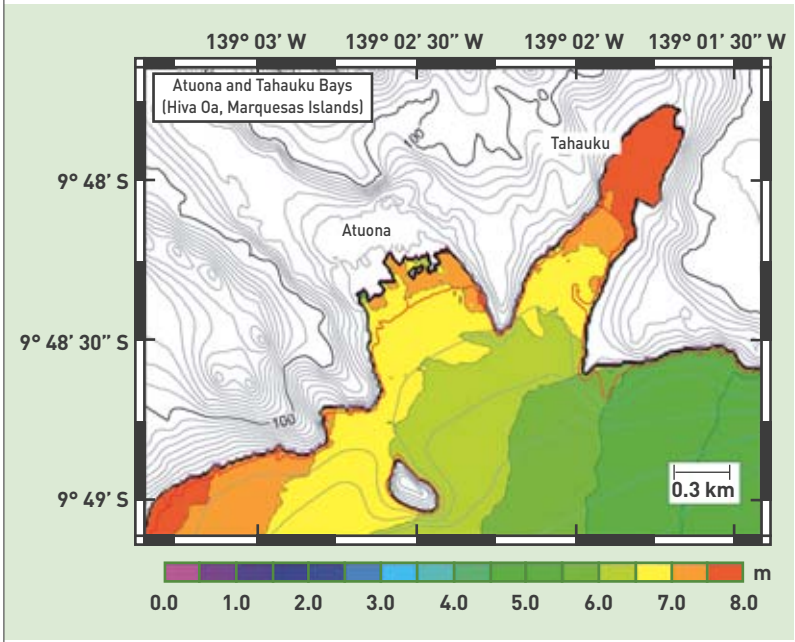

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Figure 1.
Maximum inundation runups for two bays in the Marquesas Islands, as computed according to 5 maximizing Pacific-wide tsunami scenarios. The initial coastline is shown by the red line, indicating inundations that may extend horizontally to 300 m (Atuona), or even 600 m (Tahauku). Such inundations occurred, during the 20th century, on 3 or 4 occasions in these bays.

for the purpose of *risk prevention*. The second direction involves the development of *real-time monitoring and warning methods*, on the basis of seismic recordings, in order to alert, at the earliest time – and only in the event of actual danger – civil defense organizations.

With respect to the first point, work carried out at CEA has long focused on the Pacific Ocean. Available statistics, and known events show that this is the most heavily affected basin, and the Polynesian territories, located as they are at the center of this ocean, are potentially exposed to all major tsunamis originating in the **subduction zones** surrounding the region, an event that occurs some 5 to 7 times in a century. Investigation of past events had shown that some of the Polynesian islands were systematically more heavily impacted than the others: the Marquesas Islands (French Polynesia). In this archipelago, wide bays lie directly open to the ocean, with no protective coral reef, and inundations have occurred several times per century. Locally, indeed, the language spoken in the Marquesas has a specific word for that notable phenomenon, of the sea's anomalous overflow: the *Tai Toko*.

Investigations were carried out by means of numerical simulation, in particular under the aegis of the recent ARAI project (*arai* signifying "to protect," in the Polynesian language), for which CEA conducted seismic, and tsunami risk assessment studies. The findings confirmed the vulnerability of the bays involved, chiefly with regard to tsunamis originating in South America, but equally in the Aleutian Islands, the Kuril Islands, or Tonga. The probability of inundations exceeding a runup of 3 m may be estimated as standing at more than 4 times per century (see Figure 1). The other Polynesian archipelagos prove less sensitive in this respect, some of these however, e.g. the Society Islands, and Austral Islands, being liable to be affected by waves of up to 3 m, 2 times per century. Such investigations make it possible to draw up risk prevention plans (PPRs: *plans de prévention des risques*), through the mapping of inundation zones.

Since 2004, CEA has been a participant in a number of research projects, initiated following the Indian Ocean disaster. As regards the French TSUMOD program, funded by the French National Research Agency (**ANR: Agence nationale de la recherche**), and steered by CEA, numerical simulation tools had to measure up to the exceptional database gathered, regarding the 2004 event, on the shores of the Indian Ocean, but equally to other existing simulation tools. The results obtained show that simulations based on precise knowledge of the local topography allow a quite satisfactory reproduction to be achieved, of the sequence involved in the catastrophic inundations that occurred at Banda Aceh, on the Indonesian island of Sumatra (see Figure 2), further emphasizing that such simulations should be carried out for exposed sites, well before such an event occurs. Concurrently, simulation tools are being refined, to take into account the largest possible amount of detail, with regard to the source, computation of local amplification processes, and estimate of synthetic marigrams (i.e. the modeling of changes in water levels in a harbor, or a bay, to be compared with actual **marigrams**, these recording, in particular, high and low waters, but equally the arrival of tsunamis).

CEA had previously taken part in the European GITEC (Genesis and Impact of Tsunamis on European Coasts), and GITEC–TWO research projects, in the 1990s, in particular with the investigation of European tsunamis, specifically those that occurred in Portugal (1755, 1969). The TRANSFER (Tsunami Risk and Strategies for the European Region) project (2006–2009) was likewise supported by the **European Commission**, under the aegis of the 6th Framework Program for Research and Technological Development (**FP6**). This had the purpose of revising historical catalogs of tsunamis, drawing up inundation maps for a number of test sites, and bringing forward tools for the purpose of the future deployment of a warning system. Under the aegis of the TRANSFER project, CEA conducted investigations on the impact of tsunamis on the Balearic Islands, and in the Sea of Marmara (dividing the European, and Asian parts of Turkey), while reconsidering the tsunami risk in the western Mediterranean, which is poorly known.

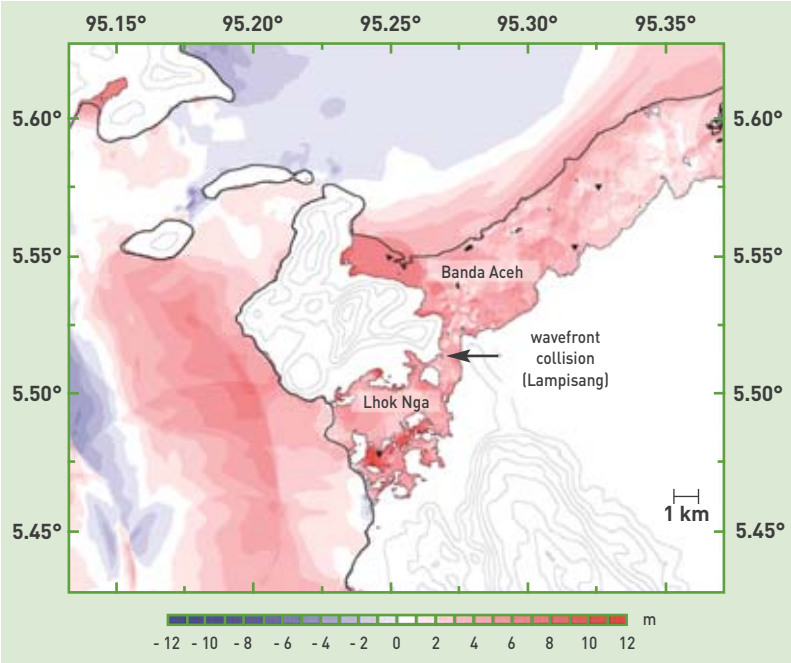

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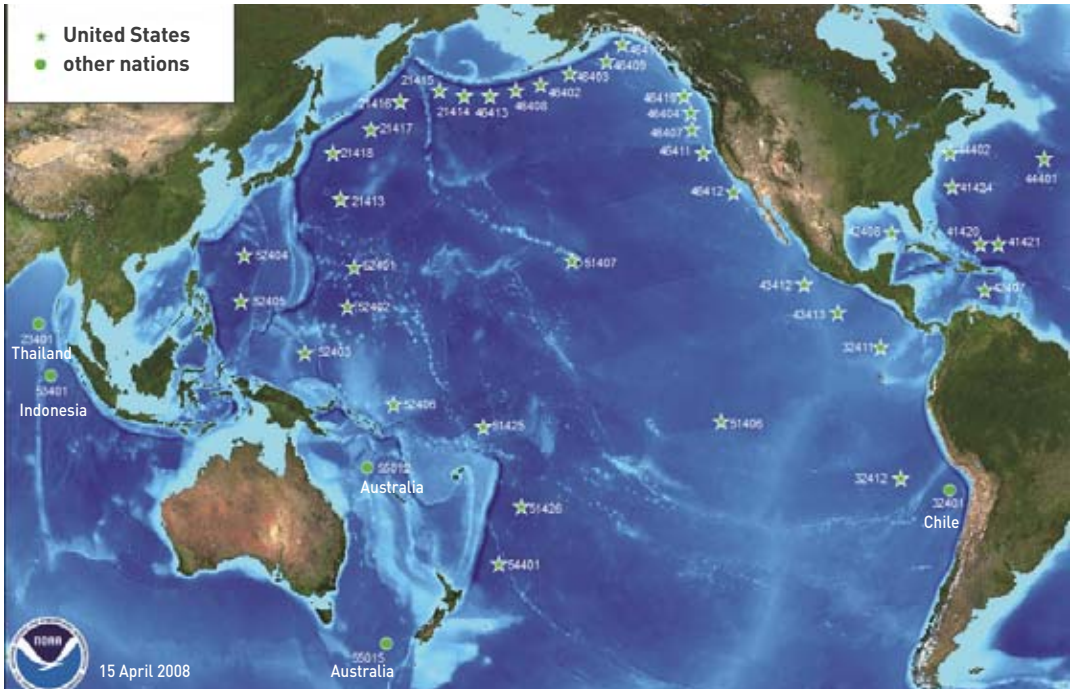
Figure 2.
Inundation in the Banda Aceh area (northernmost tip of the island of Sumatra), as simulated on the basis of a precise numerical model of the ground, using the characteristics of the earthquake of 26 December 2004. The initial coastline is shown by the thick black line. This simulation mimics the extent of the inundations, and the meeting of floodwaters.

Towards tsunami warning systems in every ocean

Since 2004, the international community, again acting under the aegis of UNESCO, has initiated warning systems for all of the exposed basins. CEA is taking part, in particular, in the construction of the forthcoming North-East Atlantic and Mediterranean Tsunami Warning System (NEAMTWS). The ensemble of studies carried out in the area of prevention is serving as a basis for, and feeding into, the discussions concerning the deployment of these systems, by making it possible to refine warning criteria. Indeed, an effective warning system should only be triggered in the event of potentially hazardous occurrences, and must, most importantly, preclude false evacuation warnings, which would discredit it. It should be emphasized that most tsunamis involve danger only at a local scale, within 100 kilometers or so from the source, or at a regional scale (< 1,000 km). Only a few events involve a potential for destruction more than 1,000 km away from the source, such as would be liable to cause catastrophic inundations at many sites.

Predicting a tsunami comes down, essentially, to two complementary sets of approaches, and findings. The first one makes use of the findings from the above-mentioned prevention studies, in the form of databases of past tsunamis, complemented by simulations of likely scenarios. Findings from such investigations contribute not only to the drawing up of risk prevention plans, but are also used in the event of an alert, for the purposes of ascertaining the potentially exposed areas.

The second approach concerns the real-time prediction of a tsunami, as an earthquake occurs. The starting



NOAA Center for Tsunami Research

The Deep-ocean Assessment and Reporting of Tsunamis (DART) buoy network, positioned across the Pacific Ocean to monitor in real time the evolution of tsunamis, by measuring wave height, and for the purposes of warning exposed distant coastlines.

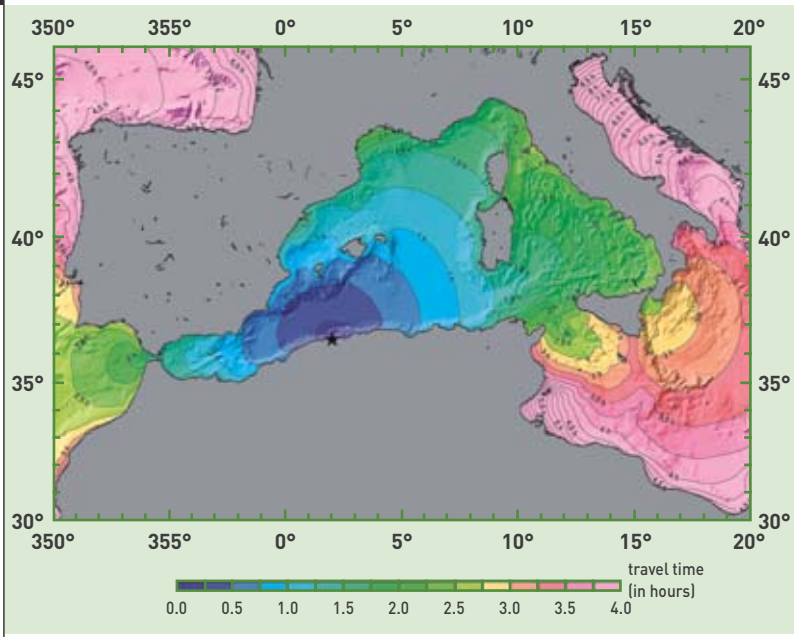


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Figure 3.
Simulation of tsunami arrival times, for a source located at a hypothesized **epicenter** in western Algeria. Coasts around the western Mediterranean are reached, potentially, from 15 to 120 minutes after an earthquake.

CEA/DAM

A view of the marigraph at Rikitea (Gambier Islands, French Polynesia), a device used to record variations in sea level. The data acquisition and transmission system is positioned sufficiently high above the ocean, to cater for very high waves.

point is the detection, as swiftly as feasible, of the source event, in order to characterize its **magnitude**, and location: this is a challenge that seismologists are currently able to meet within less than 15 minutes. Concurrently, there must be an ability to predict, with the highest possible precision, which are the zones potentially under threat of a tsunami, where it will be necessary to proceed with getting the population to safety. This is crucial in regions such as the Mediterranean, where the time interval between the earthquake, and arrival of the leading wave is extremely short, standing at a few tens of minutes (see Figure 3). For that purpose, it will be useful to use the results from the hundreds of scenarios that have already been run, and compare the simulated signals with actual recordings from sea-level monitoring stations, and, finally, take on board the relationships between these two signals, in order to recompute tsunami inundation, along the coastline. This method is currently being tested at the **Pacific Tsunami Warning Center** in Hawaii, and should be implemented in warning centers across the Pacific in the coming years.

An active contribution

CEA has been acting, since the 1960s, as the French representative in the Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System (ICG/PTWS). It is contributing to the various underlying scientific components: risk assessment, and improvements to detection, and warning systems. CEA has indeed been commissioned, in this respect, by the French State Secretariat for Overseas Territories, with the remit of defining the architecture of the sea-level monitoring network, appropriate for the regions of New Caledonia, the Loyalty Islands, and Wallis and Futuna Islands, along with the warning criteria for these several islands, and for Reunion Island, for the purposes of drawing up the specific Tsunami warning and emergency relief plan. Currently, CEA has been designated by the French government to act as coordinator for the forthcoming North-East Atlantic and Mediterranean Tsunami Warning System. The planned center, scheduled to become operational in 2012, will be hosted at the Bruyères-le-Châtel (Essonne *département*, near Paris) site, and will be specifically responsible for issuing the alert warning for the western Mediterranean, under the aegis of the international system now being set up. In this respect, CEA is to act as the tsunami "focal point" in the North-East Atlantic and Mediterranean Group; and the organization is a participant in the working groups set up to prepare for the North-East Atlantic and Mediterranean Tsunami Warning System.

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FOR FURTHER INFORMATION

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FOCUS E

How does a tsunami arise, and propagate?

The initiating event, for a tsunami, is a sudden geological event (submarine earthquake, volcanic eruption, cliff failure...), disturbing the initially quiescent ocean (see Figure). This phenomenon is quite distinct and separate from tsunami-like occurrences, due to meteorological causes. Close to the source, the ocean begins to oscillate, being brought back to equilibrium by gravity, this generating a train of waves, involving wavelengths of up to 40–300 km, propagating in all directions. Barely perceptible in the high sea (involving as they do amplitudes ranging from a few centimeters to several tens of centimeters), these waves undergo amplification as the seafloor rises closer to the surface, i.e. near shores, tsunami velocity then slowing down to a few tens of kilometers per hour, compared with 500–1,000 km/h in the deep ocean. Owing to the conservation of energy, as wavelength shortens, wave amplitude rises: a wave less than 1 meter high in the deep ocean may rise up, in excess of several tens of meters at the coastline. This is where the tsunami results in the sea overflowing, causing inundations that may penetrate far inland, in some cases.

For a submarine earthquake to cause a tsunami, it must occur at shallow depth (less than 50 km), and involve a magnitude of 6.5 at least. Above a magnitude of 8, an earthquake can generate a potentially destructive, ocean-wide tsunami. Host as it was to 5 major tsunamis during the 20th century, the Pacific region was already well identified as a risk area, before the occurrence, on 26 December 2004, off the northwestern tip of the Indonesian island of Sumatra, in the Indian Ocean, of the largest event to have arisen in that region, since the setting up of worldwide seismic networks, with a magnitude estimated at 9.2. The fault involved ruptured over a length close to 1,500 km. Rupture duration was more than 9 minutes, the rupture causing displacements of as much as 15 m. More than 500 aftershocks[1] were detected in the hours that followed. The tsunami inundated coasts over distances of several kilometers, across relief that was very flat in the main, up to an elevation (runup) of 20–30 m; it ultimately caused about 280,000 casualties. In the Mediterranean, tsunamis are a more infrequent occurrence.

(1) Earthquakes of smaller intensity, following the largest (the so-called main shock) in a sequence of earthquakes located within a proximate zone.

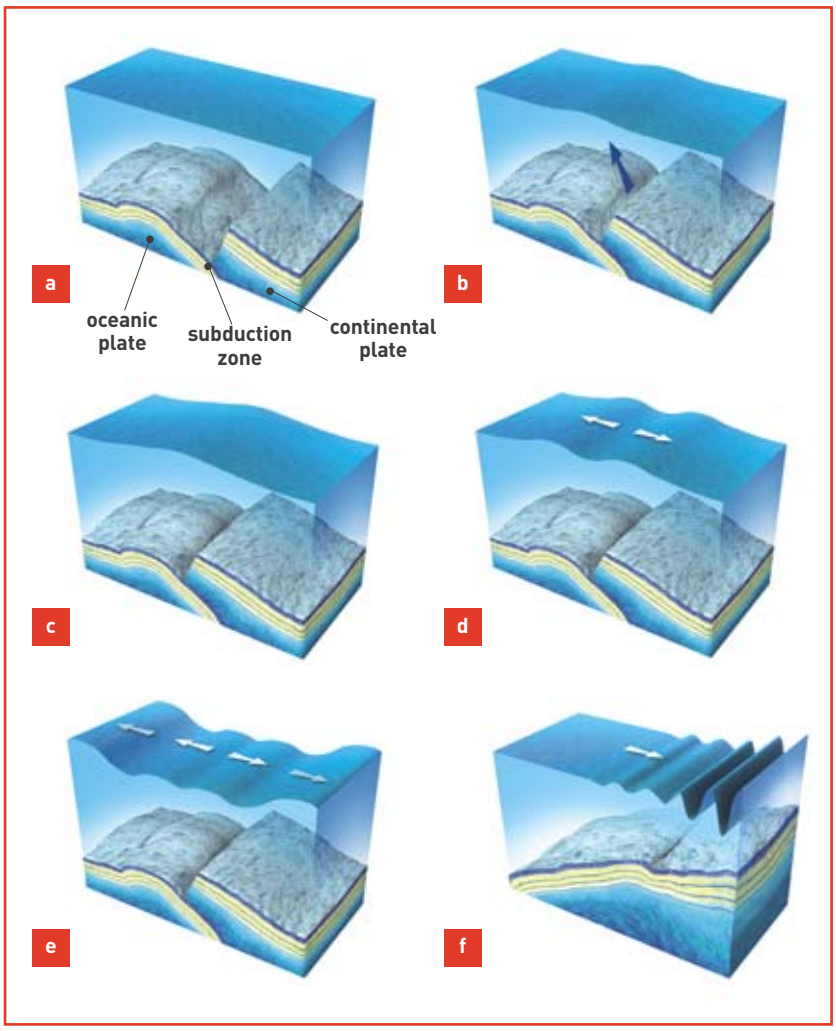

Figure.
A situation involving a subduction zone, where an oceanic plate is slipping under a continental plate (a). In a strong earthquake, the overthrusting continental plate is abruptly uplifted by several meters, pushing upward the overlying volume of water (b). The surface bulge (c) begins to propagate in all directions (d). Subsequently, the wave train increases in intensity (e). As the seafloor rises closer to the surface, near the shore, the waves slow down, even as they gain in amplitude (f). They may reach distant coastlines, thousands of kilometers away, where inundations may affect locations at up to several meters elevation, in extreme cases.

No destructive tsunamis have occurred there, since the 1956 event in the Aegean Sea, involving waves rising up to 10 m on the Greek coastline. In the Atlantic Ocean, the last major tsunami is the one that devastated Lisbon (Portugal), in 1755.

Aside from strictly seismic detection resources, specific resources are deployed, for the purposes of characterizing tsunamis. Monitoring stations provide, in real time, sea level measurements (marigraphs set up on the coastline, which monitor sea level, and yield marigrams; or offshore tsunameters, linked to pressure sensors positioned on the sea floor), allowing the evolution of the ocean's level to be monitored over time. Satellites, including e.g. the French–US JASON satellites, likewise provide precise measurements of ocean surface levels, however they are of no use for tsunami warning purposes. For major tsunamis, as e.g. the 2004 event, inversion of the altimetry data thus obtained makes it possible to provide a description of the tsunami source. The ensemble of marigraph, and satellite data may thus be subjected to inversion, to determine the tsunami source, using an approach comparable to that implemented by seismologists, to determine earthquake sources from seismograms.

Radon, an atmospheric **tracer**

Owing to its natural radioactivity, radon produced in the Earth's crust is already yielding crucial information, with respect to atmospheric transport. Presently, it is further used to monitor greenhouse gas fluxes in the atmosphere. Research scientists hope that this noble gas, which is a very good tracer of air masses, will further improve the quantification of releases, and fluxes of such greenhouse gases such as CO_2.

CEA/DR

The Mace Head observatory (Ireland).

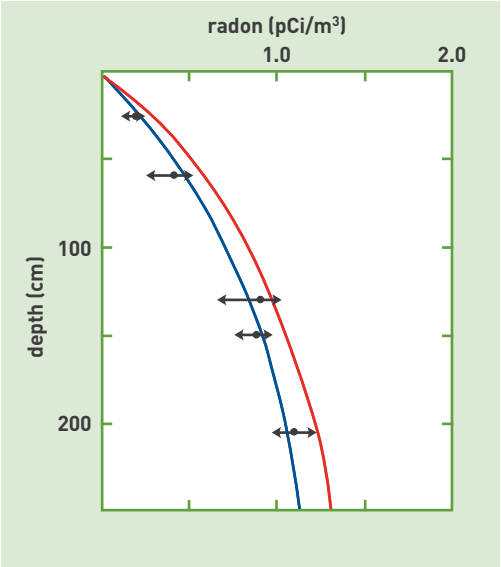

Figure 1.
Typical variations in ^{222}Rn concentrations, as a function of soil depth. The *x*-axis shows ^{222}Rn concentrations (pCi/cm^3), as measured in the ground (1 pCi = 0.038 Bq), while the *y*-axis shows soil depth (cm). The fall in concentrations close to the surface should be noted.

Radon stands apart from the other gases present in the **atmosphere**, owing to its natural **radioactivity**. It is one of the noble gases. The radon-222 **atom** is formed from the **decay** of **radium-226**, one of the daughter products in the decay chain of **uranium-238**, the most prevalent form of this mineral. Occurring as it does in virtually all rocks, in minute amounts (1–10 parts per million), uranium stands in radioactive equilibrium with all of its daughter products, down to radium. Formation, and **decay** rates, for the various **radionuclides** involved, are thus about equal, corresponding to the generation of 0.7–7 atoms of radon (radon-222) per minute, per gram of material. A tiny fraction of this radon, yielded by rocks, is able to escape into the atmosphere, and, if it is trapped in soil, the radon atom reaching the Earth's surface decays, following the uranium chain. Measurements, carried out at the Earth's surface, over large areas, have shown that the radon flux stands, on average, at around 1 atom cm^{-2} s^{-1} (see Figure 1).

As CEA research scientists, led by Jacques Labeyrie and Gérard Lambert, were measuring the radon flux emanating from soils, and radon concentrations present in the atmosphere, a team from the **Lamont–Doherty Earth Observatory** at **Columbia University** (New York [USA]), led by Wally Broecker, was measuring even smaller quantities of radon in seawater. Computations, taking into account gas exchanges between the ocean, and the atmosphere, further showed that the radon flux emanating from the ocean turns out to be a hundred times smaller than the one from continental surfaces.

This difference, found between oceanic and terrestrial radon fluxes, has allowed researchers to clarify a number of aspects of atmospheric dynamics, and transport, that were not previously understood. Thus, in the absence of these investigations on radon, valuable information could never have been collected. The findings made, over the past three decades, have thus made it possible to shed light on a whole range of issues.

Air masses over the oceans: transit times, and active exchange periods

As regards the Atlantic, Pacific, Indian, and Southern (or Antarctic Circumpolar) oceans, it should be understood that, owing to the distribution of land masses across the Earth's surface, but equally owing to radon fluxes standing at about 1 atom cm^{-2} s^{-1} over land areas above water, oceanic radon concentrations vary, on average, from 35 m**Bq** m^{-3} to 70 mBq m^{-3} (see Figure 2). Further more, the radioactive half-life of radon of 3.8 days must also be taken into account. From all these data, it may be understood that radon concentration, for an air mass sweept away from a continent with a concentration of 50 mBq m^{-3}, subsequently in transit over the ocean for 10 days, with no encounter with another continent, sees its concentration fall to 8.1 mBq m^{-3}. Such results show how, in the absence of any dilution process, radon concentration, in that air mass, makes it possible to date its last encounter with a continent. This essential property was used to show that some air masses cross the Pacific Ocean in less than 5 days, i.e. 3 times faster than any other means of marine transport. To account for such record transit times, research scientists carried out measurements, using airplanes specially outfitted for the purpose of sampling air at high altitude. Their findings show that, in spring and summertime, air lying at the surface of the continent of Asia is initially transported at altitude, and subsequently carried, by high-altitude (about 10 km) in **jet streams,** across the North Pacific. Caught by descending currents, this air mass then reaches the lower layers of the atmosphere above the North American continent. Thus, by way of measurements, and **modeling** of radon in three-dimensional models of the atmosphere, research workers were able to evidence the major mechanism involved in intercontinental pollutant exchange.

			half-life $T_{1/2}$
	$^{238}_{92}U$		
gaseous element	$^{222}_{86}Rn$		3.825 days
short-lived radon-222 daughter products	$^{218}_{84}Po$	(RaA)	3 minutes
	$^{214}_{82}Pb$	(RaB)	26.8 minutes
	$^{214}_{83}Bi$	(RaC)	19.7 minutes
	$^{214}_{84}Po$	(RaC')	$1.5 \cdot 10^{-4}$ s
first long-lived element in the decay chain, ß-emitter at 0.017 MeV	$^{210}_{82}Pb$	(RaD)	20.4 years
ß-emitter at 1.17 MeV	$^{210}_{83}Bi$	(RaE)	5.02 days
α-emitter at 5.30 MeV	$^{210}_{84}Po$	(RaF)	138.3 days
	$^{206}_{82}Pb$		stable

Table.
The radon-222 decay chain.

Exchange times between lower, and higher layers of the atmosphere

A number of **vertical profiles** of radon concentration, as measured above continental landmasses, show that atom numbers decrease by a factor 10–100, on average, as elevation increases, above the Earth's surface, up to an altitude of 12 kilometers. Taking these vertical profiles together, along with the averages for two

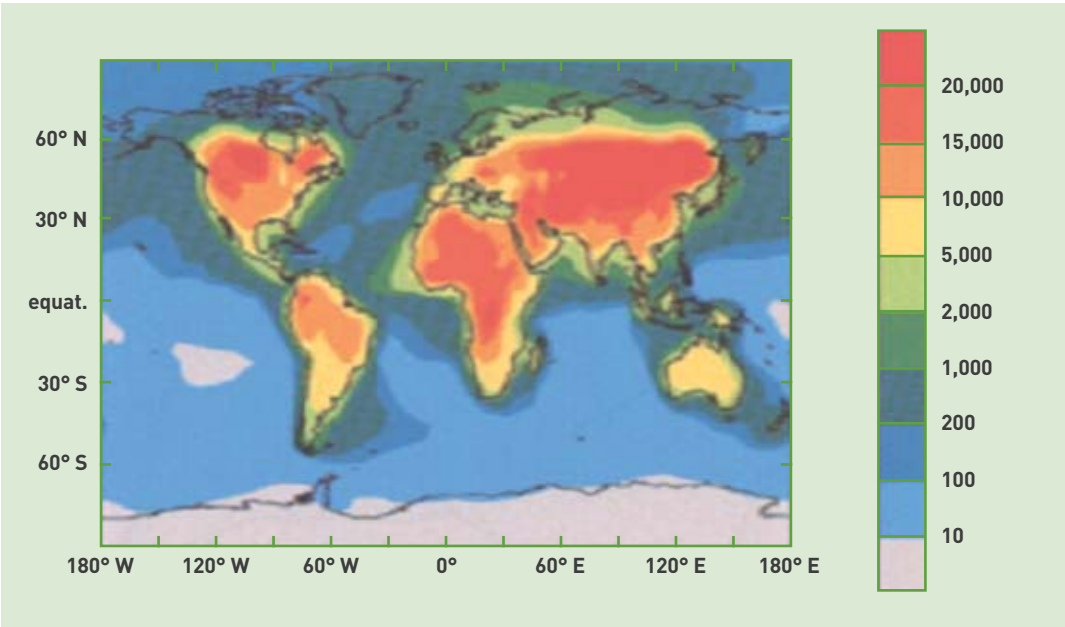

Figure 2.
Airborne radon concentration in the surface layer of the atmosphere (mBq·m^{-3}). Strong concentration gradients arise between continents, and oceans.

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The tower at Traînou, in the forest near Orleans (central France), from the top of which LSCE teams carry out CO_2 measurements. The tower rises to 180 meters.

seasons, summer and winter, a contrasted picture emerges: from 0 to 12 kilometers, radon depletion turns out to involve a factor 100 in wintertime, whereas only a factor of 10 is inferred for summertime. Only through atmospheric modeling could this seasonal difference be explained, it revealed its intimate connection to **convection**, arising over continents. Thus, in summertime, when considerable quantities of sensible heat are exchanged with the atmosphere, air rises rapidly from the surface to the upper layers of the atmosphere: for instance, a particle of air that has been in recent contact with the surface may be exchanged by way of rising **convection currents**, up to an altitude of 10 kilometers. Owing to such recent contact with the surface, the air at altitude is more strongly enriched with radon in summertime than in wintertime. At altitude, the difference in radon concentrations found for these two seasons is thus the outcome of convection processes.

"Radon storms" over the Indian Ocean

It was while carrying out routine radon measurements in the isles of the French Southern and Antarctic Lands (Crozet Islands, Kerguelen Islands, Amsterdam Island), and at Dumont-d'Urville (Adélie Land) that Georges Polian, a research engineer with the French CRNS, noted episodes, lasting some 10 hours or so, during which radon concentrations would take on quite unusual values, since they exceeded by 10- or 30-fold the regular background, measured year round. G. Polian gave such episodes the singular name of "radon storms." He went on to suggest that the radon thus measured did not come from the ground of these southern islands, on the basis of the **isotope** 220 of that gas. The explanation for such steep increases in concentration still needed to be uncovered, in long-distance transport processes. Two teams, from **Harvard University** (USA), and **Hamburg University** (Germany), working independently, accounted for these "radon storms" by way of atmospheric transport models. These researchers were thus able to show that this phenomenon arises from air masses that have been in recent contact with the African continent, prior to undergoing rapid transport by **advection** to the Crozet, or Kergelen Islands or Amsterdam Island. In such episodes, air is expelled from the continent owing to the pressure gradient between the passing of a low-pressure area, located to the south of South Africa, and the **Mascarene** High in the vicinity of Madagascar. There ensues a very strong air current, directed out to the ocean, subsequently funneling air from Africa to the subantarctic islands in only a few days.

Variations in radon concentrations between winter and summertime

As a rule, radon measurements carried out over continental sites show markedly higher concentrations in wintertime than in summertime. At first blush, this difference is not due to seasonal variations in radon flux, but rather to the ventilation occurring between the lower layers of the atmosphere (below 2 km), and higher layers (between 2 and 12 km). Indeed, in wintertime, exchanges between low-lying layers, and the free **troposphere** turn out to be supressed, whereas in summertime such exchanges become much more intense. Consequently, in winter, radon tends to stay confined in the lower layers of the atmosphere, resulting in increased concentrations close to the ground. By contrast, in summer, exchanges arising between the surface and the troposphere bring down, from high altitudes to the surface, radon-depleted air, resulting in dilution of concentrations, which accounts for the observations of lower concentrations.

Radon to make for improved quantification of CO_2 fluxes from soils

The ability of research scientists to make precise measurements of greenhouse gas fluxes stands as one of the major challenges for the future, if climate change is to be better understood. However, the proper determination of man-made fluxes entails, as a prerequisite, that natural fluxes be quantified, for such gases as CO_2, and **methane**. One of the existing techniques, the **eddy correlation** technique, involves the very precise measurement of concentrations, for a given gas, at two different altitude levels: from the differences recorded, between these two levels, an instantaneous flux may be derived. By way of a simple illustration of the way that flux may be derived, from concentration readings, let h be the height of the atmospheric boundary layer, uncoupled from the upper layers of the atmosphere, and lying close to the surface across which these gases are being emitted (typically, from 0.5 km to 2 km); the variation in the concentration, at time t, $C(t)$, of an atmospheric tracer, well mixed across that

P. Bazoge/CEA

Taking air samples above the forest near Orleans (central France).

atmospheric layer, is then solely dependent on height h, and may be expressed as follows:

$$\Delta C(t) = \frac{F}{h} t,$$

where $\Delta C(t)$ stands for the variation in concentration observed, from time 0 to time t. F, the flux of the gas being investigated, is assumed to remain constant over the time interval subject to the measurement. The same assumption is made as regards the height of the atmospheric boundary layer, h. Finally, the exchange flux between the lower (up to 2.5 km) and upper layers of the atmosphere (free troposphere, between 2.5 km and about 10 km) is assumed to be zero.

Unfortunately, such a flux, as measured by this technique, is only representative of a small area around the measurement point (typically, 1 km^2, under unstable atmospheric conditions). Flux values a few kilometers away from that location may be quite different. The notion fairly soon emerged, therefore, that precise concentration measurements might make it possible to quantify fluxes of such gases as CO_2, CH_4, and N_2O, by way of an adequate knowledge of large-scale (of the order of 100 km^2) ^{222}Rn fluxes. Let us then assume that the radon flux, over the region being considered, is known, with a fair precision (better than 30%, say); the ratio of the fluctuations in concentrations of the two gases, CO_2 and radon, may then be expressed as follows:

$$F_{CO_2} = F_{^{222}Rn} \frac{\Delta C_{CO_2}}{\Delta C_{^{222}Rn}}$$

A correction allows the fact to be taken into account, that oceans emit no radon. The accuracy of this method entails that a number of conditions be met, concurrently:

- a near-constant radon flux above the entire surface area being considered;
- radon and CO_2 sources subject to variations in an identical manner, in spatial terms;
- knowledge of the time spent by the radon involved above oceans;
- identical properties, for both gases, with respect to their destruction, or generation, in the atmosphere.

While the second, and fourth conditions do turn out to be not fully met, a number of teams from CEA, and other institutions, have been able to put this method to good use, for the purposes of greenhouse gas measurements.

Michel Ramonet->LSCE/CEA-CNRS-UVSQ

Airborne atmospheric CO_2 measurement system.
Top, sample flask carrying case; middle, the continuous CO_2 measurement instrument, dubbed Condor; bottom, cylinders holding compressed air, used as reference by the instrument.

To sum up, radon yields crucial information, with respect to the understanding of atmospheric transport. A noble gas, it may be of use not only for the investigation of dynamic processes in the atmosphere, but also for the understanding of long-distance transport. More recently, a new, highly promising avenue has opened up, that will without doubt allow the quantification of greenhouse gas releases, and enable better deployment of actions that may help curb climate change.

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FOR FURTHER INFORMATION

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Nucleonic tracers and gauges highlight **sediment dynamics** in **fluvial** and **coastal** environments

Fluid mechanics proving unable to describe the phenomena involved in sediment transport by dint of equations only, the contribution from nucleonic techniques will help shed light on the sedimentological issues raised by the action of currents and swell.

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The oceanographic vessel *Hermano Ginez*, during a tracer detection operation, for the purposes of measuring dispersion coefficients in the Rio Orinoco River (Venezuela).

Sediment transport processes induced by the action of currents and swell remain as yet inadequately known, despite the economic burden of the structures, and works programs required to take into account their detrimental effects. Such effects include, in particular, silting up of dams, operating difficulties for overflow evacuation systems, the impact of draining slushes operations, coastal erosion, dredging operations, discharges of all sorts into the aquatic environment, of pollutants in particular…

Even with the benefit of the most sophisticated theories, fluid mechanics still proves unable to solve the problems that arise in this respect, solely by way of equations. As a result, experiments and measurements remain indispensable, be it for natural environments, or physical models. Now, the lack of resources to carry out such measurements is hindering endeavors to understand the physical processes involved in solid transport, and, even more so, attempts to estimate their intensity. This accounts for the rise, and development of **nucleonic techniques** (tracers, and **gauges**), making use of ionizing **radiation**–matter interactions, and their ongoing enhancement. These techniques, indeed, afford valuable advantages, owing to their specific characteristics, making it possible to carry out:

- direct measurements of tracers, in natural as in physical model conditions;
- **Lagrangian measurements** of motions, with the observation of images of tracer spatial distribution at any given time;
- measurements involving the monitoring, on a small fraction (tracers), of sediment content, ensuring fast sounding of phenomena;
- continuous **turbidity** measurements, even through an opaque wall…

These techniques were developed, in a practical manner, in endeavors to anticipate, and meet the demands of users such as certain port authorities, in France or from other countries, hydraulics laboratories, French government local roads and infrastructures agencies, universities, the French Center for Maritime and Waterways Studies (Centre d'études maritimes et fluviales), the French Research Institute for the Use of Marine Resources (**IFREMER: Institut français de recherche pour l'exploitation de la mer**), or such international organizations as the **International Atomic**

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Lowering a radiotracer detection sled into the water, for the purposes of measuring bedload transport of sand in the littoral zone.

Energy Agency (**IAEA**), and the **International Water Management Institute**. Currently, alongside radioactive tracers, nonradioactive tracing techniques are being developed (whether **fluorescent**, or radioactivable, magnetic…). The very wide range of performance they afford make it possible to respond to issues for which radioactive tracers are ruled out.

Tracers

The use of tracers, nowadays, is a well-known technique. The first step involves introducing a **sediment**, labeled by means of an **element** exhibiting a specific, measurable property, into the zone subject to investigation. The subsequent step has the object of monitoring the motions, as a function of space and time, of the cloud formed by the labeled particles, which calls for the use of appropriate detectors, or sampling. The cycle is completed with the interpretation of the quantitative findings, taking into account hydrometeorological parameters recorded at the same time. Since the data thus collected have a global character, this is known as an integrating method. In effect, it appears it is not feasible to record such fundamental parameters as critical entrainment velocity, or floor surface roughness. For such experiments, researchers use two kinds of tracers.

Radioactive tracers

Currently, specialists can draw on a large number of **radionuclides** (see Table), enabling them to address, in natural or laboratory conditions, the various "sedimentological" issues, relating to a very wide range of particles, from silt to gravel:

- for gravels (involving diameters larger than 5 cm), labeling is effected individually, with a radioactive source consisting of a metal wire, of **iridium-192**, **tantalum-182**, or **silver-110**;
- for sands (involving diameters of 0.040–2.5 mm), selected for their **grain-size** distribution, identical to those found in the natural sediments from the site considered, or as forming a representative fraction of these sediments, simulation must be resorted to, using special glasses, with a density of 2.65; these glasses are then made radioactive , after a short time inside a nuclear reactor;
- silts, or cohesive sediments (involving diameters smaller than 40 **µm**) are labeled directly, by **chemisorption**, using radioactive solutions; the physicochemical reactions involved are selected, and carried out so as to ensure that the hydrodynamic behavior of the labeled sediments remains identical to that of the natural sediments.

The employment of radioactive **isotope** generators has experienced major growth, and development, in laboratory experiments, particularly in the field of nuclear medicine, where they are in daily use. These are automated, shielded systems, making it possible to obtain readily a radioactive solution at the time of use. The quantities required for the proper completion of a tracer experiment are small: 200 gravel stones per site, 0.25–1 kg radioactive glass, or 5–15 liters silt suspension at 200 g/L prove adequate, as a rule, making for easy onsite product handling injection, and, most importantly, rapid integration into the medium. The introduction of tracer sediments may then be effected either by deposition onto the sea or river bed, or by setting up a cloud of suspended particles, simulating a discharge, or, finally, by mixing with fine sediments, within a dredging well, prior to carrying out discharge operations. Along with **scintillation** radiation **detectors**, of the oceanographic type, which prove both sensitive and hard wearing, portable, autonomous embarked measurement electronics is employed. Combining such items of equipment makes it possible to undertake experiments in distant lands, with limited naval resources. This stands, therefore, as a particularly rugged method, compatible with field applications. Indeed, sensors may be either towed behind a modest-sized (10–20 m long) vessel, or positioned on the sea or river bed, for the purposes of bedload transport measurement, or held in suspension for discharge investigations (see Figure 1). In the latter case, combining detectors and pressure sensors allows readings of submersion depth to be provided. The vessel's position is also recorded, on a continuous basis, by means of a radio-positioning system.

isotope	half-life	form	domain of use
In 113m	100 min	deposit	physical model dispersion study
Tc 99m	6 h	deposit	sewage treatment plant dispersion study physical model
Au 198	3.7 d	deposit ground glass	dispersion study discharge of dredged materials
Hf 181	45 d	deposit	sedimentology sewage treatment plant
Hf 175	70 d	deposit	sedimentology sewage treatment plant
Tb 160	60 d	deposit	sedimentology
Ir 192	74 d	ground glass	sedimentology
Ta 182	115d	source	sedimentology
La 140	40 h	activation	as for Au 198

Table.
Instances of radionuclides used as tracers for the investigation of sediment dynamics.

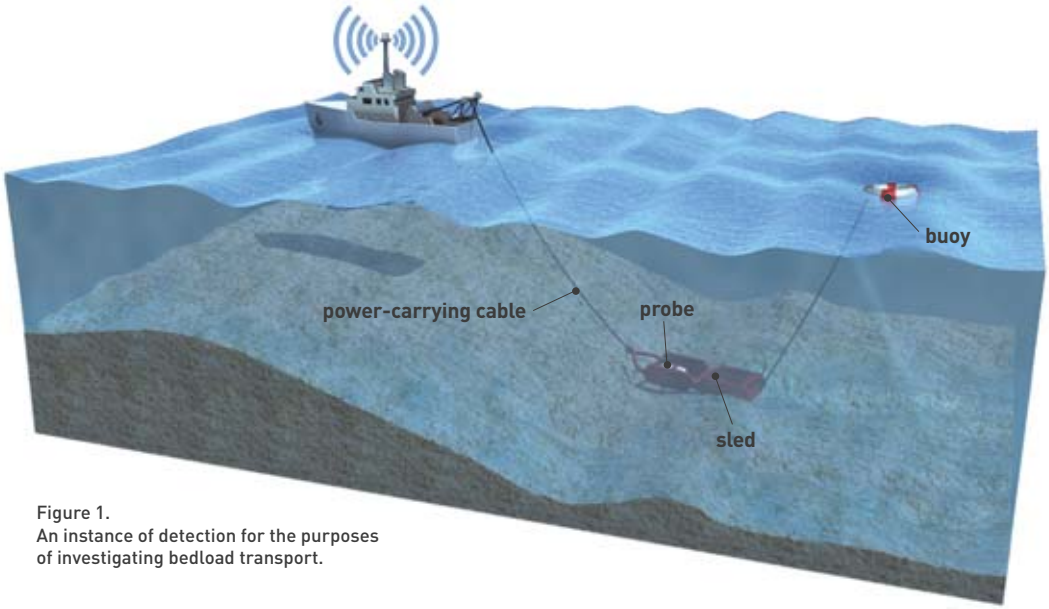

Figure 1.
An instance of detection for the purposes of investigating bedload transport.

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Detection of tracers on a river bed. Investigation of bedload transport of sandy sediments in the Rio Orinoco River (Venezuela).

Once the operation is completed, and the measurement readings collected, their interpretation yields a wealth of qualitative, and quantitative findings. As regards sediment motions along the sea or river bed, such findings concern motion direction, or directions; maximum, and average horizontal displacement velocities; the quantities of sediment involved in bedload transport, returned to suspension, or subject to possible overlaying… On the other hand, as regards displacements of sediment suspensions, artificially discharged into the environment (e.g. industrial, and urban discharges, or dredged materials), the information yielded concern excursion, and drift (direction, horizontal velocity); longitudinal, and transverse dispersion coefficients; dilution rate as a function of time, and of the distance traveled by the cloud; average particle sedimentation rate; the quantities of material depositing on the seabead…

The use of tracers in natural environments has enabled a whole range of studies to be carried out:

- systematic site studies, as e.g. those carried out around the harbor, and coastline at Zeebrugge (Belgium), in the bay around the mouth of the River Seine (western France), at Cap Breton (southwestern France), or Honfleur (western France)… In this respect, a CEA team, led by Charles Beck, carried out, in particular, an altogether exhaustive investigation on the French North Sea coast – a maritime region characterized by a succession of sites involving sandy beds, featuring subaqueous dunes, megaripples, and sand ribbons. The technique used is that of the sideways-looking sonar, combined with point sampling, carried out however at numerous locations. Injections of radioactive tracers (iridium -192), at 8 points located in 3 different zones, at depths ranging from –4.5m to –20 m, allowed the drawing up of precise **bathymetric** maps. The broad spread of readings obtained evidenced a very wide difference in sediment dynamics, on either side of Cape Gris Nez (northwestern France, near Calais). This finding accounts, in part, for the very strong erosion affecting beaches located to the northeast of Wissant (close to Cape Gris Nez), and the sediment transit – very intense, though varying, depending on depth – generated by the action of swell, and tide currents. Such transit remains low (about 0.03 m^3/m/d) when depths are greater than –15 m, rising however to 0.2 m^3/m/d, should water height, at low water, remain less than –5 m. It should be noted that theoretical calculations yield an estimate, on average, of 0.4 m^3/m/d, at a depth of –18 m, for currents of 0.5 m/s, 1 m from the bottom; such computed values have yet to be corroborated by measurements;
- studies to gain knowledge of discharges of dredged materials, as carried out e.g. in the harbors at Le Havre (western France), Antifer (north of Le Havre), Lorient (western France), or Singapore…
- investigations on the recycling of dredged materials, as occurs at the ports of Lorient, and particularly Zeebrugge, where it was found that more than two thirds of materials discharged 18 km away from the coast, over seabed lying at –15 m, swiftly return (within less than 100 days) to the coast, due to tide currents. These materials are thus involved in coastal transit processes, prior to undergoing deposition again, in the calm waters of harbor basins. Such recycling, over a stretch of coast more than 60 km long, was evidenced by means of radioactive elements (**hafnium**, **terbium**) that do not occur naturally. Carried out as they were by specialized laboratories, some measurements required dilutions to 10^{-14};
- investigations of a general character, on the mechanism involved in "silt plug"/fluid mud formation in estuaries, or the effects of swell on sediment transport processes;

• investigations of solid transport processes under torrential regime conditions, of great complexity, involving as they do too many parameters for a treatment making sole use of mathematical models. This resulted in a large number of experiments, carried out, in particular, in the eastern Pyrenees Mountains, in southern France (Verdouble, Cady, Têt, Lentilla, Agly rivers), in the Vosges Mounts (eastern France: Bruche, Mossig, Doller rivers), and in the island of Corsica, in the Mediterranean (Fium' Orbo River), but equally, highly successfully, on shingle barrier beaches;
• investigations of discharges in particulate form (organic, and clay materials). This will allow the systematic analysis of urban discharges at sea, contaminated by chemical, and biological pollutants; but equally the treatment of mechanical pollution in rivers (Doubs River, eastern France), due to fine particles returned to suspension by dredging. The findings from these investigations served for the drawing up of recommendations on extraction conditions for sands, and gravel;
• investigations involving **physical models**, and **laboratory channels**, resulting in the first theoretical, and experimental techniques for the estimate of solid transport in free-surface flows. These investigations rely on the **Eulerian method**, involving measurement of a quantity at a fixed point, as a function of time. Now, constant transport undergone by the upper layer of the sediment bed is the outcome of an alternation of jumps, and pauses for the sand grains, depending on instantaneous, unpredictable hydrodynamic forces, in the characteristic manner of a random process. Radioactive tracers, by allowing Lagrangian measurements, thus prove highly useful, for the purposes of determining the paths of individual particles, and groups of particles, along an entire channel. Further investigations, likewise carried out in laboratory channel conditions, allowed the simultaneous determination of the solid flow rate due to bedload transport, and solid flow rate in suspension. Recently, tracers have also been used for the investigation of the mechanisms involved in discharges of dredged materials in a channel. In all of the hypothesized situations considered, radioactive tracers proved themselves as able to play a prime role, and, patently, an irreplaceable one, owing to their high sensitivity, for measurement purposes.
These numerous studies militate in favor of using tracers in natural environments, particularly owing to the great potentials they afford, and their flexibility of employment. Indeed, the experience gained shows that these various processes yield a good estimate of the quantities of sediment undergoing transport, involving, in the worst cases, an uncertainty lying in the


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Detecting radiotracers on an extensive intertidal zone, on the west coast of the Cotentin Peninsula (western France).


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Releasing radiotracers into water for the investigation of discharges of dredged materials.

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An instance of dredged material disposal, effected by a split-hull type dredger.

50–100% range. For measurements in natural environments, this is a satisfactory result, bearing in mind that, between the various empirical formulas used to estimate equilibrium solid flow rate, the discrepancies found often involve a factor 10, or even larger, in some cases! Be that as it may, tracer techniques still remain restricted in space (1 km^2), and time (6 months, at most), but equally limited owing to the physical impossibility of detecting the radionuclides used, beyond a burial depth of 0.8m. Recently, for an investigation of discharges of dredged material, carried out for the Zeebrugge (Belgium) port authorities, these limits were pushed back to a considerable extent, to several tens of kilometers in a marine environment. Of course, all of these operations remain subject to authorization by the French Nuclear Safety Authority (**ASN**: **Autorité de sûreté nucléaire**).

Nonradioactive tracers

While a number of these tracers have been around for some years, others are currently undergoing development:

- fluorescent tracers, chiefly intended for use with sandy soil particles, may be detected at the **intertidal zone**, *in situ* or by collecting samples, subsequently measured in the laboratory;
- radioactivable tracers are used to label sediments (silts, or sands) by means of an element, activated inside a nuclear reactor, selected according to the trace elements naturally occurring at the site subject to investigation; measurements are made by taking samples, subsequently activated in a reactor, and finally analyzing sample trace-element content, by the low-background **gamma spectrometry** method;
- magnetic tracers, currently undergoing development, both as regards the tracers themselves, and the means of detection, allow a number of different principles to be considered: electron paramagnetic resonance (EPR), **magnetic susceptibility**, total magnetism…
- tracers labeled by means of passive **padio-frequency identification** (**RFID**) tags a few millimeters in diameter are used only for gravel stones, solely for *in situ* measurements (tidal banks), using a portable antenna. Fluorescent, and activable tracers were recently used, in conjunction, to carry out an investigation of solid transfers in large irrigation networks (Jamrao canal system) in Pakistan (Sindh Province).

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JTD3 transmission gauge (left), and JTT4 backscatter gauge (right).

Radiometric detectors, or nucleonic gauges

The effectiveness of this class of detectors is due to their optimum combination of an ionizing radiation source, and an appropriate detector. The radiation–matter interaction thus examined allows continuous measurement of the concentration, or density of sediments, whether in suspension, or forming deposits. Such an operation allows nondestructive measurements to be carried out, with no sampling required, even through an opaque wall, or directly in water. Such data, processed in real time by computer, stand as an aid to decision, or to infrastructure or installation management. Specialists consider two distinct types of such devices (see Figure 2). First, **transmission gauges**, where the source, and the detector are positioned on either side of the sample being measured, making it possible to evaluate the amount of radiation passing through the material. And, second, **backscatter gauges**, where the source, and detector lie on the same side of the sample; in this case, the radiation of interest is that scattering in the material. The various types of gauges available include, in particular:

- field equipment, more specifically suitable for:
  – turbidity measurements, carried out directly *in situ*, or through a pipe;

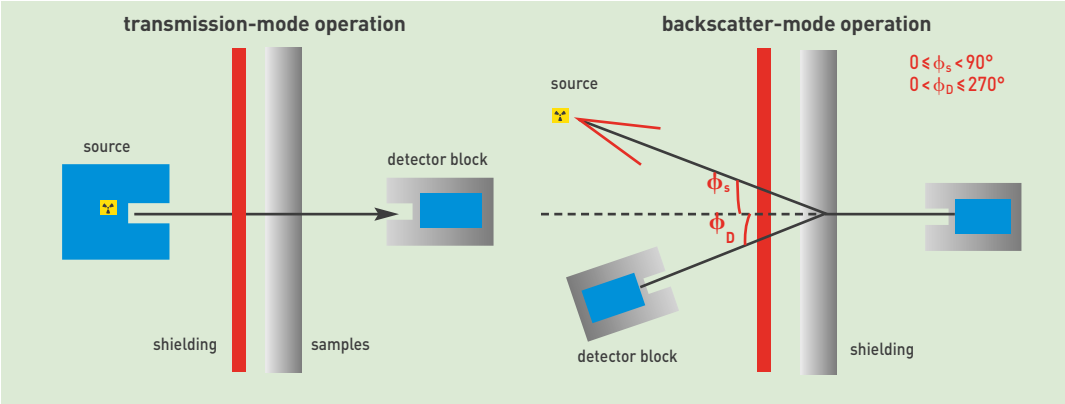


Figure 2.
The two gauge setups.

– measurements of **vertical density profiles**, for materials deposited in silted up channels, dredging wells, and dam reservoirs. The information obtained, complementing that provided by ca fm qms l bcpq, which only serve to locate the water–liquid silt interface, make it possible to extend the limits of depths open to navigation. For a conventional shipping channel, this means savings of several million euros per annum;
– the control of dam reservoir draining operations;
– measurements of height variations in sedimentary formations, and of transport direction.

• specialized laboratory equipment, for the purposes, on one hand, of non-invasive, nondestructive measurements of density profiles in sediment core samples; and, on the other hand, measurements of the compaction gradient in fine sediment, as a function of time, height of deposit sample, initial suspension concentration, and height of sedimented volume.

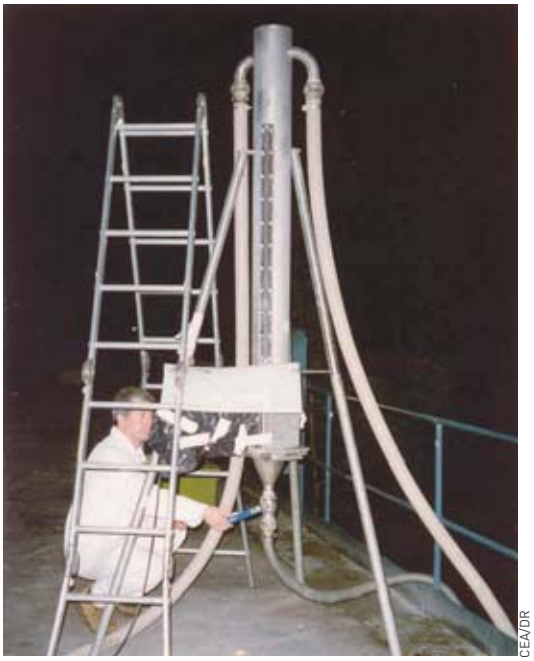
All such devices comply with safety standards for contact irradiation, and their deployment requires clearance, in France, by ASN. Their design makes them suitable for use by personnel not directly assigned for work under ionizing radiation conditions. Most commonly, the precision of these devices stands at 1%, with a confidence level of 68%. They turn out a performance that is all the better, proving unrivalled in this respect, the higher the concentration. However, below 1 g/L, other processes are called for.

To sum up, it has to be pointed out that industry, shipping, tourism do tend, at times, to involve an exploitation, and domestication – effected with a greater or lesser degree of brutality – of rivers, estuaries, and shorelines. Receding coastlines, extraction of granulates, discharges of wastewaters, and dredged materials, dam reservoir draining operations… all stand as issues of current relevance. Solving the problems involved entails a precise knowledge of transport, dilution, and sedimentation mechanisms, and measurement of the parameters governing these processes, in order to define the best management mode feasible for fluvial, estuarial, and coastal environments. As confirmed by findings from many studies, nucleonic tracers, and gauges remain, currently, as one of the few means available, enabling engineers, hydraulics specialists, and researchers to obtain the information, and measurements that are indispensable, if they are to meet their respective remits.

Of the areas involving a strong economic, and ecological impact, six should experience growth that will continue unabated, or even intensify. These areas cover:

• management of dredging operations owing to discharges of materials dredged for navigability purposes, in silted up channels;
• seashore stability, with regard to the effects of swell, and currents on sediment transport processes, and those of marine granulate extraction;
• residential, and industrial discharges in particulate form, into estuaries and at sea;
• continuous measurements of suspended materials (SMs);
• studies on the management of dam reservoir slushes operations.

As borders open up, across Europe, these techniques should allow French civil engineers, charged with meeting the issues set by solid transport processes, to offer original, high-performance, cutting-edge processes, compared to those employed by their competitors, who, for the most part, do not have access to this extra, complementary asset provided by nucleonic tracers and gauges.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SERES gauge in measuring position over the Génissiat hydroelectric dam (southeastern France).

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FOCUS A

Journey to the center of the Earth, and the outer reaches of the atmosphere

The Earth is a solid, rotating sphere, with a mean diameter of 12,750 km, surrounded by a gaseous envelope, the atmosphere. About 71% of its surface is covered with water, the remainder consisting in continents, and islands, of variegated relief, and very unevenly distributed.

The Earth's internal structure

Formed some 4.57 billion years ago, through the accretion of meteorites, the Earth consists in a succession of envelopes, of diverse thicknesses and compositions, the main envelopes comprising, from the surface to the planet's center: the lithosphere, the mantle and the core (see Figure 1). These layers were identified through investigations on the propagation of seismic waves, traveling through and across the globe in all directions, this determination being based on the fact that the velocity of a seismic wave changes abruptly, in a major way, as it crosses into a new medium. This method made it possible to ascertain the state of matter, at depths that are beyond human reach.

The lithosphere (0–100 km), i.e. the globe's superficial shell, is divided into a number of rigid segments, the tectonic plates, which move across the viscous material in the underlying region, in the upper mantle, known as the asthenosphere, and are in constant motion. Comprising as it does the Earth's crust, and part of the upper mantle, the lithosphere's depth varies, from 100 km under the oceans, to 300 km under the continents. The continental crust, which is solid, and mainly granitic,[1] though in places overlain by sedimentary rocks,[2] has a depth standing, on average, at 30 km under continents, which may reach 100 km under mountain ranges. The oceanic crust, like-

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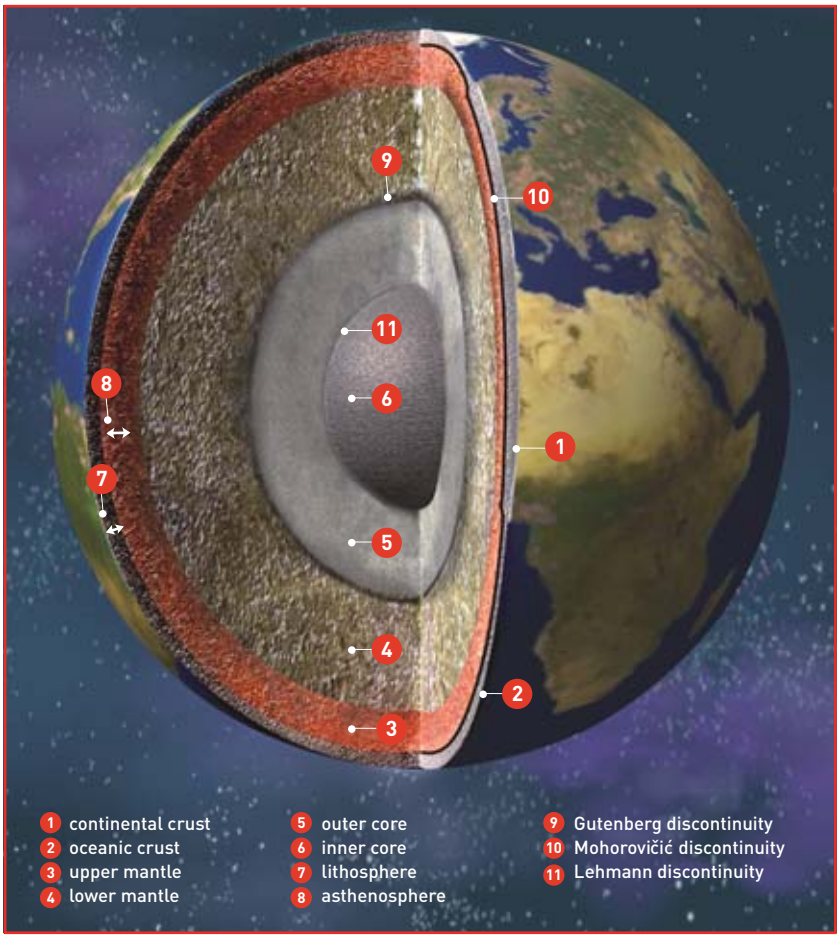
(1) Granite: a dense, magmatic rock consisting of crystals visible to the naked eye, mainly quartz (silica [SiO_2]), micas (minerals chiefly consisting of aluminum silicate, and potassium), alkali feldspars ($KAlSi_3O_8$), and sodium plagioclases ($NaAlSi_3O_8$).

(2) Sedimentary rocks: rocks arising from the accumulation, and compacting of debris of mineral provenance (degradation of other rocks), or of organic origin (animal or vegetal remains, fossils), or from chemical precipitation.

StockTrek

The Earth is covered with water over some 71% of its surface.



StockTrek

Figure 1.
The Earth's internal structure.

StockTrek

Lava flow in Hawaii. Magma wells up from the Earth's interior, and flows out in the form of lava.

Page 21 cont'd

wise solid, and chiefly consisting of basaltic rocks, is relatively thin (with a thickness of around 6–8 km). The Earth's crust accounts for some 1.5% of the Earth's volume. The upper, solid part of the mantle, consisting of peridotites,[3] also exhibits varying depth, according to whether it lies under an ocean or a continent. The transition region between crust and mantle, discovered in 1909 by Croatian geophysicist and seismologist Andrija Mohorovičić, is known as the *Mohorovičić discontinuity*, or *Moho*.

The upper mantle (100–670 km), chiefly consisting of peridotites, is more viscous than the lower mantle (670–2,900 km), essentially composed of perovskites,[4] as the prevailing physical constraints in that region make it partly liquid. The lower mantle is not liquid, as might be inferred from the lava flows involved in some volcanic eruptions, however it is less "hard" than the other layers. It exhibits the properties of an elastic solid. The mantle, with a temperature higher than 1,200 °C, accounts for about 84% of the Earth's volume. The transition region between the mantle and the Earth's core was located, in 1912, at a depth of 2,900 km, by German seismologist Beno Gutenberg, and is consequently known as the *Gutenberg discontinuity*.

The outer core (2,900–5,100 km) essentially consists of iron (to about 80%), nickel, and a few lighter elements. This metallic core, the fluidity of which was determined, in 1926, by British geophysicist and astronomer Harold Jeffreys, exhibits a viscosity close to that of water, an average temperature of 4,000 °C, and a density of 10. The convective motions arising in this huge mass of molten metal, linked to the Earth's rotation, are the processes that give rise to the Earth's magnetic field.

The inner core (5,100–6,378 km) was discovered in 1936 by Danish seismologist Inge Lehmann. Essentially metallic in composition, it has formed owing to gradual crystallization of the outer core. The prevailing pressure keeps it in a solid state, with a density of about 13, in spite of a temperature standing higher than 5,000 °C. The transition region between the outer and inner core is known as the *Lehmann discontinuity*. The core accounts for about 15% of the Earth's volume.

Within the planet's core, radioactive elements (potassium, uranium, thorium) decay, yielding considerable heat. This provides the various layers in the Earth's structure with the energy required to sustain the motions affecting them, while allowing molten rocks (magma) to rise up from the Earth's interior. Part of the magma solidifies as it comes into contact with the Earth's crust, which is cooler, whereas a fraction breaks out at the surface, in lava form.

The Earth's atmosphere

The gaseous envelope surrounding the Earth, held close to the planet's surface as it is by gravity, the atmosphere is indispensable to life. It contains the air we breathe, shields all lifeforms from the Sun's harmful radiations through its ozone layer, stands as a major component in the water cycle, and markedly contributes to making the average temperature milder,

(3) Peridotite: a rock formed as a result of the slow cooling of magma, consisting of grains visible to the naked eye. It chiefly consists of olivine, pyroxene, and hornblende (a hydrated mineral, characterized by the $[Si_4O_{11}(OH)]^{7-}$ anion).

(4) Perovskite: named after Russian mineralogist L. A. Perovskii, this refers broadly to a crystal structure common to many oxides, of general formula ABO_3. Perovskites exhibit a variety of electrical, and magnetic properties, depending on the nature of A, and B.

at the planet's surface owing to the **greenhouse effect** it generates (see Focus C, *Greenhouse gases and aerosols at the center of the climate change debate*, p. 66). Indeed, in the absence of any atmosphere, surface temperature would stand at around –18 °C, rather than the 15 °C observed.

Atmospheric air consists in a mixture of gases (see Table), holding suspended particles, both liquid (water droplets...), and solid (ice crystals, dust particles, salt crystals...), with most of its mass lying close to the Earth's surface. At sea level, atmospheric pressure stands at 1,013.25 **hPa**. Gas **molecules** become rarified, and disperse at higher altitude, and pressure falls off. The atmosphere is thus ever less dense as altitude increases, until it finishes by "blending into" outer space.

The atmosphere comprises a number of layers, within each of which temperature varies differently, as a function of altitude: the **troposphere**, the **stratosphere**, the **mesosphere** and the **thermosphere** (see Figure 2). In the **troposphere** (from the Earth's surface to 8 km over the poles, 15 km at the equator), temperature declines swiftly with altitude, at a rate of about 6.4 °C per kilometer. Temperature varies, on average, from 20 °C at ground level to –60 °C at the upper boundary of this region. As this layer holds 80–90% of the total air mass, and virtually all of the water vapor, pressure and density are highest in this region. It is in this region that most meteorological phenomena (cloud formation, rain...) take place, together with the horizontal and vertical motions of the atmosphere (thermal convection, winds). In the topmost layer of the troposphere, known as the **tropopause**, temperature undergoes an inversion, and begins to rise. The height of this region varies, from the poles to the equator, but equally according to the seasons.

In the **stratosphere** (from 8–15 km to 50 km), temperature stays constant over the first few kilometers, then rises slowly, and far more swiftly thereafter, increasing with altitude up to 0 °C. This region contains, at an altitude of around 25 km, a large part of the **ozone layer**. Ozone is produced through the effects of solar radiation on oxygen molecules. The ozone layer acts as a protective shield, by absorbing the Sun's **ultraviolet radiation**, resulting in the layer heating up. It is in the stratosphere that short-wavelength light rays undergo scattering over the air's constituent molecules – hence the sky's blue color in daytime – and it is host to violent winds, racing

Skip to page 24

gas	volume (ppmv)	
nitrogen (N_2)	780,840	(78.084%)
oxygen (O_2)	209,460	(20.946%)
argon (Ar)	9,340	(0.934%)
carbon dioxide (CO_2)	382	(0.038 2%)
neon (Ne)	18.18	
helium (He)	5.24	
methane (CH_4)	1.745	
krypton (Kr)	1.14	
hydrogen (H_2)	0.55	
nitrous oxide (N_2O)	0.30	
ozone (O_3)	0.04	
water vapor (H_2O)	from 1% (in polar regions) to 4% (in equatorial regions) (highly variable)	

Table.
Composition of the atmosphere, in the vicinity of the Earth's surface.
In thermodynamic terms, atmospheric air is treated as a mixture of two gases: dry air and water vapor.
Greenhouse gases appear in purple. CO_2 concentrations stood at 280 ppmv in 1800, 345 ppmv in 1998.

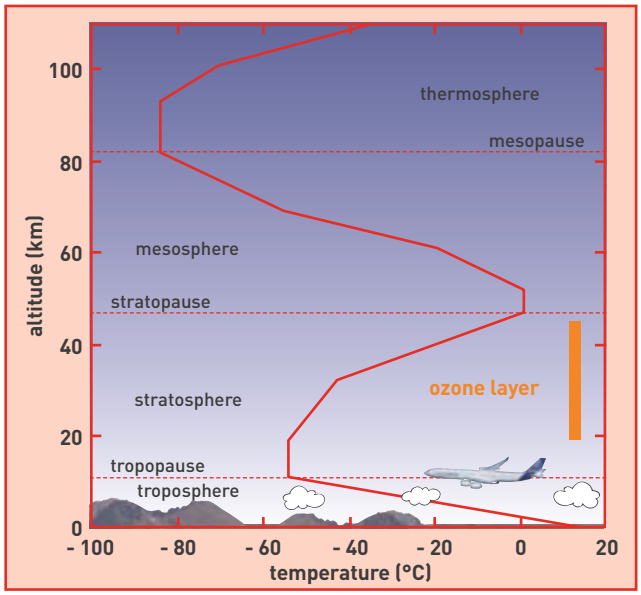
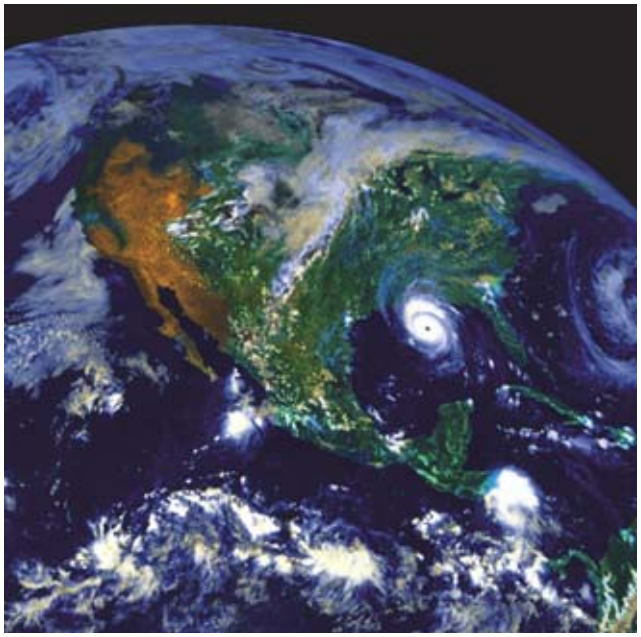


Figure 2.
The layers in the atmosphere. Their boundaries are determined on the basis of discontinuities in temperature variations, as a function of altitude.



StockTrek

Most meteorological phenomena take place in the troposphere, the region where pressure and density are highest.

StockTrek

The stratosphere holds a major part of the ozone layer, which acts as a protective shield against the Sun's harmful radiations.

C. Morel/Our Polar Heritage

Polar auroras – here an aurora borealis (Northern lights) – are caused by the interaction between solar wind particles and the upper atmosphere. They occur in the ionosphere, a region characterized by a high concentration of electrically charged particles.

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at velocities of up to 200–300 km/h. In the top layer of the stratosphere, known as the **stratopause**, temperature begins to decline again.

In the **mesosphere** (from 50 km to 80 km), temperature decreases swiftly with altitude, down to –80 °C. This is the coldest layer of the atmosphere, and it is as a rule in this region that meteorites burn up as they enter the atmosphere. In the top layer of the mesosphere, known as the **mesopause**, temperature begins to rise again.

In the **thermosphere** (from 80 km to 350–800 km), temperature again increases with altitude, rising well above 1,000 °C. This heating up is due to the strong absorption, by oxygen, of ultraviolet radiation emitted by the Sun. In this region, while temperatures are high, density is extremely low, and the prevailing pressure is very low. Oxygen molecules break up into two oxygen **atoms**. The upper boundary of this layer is known as the **thermopause**.

Aside from temperature, other criteria may serve to define distinct layers in the atmosphere.

The **ionosphere**, a region coterminous with the thermosphere, is characterized by a high concentration of electrically charged particles. There, solar energy is so strong that it "breaks up" the molecules in the air, yielding **ions** and **free electrons**. This layer exhibits the property of reflecting **radio waves**. A fraction of the energy radiated by a radio transmitter is absorbed by the ionized air, the remaining fraction being reflected downwards, thus allowing communications to be set up between various points on the Earth's surface, which, in some cases, may be far distant from one another. It is in the ionosphere that **auroras** occur. Lying at an altitude of 60–70 km, the **neutropause** stands as the boundary between the ionosphere and the **neutrosphere**, which is the lower region of the atmosphere, where electron concentration remains insignificant.

In the **exosphere** (from 350–800 km to 50,000 km), the region extending beyond the ionosphere, the laws of gas physics cease to be applicable. Molecules disperse, and become rarified as altitude increases. The lighter, more agitated molecules may then escape the Earth's attraction, and be lost forever, ultimately, to interstellar space. It is in this layer that most satellites are placed into orbit.

At an altitude of around 2,000 km, ions account for the greater part of the particles present. They form the **magnetosphere**, where the Earth's magnetism takes over from gravitation. This region, chiefly holding **protons** as it does, is also known as the **protonosphere** (or protosphere). The magnetosphere acts as a shield, protecting the Earth's surface from the harmful effects of the solar wind.

In like manner, if the criterion used is that of the air's changing composition along a vertical direction, the atmosphere may be divided into two regions: the **homosphere** (from the Earth's surface to an altitude of 80 km), within which the composition of dry air undergoes little variation, and the **heterosphere**, extending above it. The level above which air composition alters significantly is known as the **homopause**.

FOCUS B

The main extraction, separation, and analysis techniques

Whether of natural or anthropic provenance, substances found in the environment call for the use of analytical methods that are flexible – the aim being both to detect, and identify extremely diverse compounds – and highly sensitive. They further entail the implementation of rigorous procedures, operating step by step.

Rigorous preparation of samples

Standing as a fundamental step in the analytical process, the pretreatment of samples involves either preconcentrating substances occurring with too low a content to allow direct detection, or separating them from an overly complex matrix. If research workers spend nearly 60% of the time required, for an overall analysis, on this preliminary step, it is because, according to a number of studies, it accounts for nearly 30% of errors in findings. Presently, these same research workers have developed a gamut of fast, economical, automated, reliable techniques, for the purposes of treating samples, depending on their nature, or the concentration being considered:

• Solid-phase extraction (SPE) allows the isolation of chemicals present in a liquid (e.g. water), through use of an absorbent polymer, conditioned as a rule in filtration cartridge form. This proves highly effective for the purposes of preconcentrating traces, in highly dilute media, or purifying samples.

• Fiber-supported solid-phase microextraction (SPME) is used to extract chemicals present in a gas, or a liquid (e.g. air, or water), this being effected by means of an absorbent polymer, coating a glass fiber a few millimeters long, placed in contact with the sample. As SPME requires neither solvents, nor any specific equipment, it thus proves simple to deploy. This is an innovative technique, seeing increasing use for the purposes of air quality monitoring, or the analysis of organic micropollutants in water.

• Stir-bar sorptive extraction (SBSE) sees broader employment, for the purposes of extracting chemicals present in a liquid (water). Such extraction is effected by means of an absorbent polymer, coating a (magnetic) stir bar, impelled inside the sample. Based as it is on the same principle as SPME, this technique allows the extraction of greater quantities of analytes, and thus makes for increased sensitivity.

• Solvent extraction – this as a rule involving a volatile solvent, sparingly soluble in water (a light alkane, ethyl acetate...) – allows the extraction of molecules from aqueous media. Solvent–water separation is effected simply, through settling.

• Preparative ion chromatography, which relies on the interaction, in an aqueous medium, of ion species with ion-exchange resins, allows the extraction of inorganic substances (ions) occurring in trace form, from a complex environmental matrix.

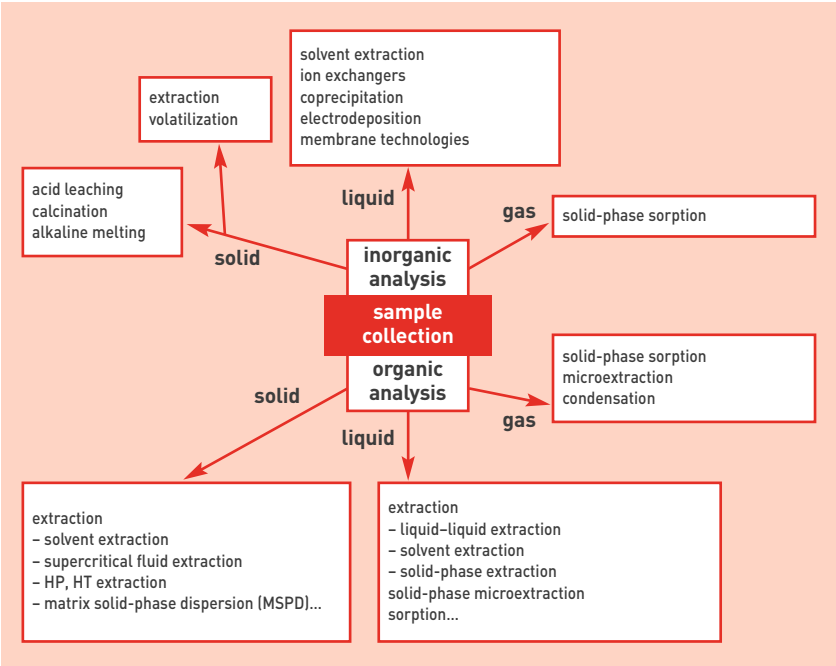
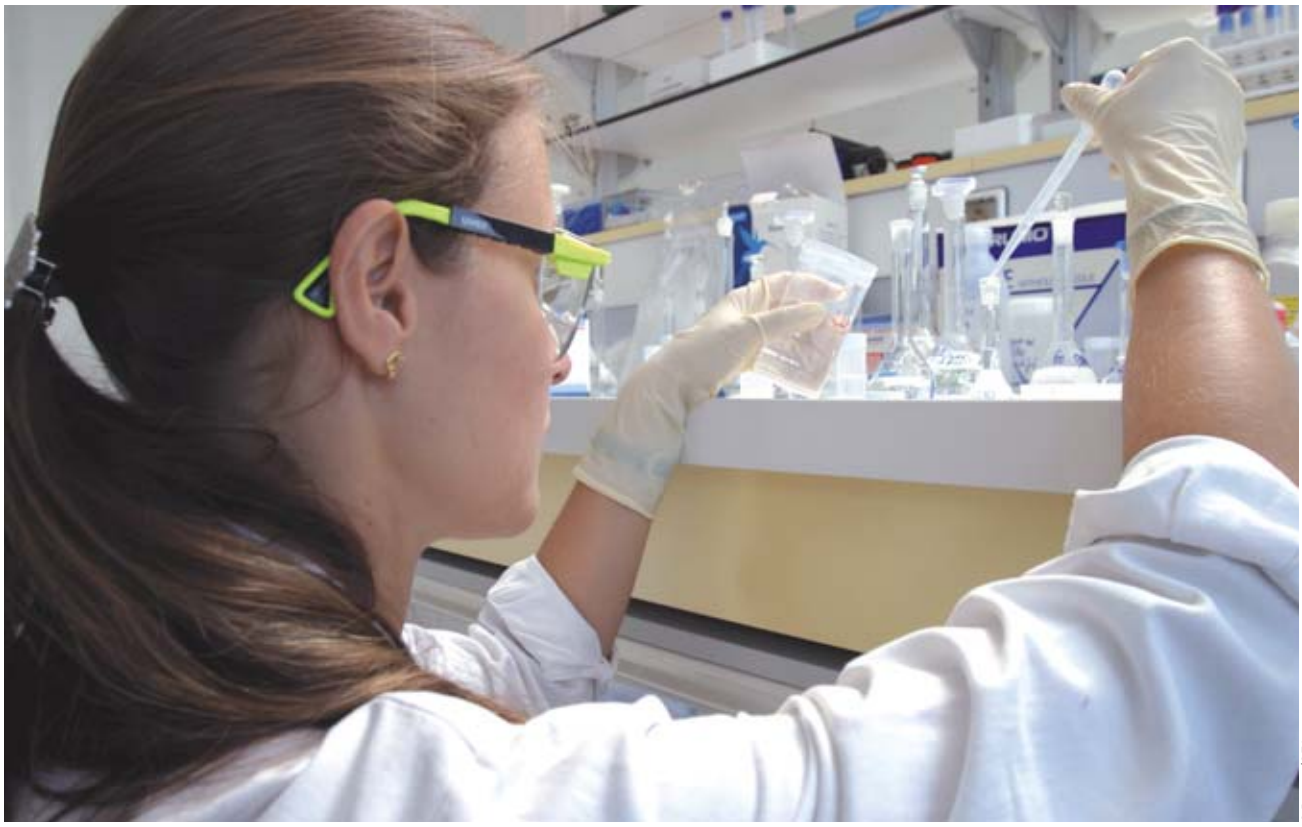


Figure 1.
Examples of pretreatment techniques for environmental samples

Separation for selection purposes

Used nowadays for the purposes of identifying, or titrating, the chemical compounds in a mixture, chromatography was invented, in 1906, by Russian botanist Mikhail Tsvet (1872–1919), who was seeking to separate out various plant pigments. Nowadays, the technique involves allowing a solution of the substance being investigated to percolate through a column, packed with adsorbent materials: the constituents, each traveling at different rates, become partitioned into distinct regions, or bands, which can simply be considered separately, for analytical purposes.

• Liquid chromatography (LC), or high-performance liquid chromatography (HPLC) relies on the separation of the substances present in a mixture through their introduction into, and subsequent differential migration along, a separation column (chromatographic column) through which an eluting liquid (e.g. a mixture of water and methanol) advances. Thereafter, a sequence of physicochemical interactions between the substances subject to analysis, and the two separation phases (the stationary phase, and the mobile, eluent phase) allows the constituents to be separated out. Coupling the chromatographic separation module with specific detectors (mass spectrometer, UV–visible absorption spectrometer...) results in a variety ofanalytical instrumental setups (HPLC–MS, HPLC–UV...).



C. Dupont/CEA

In the analytical chemistry laboratory. Separation, and purification of actinide traces in environmental samples, as preliminary steps for mass spectrometry measurements.

• Capillary electrophoresis (CE), as indeed all electrophoretic separation methods, is used to separate electrically charged particles (ions), through their differential migration under the influence of an electric field. Each species migrates at a specific rate, which is a function of its charge-to-size ratio. As regards, more specifically, capillary electrophoresis, as its name implies, the separation support medium is a capillary, filled with a specific liquid medium (the electrolyte), and immersed at either end in electrolyte reservoirs, connected by way of a high-voltage generator. The sample is inserted into the electrolyte flow, and the sample's constituent species migrate at their respective specific rates, these being dependent, as a whole, both on the distance between the injection, and detection points, and migration time.

• Gas chromatography (GC) allows the separation of volatile, or semivolatile substances from a complex mixture. This relies on the introduction of the mixture, by vaporization, into a separation column (chromatographic column), and subsequent differential migration (elution) of the substances, due to entrainment by a carrier gas (e.g. helium). Chromatographic columns, nowadays, chiefly involve capillary tubes, 30–100 m long, internally coated with an appropriate polymer, with regard to the substances subjected to analysis. A detection system, located at the column outlet, measures the signals emitted by the various constituents, allowing their identification, and quantification (e.g. GC–MS).

• Ion chromatography (IC) relies on the application of the various liquid chromatography methods to the analysis of organic, or inorganic ions (whether anions, or cations).

Analysis to gain knowledge

To determine a sample's composition, researchers can draw on the full range, and variety of spectrometric methods, i.e. methods of spectral analysis allowing the material's composition, and structure to be ascertained. Such methods may be grouped into two categories: radiation spectrometry, and mass spectrometry, this in turn being subdivided, as a rule, into atomic spectrometry, and molecular spectrometry.

Radiation spectrometry

Radiation spectrometry relies on the interaction of electromagnetic radiation with matter. It makes use of processes as diverse as emission, absorption, fluorescence, and diffusion, whether involving visible, or nonvisible radiation. Whether in the atomic, or molecular state, every substance exhibits a characteristic spectrum, whether the spectrum considered be an emission, or an absorption spectrum (or indeed a diffusion, or fluorescence spectrum); it is thus sufficient to recognize the occurrence of that spectrum, to have evidence of the presence of the corresponding substance.

• Atomic absorption spectrometry relies on the principle whereby atoms may absorb photons of a certain wavelength (characteristic of the element subject to analysis). The number of photons absorbed being related to the number of atoms absorbing them, the element's concentration may thus be derived from such a measurement.

• Emission spectrometry is based on the characteristic photon emission yielded by atoms excited by an energy input. Such

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energy may be provided by means e.g. of an inductively coupled argon plasma source; this allows the measurement of elemental content (copper, lead, tin, arsenic, nickel...), however without yielding any information as to the chemical form in which these elements occur in the sample.

• Glow-discharge spectrometry (GD-OES) involves the process of cathodic sputtering of the sample undergoing analysis, this being positioned in a source operating on the cathode-ray tube principle. The elements sputtered into the glow discharge lamp are then identified from their light emission spectra. The glow-discharge source may also be combined with a mass spectrometer.

• Laser-induced breakdown spectroscopy (LIBS) is an optical emission spectroscopy technique, making use of the interaction of a pulsed laser beam with a material, resulting in the latter's vaporization, in plasma form. The ejected excited atoms, and ions, as they relax, emit a UV, and visible spectrum made of lines, the wavelengths of which allow the identification, and quantification of the elements present in the sample.

• X-ray fluorescence spectrometry involves bombarding the material with X-radiation, the material then reemitting energy, in the form, in particular, of secondary X-rays; analysis of the spectrum allows the sample's elemental composition to be derived, in both qualitative and quantitative terms.

• UV–visible absorption spectrometry relies on the absorption of light by matter. This technique chiefly allows the measurement of chemical species concentrations in aqueous solutions, or solutions of other types.

• Infrared (IR) spectrometry allows, by way of the molecular absorption of IR radiation, the determination of the chemical bonds making up a molecule, and thus makes it possible to build up structural hypotheses. Since IR spectra can prove highly complex, they may thus be seen as a veritable molecular ID document.

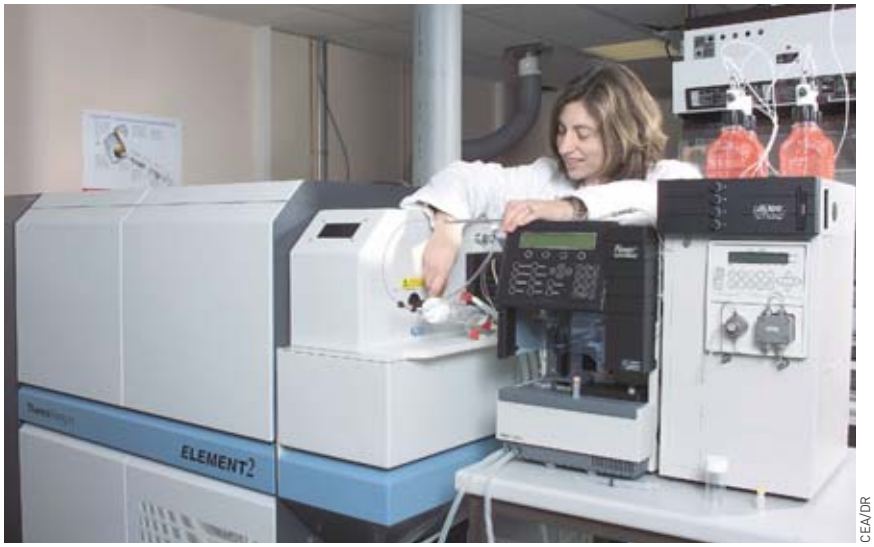
• Time-resolved laser-induced fluorescence (TRLIF) is an ultrasensitive analytical technique, used for the determination of certain actinides, and lanthanides, which are fluorescent in solution. Its principle relies on excitation, carried out by means of a pulsed laser, and subsequent time resolution of the fluorescence signal (by setting a measurement time gate, at a few microseconds' delay after the laser pulse), allowing the elimination of unwanted, short-lived fluorescence signals. Current developments involving this technique concern speciation (i.e. the determination of chemical species), and remote measurement via optical fiber in the nuclear industry, and for environmental analysis.

• Raman scattering spectrometry is employed to ascertain a sample's chemical structure, and molecular composition, by placing it under laser radiation, and analyzing the scattered light emission. This is a nondestructive method, complementing infrared spectroscopy. Raman spectroscopy is a local measurement technique: by focusing the laser beam onto a small region in the medium, that medium's properties may be probed, over a volume of a few cubic microns. This is known as micro-Raman spectroscopy.

• Nuclear magnetic resonance (NMR) spectrometry involves a principle relying on the spin alignment that occurs in certain atomic nuclei, under the influence of an intense magnetic field. These nuclei may then interact with radio waves, emitting signals that allow the molecular structure of the compounds present to be identified.

C.Dupont/CEA

Preparing samples, for the purposes of radiological analysis. Environmental samples undergoing treatment: chromatography, for the purposes of extracting radionuclides.



CEA/DR

Coupled liquid chromatography–inductively coupled plasma mass spectrometer (ICP–MS).

• Atom-trap trace analysis (ATTA) is a technique involving magneto-optical trapping of "cold" atoms, enabling the detection of single atoms, and the quantification of isotopic ratios for a few thousand atoms. A complex technique, ATTA currently ranks as one of the most sensitive, and most selective techniques available.

Mass spectrometry

Mass spectrometry and ion-mobility spectrometry stand as an ensemble of analytical techniques, allowing the detection, but equally the precise identification either of elements (inorganic mass spectrometry), or of a variety of molecules (organic, or molecular mass spectrometry). In the latter case, the molecules' chemical structure may be characterized by fragmenting them, or by measuring, with great precision, their molecular masses. For that purpose, a mass spectrometer comprises, first of all, a sample introduction system, involving either direct introduction (solid, liquid, or gaseous samples), or indirect introduction (i.e. coupled with a separation technique, e.g. chromatography, or capillary electrophoresis). It further includes an ionization source, to effect element atomization, and ionization (or to effect molecule vaporization, and ionization), a mass analyzer, this separating ions according to their mass-to-charge *(m/z)* ratio, and, finally, one or more detectors.

Many methods are available, for the purposes of ionizing atoms, or molecules.

Organic mass spectrometry involves many ways of combining the various ionization sources, and the various analyzers available. Certain sources are more widely used than others.

• The electron impact ion source, relying on the bombardment of molecules by a beam of electrons (usually with an energy of 70 eV), and the generation of positively charged ions.

• The chemical ionization source relies on negative ionization, by electron capture, involving low-energy (1–2 eV) electrons, yielded by the primary ionization of a reagent gas (methane, ammonia...) that is subjected to electron bombardment.

• Atmospheric-pressure chemical ionization (APCI), whereby liquid samples first undergo nebulization (transformation into a droplet aerosol), by means of a jet of air, or nitrogen. Heating then ensures the desolvation of the compounds present. These are then chemically ionized, at atmospheric pressure: as a rule, the mobile, vaporized phase acts as the ionization gas, and electrons are obtained by way of corona discharges at the electrode. APCI is a technique that is analogous to chemical ionization (CI): it likewise involves gas-phase ion–molecule reactions, at atmospheric pressure however.

• The electrospray ionization (ESI) source generates ions from a liquid solution, by subjecting this solution to vaporization, and nebulization, in the presence of an intense electrostatic field. As is the case with APCI, the advantage afforded by this ionization technique is that it allows multiply charged ions to be obtained, these being particularly advantageous for the purposes of characterizing macromolecules. This method further makes it possible to achieve a "soft" ionization, yielding mainly molecular ions.

• Desorption electrospray ionization (DESI) relies on the use of a nebulized solvent, containing molecules in an excited electronic state, which transfer their energy to the substances being investigated, resulting in their ionization, and desorption from a solid sample, or a liquid sample deposited onto a substrate.

With respect to inorganic mass spectrometry, numerous combinations are likewise to be found, however the ionization sources involve higher energies than is the case in organic mass spectrometry, so as to ensure complete sample atomization.

• Inductively coupled plasma is an extremely energetic atomization and ionization source, which, when combined with a mass spectrometer – in inductively coupled plasma mass spectrometry (ICP–MS) – ranks as one of the most sensitive elemental analysis techniques. It allows, in particular, measurement of plutonium at lower than femtogram levels.

• Secondary ion mass spectrometry (SIMS), involving the bombardment of a solid sample by an ion beam, allows the finescale characterization of its surface, thus providing the ability to analyze e.g. micrometer-scale particles, containing minute quantities of a given element. This technique also enables to carry out depth profiling and elemental or isotopic mappings.

• Thermal ionization mass spectrometry (TIMS) involves coupling a source effecting the atomization, and ionization of samples, deposited onto a surface brought to a very high temperature, with a mass spectrometer. This technique allows the measurement, with outstanding precision, of elemental isotopic ratios, as well as element concentrations, through the use of tracers.

• Ion mobility spectrometry (IMS), a gas-phase chemical analysis technique, involves applying an electric field to molecules held in a gas stream. Ionization is usually effected by a light source (ultraviolet radiation), or a radioactive (alpha- or beta-emission) source.

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FOCUS B

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C.Dupont/CEA

Thermal ionization mass spectrometer, allowing the very-high-precision analysis of uranium, and plutonium isotopes.

• Resonance ionization mass spectrometry (RIMS), a highly selective elemental analysis technique (owing to the ability to achieve perfect elemental selectivity at the ionization stage), is used for the purpose of avoiding numerous chemical separation operations. The principle involves subjecting a mixture of atoms in vapor phase to laser "irradiation," to excite, and subsequently selectively ionize, only those atoms involving electronic transitions corresponding to the laser wavelength. Use of a mass-dispersion system (magnetic analyzer, time-of-flight spectrometer) allows a twofold selectivity – both elemental, and isotopic – to be achieved.

Ion separation is effected by means of analyzers, which differ in terms of the technology involved, and which may be coupled together, for the purposes of determining molecular structures.

• The quadrupole analyzer involves forcing ions to travel through a complex electrostatic field, along metal rods, the ions passing through this spatial region, or otherwise, depending on their mass-to-charge ratio.

• The quadrupole ion trap relies on trapping ions in a specified spatial region, through the action of a complex electrostatic field, and sequentially directing the ions to a detector, according to their mass-to-charge ratio.

• The time-of-flight spectrometer seeks to measure the velocity of ions introduced, in controlled manner, into a spatial region subjected to an electric field, the time required for ions to travel a given distance then being related to their mass-to-charge ratio.

• The magnetic-sector analyzer involves constraining ions to follow a specific path (depending on their mass-to-charge ratio), chiefly under the influence of a perfectly controlled magnetic field, prior to arriving at a detector, which ensures their detection, and quantification.

• Ion cyclotron resonance (ICR) makes it possible to keep ions within a spatial region where an intense magnetic field prevails, and inside which each ion follows a circular path, with characteristics (radius) that are dependent on its mass-to-charge ratio. The angular frequency, for each of these ions, is measured by electromagnetic interrogation, and this allows, by way of the Fourier transform, the very precise determination of the mass-to-charge ratio for every ion.

• The Orbitrap involves forcing ions, under the influence of a complex magnetic field, to orbit around, and oscillate along, an electrode shaped somewhat like a fusiform muscle. The angular, and oscillation frequencies for each of these ions are measured by electromagnetic interrogation, allowing, by way of the Fourier transform, the very precise determination of the mass-to-charge ratio for every ion.

• The ion-mobility spectrometer relies on measuring the displacement velocity of ions subjected to the accelerating effect of an electric field, and the retarding effect of a gas, at atmospheric pressure. Measurement of ion transit times, from the injection area to the ion detector, allows the ions' chemical nature to be determined (more or less accurately, depending on the precision of the time measurements).

In every one of the cases outlined above, a detector ultimately converts the ions into an electric signal, which is amplified prior to IT processing.

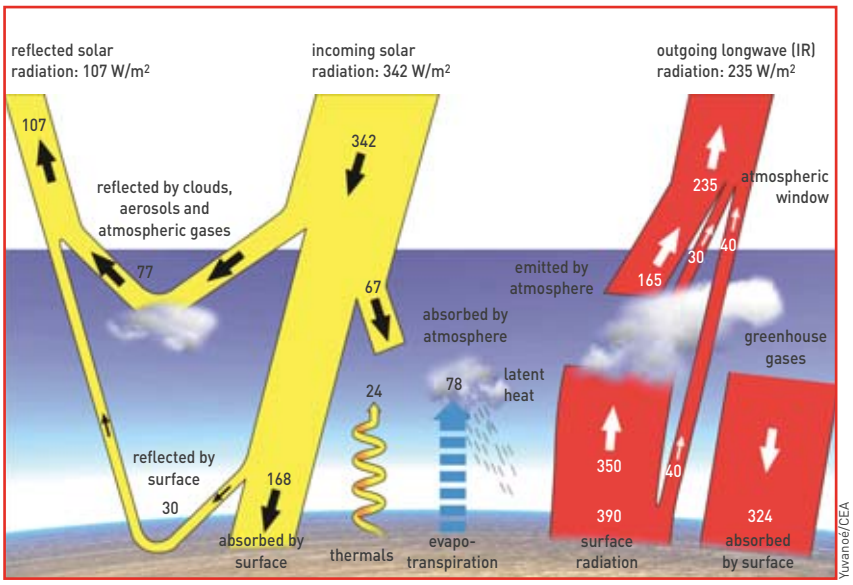
FOCUS C

Greenhouse gases and aerosols at the center of the climate change debate

Photolink

Solar radiation is reflected back into space by atmospheric air, white clouds, the Earth's surface, particularly in the Arctic and Antarctic regions.

In 1824, French mathematician Joseph Fourier had already surmised that the gases present in the Earth's **atmosphere** contribute to global warming. Thus, it is to him that we owe the first theory of the **greenhouse effect**. However, it was not before 1864 that Irish physicist John Tyndall identified **water vapor**, and **carbon dioxide** (CO_2) as the chief agents of that atmospheric phenomenon, and it was not before 1896 that Swedish physical chemist Svante Arrhenius put forward the account of the process that is still currently recognized.



Yuvanoé/CEA

Figure 1.
Energy fluxes within the climate system (IPCC diagram).

The greenhouse effect, a natural phenomenonl

It is from gardening parlance that the greenhouse effect draws its name – greenhouses being enclosed spaces, featuring walls that are transparent, to let through and trap in solar radiation, so as to raise the temperature to the requisite level for seedlings. In near space, the greater part (about 60%) of solar radiation passes right through the atmosphere, which is transparent to it, the presence of clouds notwithstanding, and heats up the planet's surface. Subsequently, 28% of that radiation is reflected back into space, by atmospheric air, white clouds, the Earth's surface – particularly by regions whiter in hue, such as the Arctic and Antarctic regions. This latter property is referred to as the **albedo**.

As for the radiation not so reflected, some 20% is absorbed by the atmosphere, and 51% by the Earth's surface, directly contributing to warming it. This heat is not fully retained by the **Earth**. It reemits some of it back into the atmosphere, where water vapor and various gases, including **carbon dioxide**, absorb that radiation, standing as a barrier that prevents that energy from passing directly from the Earth's surface into outer space, this having a twofold consequence. The result is a net warming of the atmosphere, and reemission of that

radiation, in all directions, in particular back again to the Earth's surface (see Figure 1). In the absence of that complement of heat, the planet's surface temperature would go down to –18 °C. It is this energy flow, within the climate system, that is referred to as the greenhouse effect. This is a natural phenomenon, and a well regulated one, since the energy the Earth receives is broadly equal to that emitted by the Earth into space. However, should an imbalance arise, the planet then proceeds to build up, or release the stored energy it holds, thus causing changes in temperature (see Figure 2).

Artificial disturbance of a natural phenomenon

Most greenhouse gases occur naturally. Such is the case, in particular, of water vapor, which is generated by evaporation arising throughout the water cycle. This accounts for about 0.4% of the atmosphere's composition (down to 0.1% over Siberia, 5% however over equatorial oceanic regions), standing as an agent in the natural greenhouse effect, of which it causes some 60%, while CO_2 stands as the cause of about 35%. While most greenhouse gases turn out to be of natural provenance, on the other hand the Intergovernmental Panel on Climate Change (IPCC) showed, as early as 1995, that the rise in emissions of such gases was indeed due to anthropic activities. Indeed, unprecedented demographic expansion (the world's population has soared from 1.7 billion to 6 billion over 100 years), compounded by activities stemming from the industrial revolution, has resulted in increased production, and consumption, inescapably going hand in hand with concomitant emissions, and pollution, involving a heavy environmental impact. The increased atmospheric greenhouse gas content due to such releases now ranks as the chief cause in the current imbalance in exchanges of energy between the Earth, and outer space.
Of the gases that stand out, as contributors to such an increase in the greenhouse effect, mention should be made of:

Carbon dioxide, or carbon gas (CO_2)

Concentration of this gas in the atmosphere has increased by 31%, between 1750 and 2006, rising from 280 ppm to 381 ppm, and is growing at a rate of 0.4% per annum, i.e. by an average annual increase of 1.5 ppm. Over the past few years, a steeper CO_2 increase has been evidenced, with an annual growth rate of 1.9 ppm, since 2000. CO_2 is responsible for some 39% of the rise in average surface temperature, on Earth, accounting for 60% of the increase found for the total greenhouse effect, over the past century. Such alarming outcomes may be accounted for by an inability of oceanic photosynthesis to counterbalance, at this stage, the releases that may be attributed to human activities.

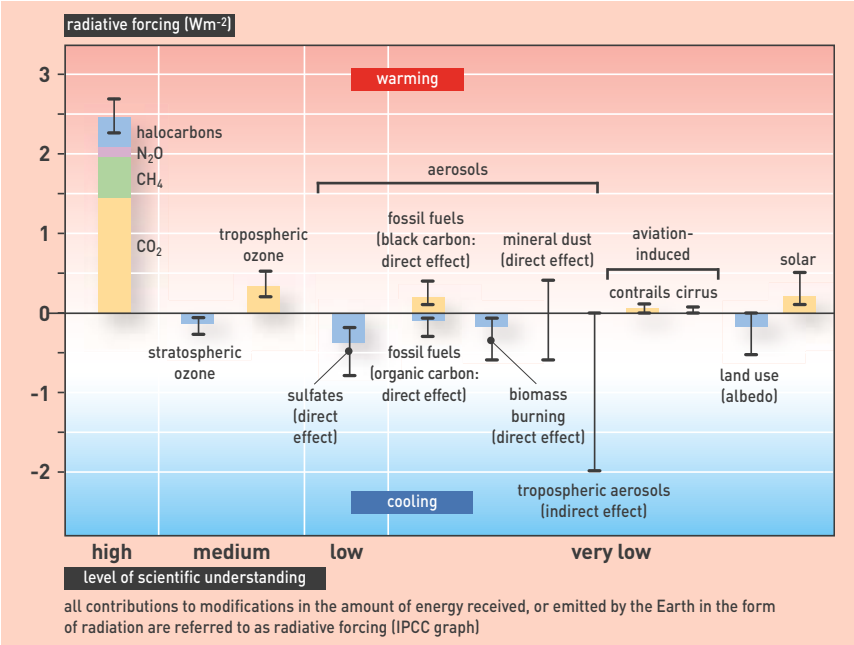


Figure 2.
Changes in radiative forcing between 1750 and 2000.

Methane (CH_4)

Accounting as it does for 1% of the increase in the Earth's surface temperature, and 20% of the increase in the total greenhouse effect, atmospheric concentration of this gas rose from 750 ppb in 1750 to 1,745 ppb in 1998, i.e. an increase of 150%. While about half of all methane emissions originate in the natural environment (e.g. from swamps, estuaries), the other half does arise from human activities (rice agriculture, direct releases into the atmosphere, digestive processes in humans, and animals, fossil fuel mining...).

Nitrous oxide (N_2O)

Whether of natural (soils, oceans) or anthropic provenance (nitrogen fertilizers, biomass burning, cattle farming, industry...), this gas contributes by 17% to the increase in greenhouse effect. Its concentration in the atmosphere rose from 270 ppb in 1750 to 314 ppb in 1998.

Ozone (O_3)

Generated as it is mainly over the equator, ozone diffuses to the poles, over which it builds up, in varying proportion, depending on the season (minimum concentrations occurring at the end of wintertime), or the time of day (night/day). In the atmosphere, ozone occurs at two levels:

- first, in the stratosphere, where it forms a protective layer around the Earth, filtering part of the ultraviolet radiation emitted by the Sun, thus shielding lifeforms on Earth, whether humans, or microorganisms, or marine phytoplankton. This protective layer is currently under threat, owing to pollution from releases of chlorofluorocarbons (CFCs), highly harmful gaseous compounds, occurring in pesticides, cosmetics, aerosols... which are the cause of the "hole" in the ozone layer. In 1998, world production of CFCs stood at 800,000 tonnes, i.e. about 100 grams per person on Earth. The "hole" in the ozone layer is the outcome of complex reactions from ultraviolet radiation on CFCs, resulting in the release of chlorine, this acting as a catalyst for the reaction destroying ozone to yield oxygen. To give an idea of its size, the "hole" in the ozone layer may spread out over an area as large as North America, and across a depth equal to the elevation of Mount Everest;
- second, ozone is found in the troposphere, i.e. in the atmosphere close to the ground, and thus in the air breathed by living organisms. Above certain concentrations, this gas stands as a hazardous pollutant. In large conglomerations, ozone arises from

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Activities stemming from the industrial revolution have resulted in increased production, going hand in hand with emissions and pollution, involving a heavy environmental impact.

reactions between **nitrogen oxides** released in exhaust gases from motor vehicles, or uncombusted **hydrocarbons**, and the oxygen in the air. If **meteorological** conditions are appropriate (as occurs in **anticyclonic** conditions), ozone removal slows down, resulting in respiratory diseases in frail persons, which has led to the setting up of air monitoring systems.

To sum up, the increase in atmospheric greenhouse gas content may be compared to the effects of installing double glazing in a horticultural greenhouse: if inputs of solar radiation stay constant, in the greenhouse, temperature inevitably rises. Of course, these various gases do not all have the same warming potential. Thus, the impact of 1 kilogram methane on the greenhouse effect turns out to be 23 times higher than that of 1 kilogram CO_2. The difference is calculated by way of the **global warming potentials** (**GWPs**) for these substances, with carbon dioxide as the reference (a substance's GWP is the factor by which the mass of that gas must be multiplied, to obtain the mass of CO_2 that would make an equal impact on the greenhouse effect). The lifetime of greenhouse gases in the atmosphere likewise varies, from 12 years for methane to 100 years for carbon dioxide. Of anthropic activities resulting in higher greenhouse gas concentrations, mention may be made, in particular, of the massive use of fossil fuels (coal, petroleum products, natural gas), deforestation for the purposes of cultivation and cattle grazing, which land uses cannot absorb as much carbon as a mature forest, rising releases of chlorofluorocarbons...

The specific issue of aerosols

Aerosols consist of fine particles suspended in the atmosphere. Of natural provenance, these aerosols originate in the ocean (sea salt, yielded by the evaporation of sea spray, **sulfates** arising from the **oxidation** of sulfur compounds released by plankton...), or continental landmasses (eolian erosion, soot arising from forest or bush fires, volcanic ashes and sulfates...). Readily transported as they are by air currents, **aerosols** may turn up at great distances from their point of production – as in the case of sand particles from the Sahara Desert, coming down onto vehicles in Europe. They may even reach the stratosphere, as happened after the eruption of Mount Pinatubo (Indonesia), when volcanic dust stayed in the stratosphere for 3 years, causing a fall in global temperature by one half-degree, for two years. On the other hand, humans, through their activities, also contribute to aerosol generation. Transportation, deforestation, industry, agriculture all yield dust. However, by far the greater part of anthropic dust production arises from the use of fossil and biomass fuels. Burning such fuels, by yielding **sulfur dioxide** (SO_2), thus causes acid rain and sulfate aerosols.

These aerosols have effects that run counter to those of greenhouse gases, in that they intercept part of the Sun's energy reaching the Earth. This is complemented by the indirect impact of aerosols on **climate**. Thus, they may act as water vapor condensation nuclei, in cloud formation, with a further incidence of aerosol concentration, influencing droplet size, and thus droplet in-cloud residence time. Another occurrence, due to aerosols absorbing the Earth's own surface radiation, is an aerosol-induced local warming of the atmosphere, altering its vertical stability; or, by way of complex chemical reactions, aerosols may influence greenhouse gas concentrations. In some cases, they may also have an effect on photosynthesis, by providing an

C. Sherburne/PhotoLink

Aerosols, i.e. fine airborne particles, are generated, in particular, by the ocean, or by forest or bush fires, but equally by volcanic eruptions.

essential input of nutrients for phytoplankton in the open ocean, or for the Amazonian rainforest.

The impacts of imbalance

According to the models drawn up by climatologists, the Earth's average temperature should rise by 2 °C over the coming century, on the assumption of a doubling in atmospheric greenhouse gas concentrations. Such global warming will not be without its effects on the planet itself, as investigations carried out by paleoclimatologists have shown that, in past times, a variation by only a few degrees was enough to result in major changes across the face of the Earth.

Among the chief consequences of global warming, a rise in sea levels must be anticipated, which, according to medium-range hypotheses, should reach 50 cm over the coming century. Owing to the melting of part of the polar ice sheets, and ocean warming, the loss of land area could be by as much as 6% in the Netherlands, 17% in Bangladesh, thus threatening nearly 92 million people living in coastal areas. In France, areas such as the delta of the Rhone River, in the south, would doubtless be affected. On top of such changes affecting landscapes comes a serious threat of famine, particularly in South, East, and Southeastern Asia, as well as in the tropical regions of Latin America. Hand in hand with more intense, longer-lasting heatwave episodes, public health-related risks will rise, with an expected increase in cardiovascular diseases, or swifter transmission of diseases such as malaria, yellow fever, or various types of encephalitis. As regards changes in climate, experts tend to anticipate increased frequencies, and durations for floods, and droughts. For instance, in France, in the event of a 2 °C rise in average temperature, wintertime precipitations would increase by 20%, while summertime precipitations would fall by 15%. Changes affecting oceanic currents should also play a major part. Thus, a slowing down in the Gulf Stream current, in the North Atlantic Ocean, could result in a marked falling off in temperatures across Western Europe, whereas temperatures would rise around the rest of the planet.

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Among the chief consequences of global warming, a rise in sea levels must be anticipated (estimated at 50 cm over the coming century), due to the melting of part of the polar ice sheets and ocean warming.

International action to mitigate climate change

Climate change and changes in the global environment have spurred an international reaction, along with the organization of a number of world conferences. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC), signed in Rio de Janeiro (Brazil) – and adopted by 178 states, and the European Union – set out a number of goals, the objective being a "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (article 2). Concurrently, the convention required developed countries to adopt policies and measures aimed at returning, individually or jointly, to their 1990 levels their emissions of carbon dioxide and other greenhouse gases.

However, by 1997, governments deemed the commitments made under the UNFCCC were proving inadequate. Now assembling in Kyoto (Japan), they decided, rather than to commit to a stabilization of emissions, to agree on quantitative greenhouse gas emission reduction targets, and timetables: a reduction of 10%, below 1990 levels, by 2012, i.e., for industrialized countries, an aggregate reduction in emissions by 5.2%. This outcome was made possible through the European Union's positive attitude, and its commitment to ensuring significant results. Nevertheless, such a percentage is still quite small, compared to the 25% increase in emissions recorded since 1999 – the more so since the United States did not ratify the Kyoto Protocol, while other, developing countries such as China or India, have been increasing their pollutant emissions. In the meantime, another conference was held, in Buenos Aires (Argentina), in 1998. This made it possible to set out compliance rules, and guidelines, along with detailing specifics for the general provisions carried in the Kyoto Protocol: emissions trading mechanism, sanctions, specifying best practice recommendations... Concurrently, a Conference of the Parties (COP) meets annually, to discuss climate issues. The 2009 COP meeting is to be held in Copenhagen (Denmark). This will stand as a major milestone, the aim being to arrive at a worldwide agreement on CO_2 reductions for the period beginning in 2012, when the Kyoto Protocol expires.

France: a special case

With emissions levels standing at 1.7 tonne carbon per year, per capita, in 1995, France ranks as one of the developed countries least contributing to the greenhouse effect. This result is due, first of all, to the energy conservation policy set in place after the first oil crisis, together with the use of nuclear energy for electrical power production. It is further due to the adoption of a national climate change mitigation program. This program provides for a number of measures, aimed at achieving reductions in emissions of carbon dioxide, methane, and nitrous oxide, in such sectors as construction (more stringent thermal regulations), industry (tax incentives to promote energy conservation), or transport (provisions to reduce vehicle energy consumption).

FOCUS D

Plate tectonics and earthquakes

The Earth's **crust**, i.e. the superficial, outermost portion of our planet, envelops the deeper layers, namely the **mantle**, and the **core** (see Focus A, *Journey to the center of the Earth, and the outer reaches of the atmosphere*, p. 21). Its thickness is augmented by that of the uppermost part of the mantle, together with which it forms the **lithosphere**, a mosaic comprising a dozen rigid plates (the so-called lithospheric plates), including 7 major plates, and 5 minor plates (see Figure 1). With a thickness varying from about 10 to 100 kilometers, these plates move across the underlying, more plastic part of the mantle, the **asthenosphere**.

In 1915, German meteorologist and astronomer Alfred Wegener published his hypothesis of **continental drift**. It was not before 1967, however, that this took on a formalized form. The theory was initially known as **seafloor spreading**, subsequently as **plate tectonics**. This describes the motions of these plates, moving as they do – either drawing apart (Arabia is thus moving away from Africa), or coming together – at a rate of a few centimeters per year. The source of the force setting the plates in motion is still a matter for debate: is this due to a **subduction** movement, initiated at the (cold) edge of a plate, resulting in a (hot) upwelling of the mantle at the opposite edge? Or is this due, conversely, to a hot upwelling of the mantle, "thrusting" against the surface, and causing the opposite, cold edge of the plate to go under? Or to the effect of a stress of a more mechanical nature, such as the weight of the subducting crust slab, pulling the plate with it, or the weight of the young crust pushing it along?

Be that as it may, these motions form the counterpart, at the surface, of the process of **convection** taking place within the mantle. This process is powered by heat (temperature stands at some 1,300 °C, at a depth of 100 km), coming from **radioactive decay** of rocks in the Earth's core, to wit potassium, **uranium**, and **thorium**. Convection is one of the three mechanisms through which cooling of the Earth takes place, by removing heat at its surface – along with **heat conduction**, and radiative transfer. Some regions in the mantle thus become hotter, and consequently less dense, and rise through buoyancy. The material cools at the surface (thus removing the heat generated inside the planet), becoming cooler, and consequently denser (and at the same time more "brittle"), causing it to sink again. This "conveyor belt" process leads to the emergence of relatively stable regions, in areas where matter is rising (**ridges**), or sinking (**subduction zones**), matter being displaced across the surface of the mantle, from the former to the latter areas. The Earth produces **magma** both along the rising, and sinking currents.

The motions driving the displacement of tectonic plates are found to be of several types. **Divergence** (spreading), whereby two plates move apart, allows the mantle welling up between them to replenish the oceanic lithosphere. The divergent interplate boundary corresponds to a ridge, which at the same time is a region of intense **volcanic** activity. **Convergence** involves two plates drawing together, resulting in three types of boundary. In **subduction**, one of the plates (as a rule the denser one, in most cases oceanic crust) dips under the continental crust. The area around the island of Sumatra, for instance, is thus a subduction zone, where the dense Indian–Australian Plate plunges under the less dense Eurasian Plate, at an average rate of about 5 cm per year. The **collision** of continental plates, on the other hand, is the cause of mountain range formation,

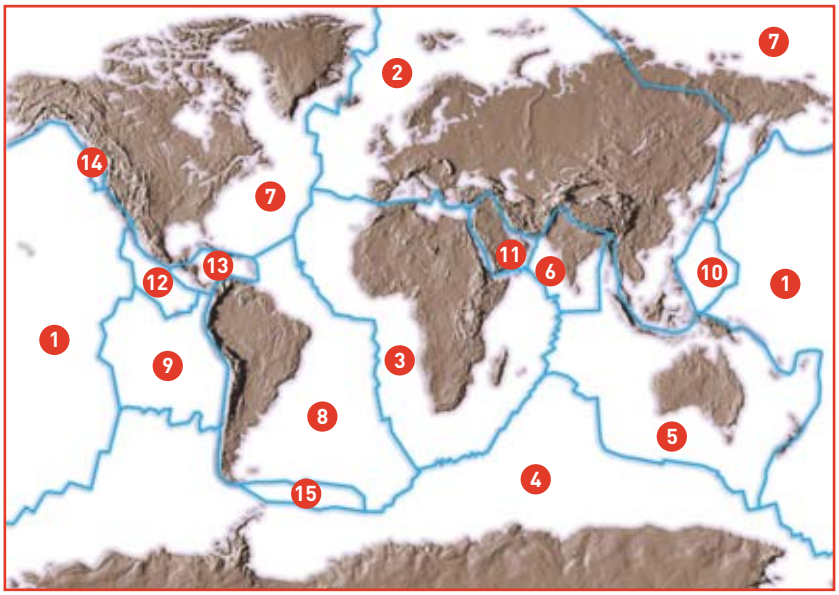

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Figure 1.
The Earth's outermost layer is subdivided into a number of rigid plates, slowly moving across the underlying viscous material in the asthenosphere, while rubbing one against the other. Certain plates may in turn be subdivided into several plates, involving smaller relative motions.

	plate	average velocity
1	Pacific Plate	10 cm/year northwestward
2	Eurasian Plate	1 cm/year eastward
3	African Plate	2 cm/year northward
4	Antarctic Plate	rotating about itself
5	Australian Plate	6 cm/year northeastward
6	Indian Plate	6 cm/year northward
7	North American Plate	1 cm/year westward
8	South American Plate	1 cm/year northward
9	Nazca Plate	7 cm/year eastward
10	Philippine Plate	8 cm/year westward
11	Arabian Plate	3 cm/year northeastward
12	Cocos Plate	5 cm/year northeastward
13	Caribbean Plate	1 cm/year northeastward
14	Juan de Fuca Plate	2.8 cm/year northeastward
15	Scotia Plate	3.6 cm/year westward

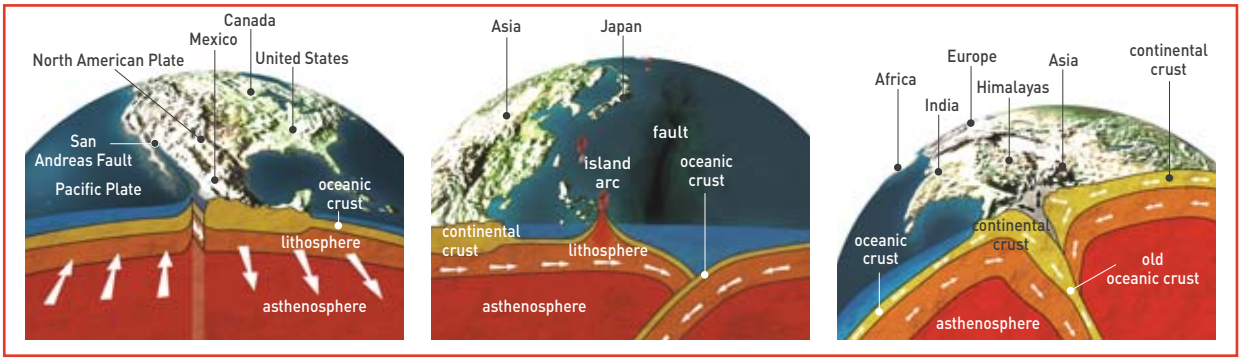

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Figure 2.
At left, an instance of transform boundary. The Pacific Plate and the North American Plate are slipping past each other, on either side of the San Andreas Fault, which is the source of Californian earthquakes. Middle, an instance of subduction. The formation of volcanic island arcs, extending from Japan to the Kuril Islands, and the Aleutians, is due to the fact that the Pacific Plate is plunging under the Eurasian Plate. At right, an instance of collision. The formation of the Himalayas is the result of the contest between the Indian Plate, and the Eurasian Plate, which overlap and undergo uplift.

e.g. the uplift of the Himalayas, at the boundary between the Indian, and Eurasian Plates (see Figure 2). Finally, **obduction**, or overthrusting, involves the transport of a section of oceanic lithosphere on top of a continent (no convergence process of this type is currently active). Another kind of interaction involves friction between plates: **transcurrence**, or **transform boundaries**, where two plates slip horizontally past each other (see Figure 2).

In effect, the three main families of **faults** are associated, respectively, to these interaction types: normal faults (divergent, extensional); reverse faults (convergent, compressional); and strike–slip faults (transcurrent: both the extension, and compression axes lie in the horizontal plane). Plate motions, classically monitored by means of conventional instruments (theodolites, distance meters), are increasingly tracked by way of satellite resources, namely the Global Positioning System (GPS), which proves particularly well suited to the requirements of deformation measurements, across a given region (see *GPS measurement of deformation: a method for the investigation of large-scale tectonic motions*, p. 95).

It is along interplate boundaries that most **earthquakes**, and **volcanoes** arise, as a consequence of the selfsame deep phenomena. A certain number of volcanoes are found to arise, however, right at the center of plates (these locations are known as **hotspots**). These hotspots are thought to be the surface manifestation of convecting blobs of material, less dense than the mantle as a whole, rising straight through the latter. Such hotspots – the largest ones are located under the islands of Hawaii (USA) and La Réunion (France) – scarcely move relative to one another, while plates "ride past" above them.

Volcanoes and earthquakes as markers of deep motions inside the planet

Volcanoes may be of the *effusive*, or *explosive* type, or a combination of the two. The former let molten rock stream out of their crater(s), and often occur as chains of

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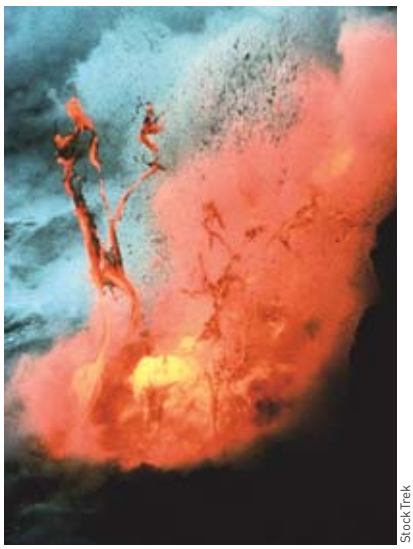
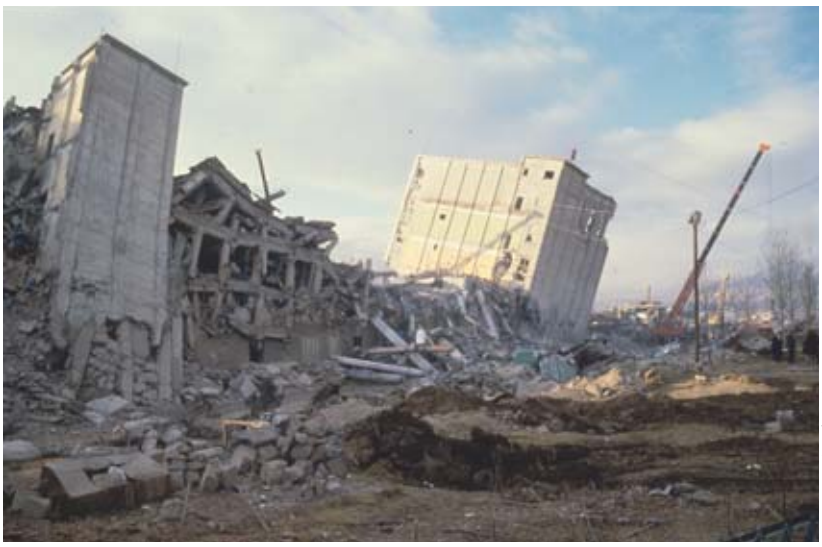


Stock Trek

The Pacific Plate is dotted with volcanic islands, such as Hawaii, where volcanoes numbered among the most active, the world over, are to be found.



CNRS Photothèque/Hervé Philip

Damage caused by the earthquake occurring in Spitak (Armenia), on 7 December 1988. This earthquake, of magnitude 6.2, resulted in a death toll of about 25,000. The violent release of strains, accumulating as plates move, scraping against one another, induces a concomitant, more or less abrupt, ground motion.

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volcanoes, especially under the sea. The second type involves volcanoes that hold in the rising pressure of imprisoned gases, until they "spring the plug;" these form alignments, and occur on islands, and continents. High-frequency, low-amplitude seismic noise (**tremors**) arises as a precursor of eruptions. Some 3,500 volcanoes have been active over the past 10,000 years.

Plate motions, as they edge one against the other, cause deformations in the Earth's crust, and a buildup of strains. When such strains exceed the crust's mechanical strength, weaker, more brittle zones fail. An earthquake is the violent release of such accumulated strains, involving more or less abrupt ground motion (from a few millimeters, to several tens of meters) along the faults.

Most earthquakes are of natural origin – the Earth experiences more than one million seismic shocks every year, some 140,000 being of a **magnitude** greater than 3,[1] while some may be due to motions of volcanic origin – however **seismic events** may also be induced by human activities, e.g. dam reservoir impounding, or **hydrocarbon** extraction from oil fields. Further, events such as mining or quarrying blasts, or nuclear tests, particularly underground tests, likewise set off seismic waves, very similar to those generated by natural events.

Regions involving intense seismic activity include *mid-ocean ridges*, subduction zones, areas around faults along which plates are slipping past each other (e.g. the San Andreas Fault, in California [USA]), and regions where collisions between continents are taking place.

The release of strains, as the earthquake occurs, gives rise to elastic vibrations, known as **seismic waves**, propagating in all directions, across the Earth and through water, from the point of initial rupture of the Earth's crust – the **focus** (or **hypocenter**) – lying somewhere between the surface and a depth of around 700 km. The **epicenter** is the point on the surface lying vertically above the earthquake focus: this, as a rule, is the point where the shock experienced at the surface is strongest. Seismic waves propagate at velocities ranging from 2 km/s to 14 km/s, with a longitudinal motion (**P waves**, this standing for pressure, or **primary** waves), or transverse motion (**S waves**, standing for shear, or **secondary** waves). P waves (6–14 km/s) act by *compression*, as in a coil spring, particles being displaced along the direction of wave propagation, whether in solids, liquids, or gases. S waves (3–7 km/s) are *shear* waves, displacing particles perpendicularly to the direction of propagation: these waves only travel through solids (see Figure 3).

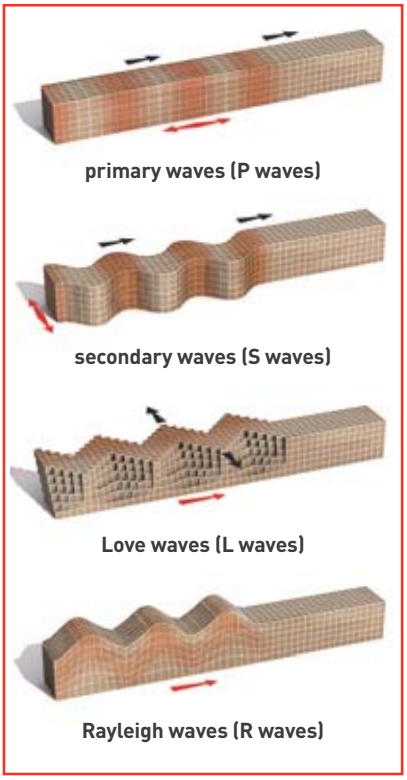
Velocity, for both types of waves, varies as a function of the density of the medium they travel through. The "softer" that medium is, the slower waves travel. Such wave phenomena are subject to physical laws, e.g. reflection, or refraction. It should be added that these waves do not all travel at the same velocity, depending on the medium they are traveling through. Further, as a P wave reaches a transition zone, e.g. the mantle–core interface, a small part of its energy is converted into S waves, making for more complicated interpretation of seismograph records. Seismologists therefore label waves by different letters, according to their provenance (see Table).

	P wave	S wave
mantle	P	S
outer core	K	
inner core	I	J

Table.
A PKP wave, for instance, is a P wave reemerging at the surface, where it is detected after it has passed through the liquid **outer core**.

Complementing these so-called body waves, surface waves – L waves (*Love waves*, causing a horizontal displacement), and R waves (*Rayleigh waves*, which are slower, and induce both horizontal and vertical displacement) – involving much larger amplitudes, propagate only through the crust, which is a less homogeneous medium than the mantle (see Figure 3).

It is through the painstaking effort initiated in the last century in seismological observatories, that tables could be drawn up, relating propagation time and distance traveled. That work thus contributed to enhancing knowledge of the **Earth's internal structure**, making it possible, presently, to **model** correctly the wave paths involved. Nowadays, methods such as **seismic tomography** further assist in improving models, in particular by taking on board three-dimensional structures.



Yuvanoé/CEA

Figure 3.
The various types of seismic wave. P wave propagation is parallel to the ground displacement induced, the ground being alternately dilated, and compressed.
In the case of S waves, rocks undergo shearing, and evidence distortion, due to vibrations perpendicular to wave propagation.
L waves and R waves propagate along the Earth's surface, and prove the most highly destructive types.

Seismic monitoring: location, magnitude, intensity, seismic moment...

Detecting a seismic event involves detecting the waves generated by it, by means of two types of facilities, appropriate for the propagation medium. Ground motions, even low-amplitude motions, are detected, both at close, and long distances, by **seismic stations**, fitted with **seismographs**, i.e. devices allowing the measurement of even the most minute ground motions, in all three dimensions, and yielding their characte-

(1) Currently, seismologists use magnitudes such as **moment magnitude**, for the purposes of estimating the size of very strong earthquakes. This magnitude, noted **Mw**, introduced in 1977 by Hiroo Kanamori, from the California Institute of Technology, is defined by the relation $\log Mo = 1.5\ Mw + 9.1$ (where Mo stands for the seismic moment, expressed in newton–meters). Information directed to the public at large usually refers to the **Richter magnitude** (open-scale magnitude), as established by Charles Francis Richter, in California, in 1935, initially defined for the purposes of quantifying the size of local earthquakes.

ristics, in terms of displacement, velocity, or acceleration.

Hydroacoustic waves, generated by undersea explosions, or explosions set off underground close to a sea, or ocean, are detected by **hydroacoustic stations**, comprising submerged receptors, and coastal seismic stations. Networking such stations around the globe (in particular in and around a region that needs to be monitored) makes it possible to determine precisely the geographic location of the earthquake focus, and to issue an alert call, if required. Indeed, while precursor signs do exist (variations in the local magnetic field, heightened groundwater circulation, reductions in rock **resistivity**, slight ground surface deformations), it is not feasible to predict earthquakes.

The first methods used for the purposes of locating seismic events, on the basis of the arrival times of the various wave trains, were based on geometric principles. For distances lower than 1,200 km, propagation times, for P waves and for S waves, are proportional, as a first approximation, to the distances traveled by these waves. The difference between the two times of arrival is thus itself, in turn, proportional to distance, this allowing the source to be located on a circle, centered on the station. By repeating this analysis, across several stations, the site of the epicenter may be geometrically located, at the intersection of the corresponding circles (see Figure 4). Current numerical methods deal with the problem globally, by treating it as an inverse problem, involving unknowns that are brought together into a 4-dimensional vector $\boldsymbol{x}$ (latitude, longitude, depth, event origin time), and data subsumed under a vector $\boldsymbol{t}$ covering the various measurements (e.g. wave arrival times). The direct problem, as noted by vector $\boldsymbol{t(x)}$, involves computing, from $\boldsymbol{x}$, the theoretical values associated to the data involved. Solving the **inverse problem** involves finding the vector $\boldsymbol{x_0}$ that minimizes the differences between $\boldsymbol{t}$, and $\boldsymbol{t(x_0)}$.

The characterization of an earthquake does not end with its geographical location. Describing the source poses a more complex problem.

Magnitude is a representation of the elastic energy released by the earthquake. Historically, this was based on the measurement – in well-defined conditions – of wave amplitudes, corrected for attenuation effects from the soils traversed. This is a logarithmic scale, energy being multiplied by a factor 30 for every increase by one unit! Over time, this definition was found to be incomplete, leading to a number of other definitions being put forward.[1] Magnitude should not be confused with earthquake **intensity**, this characterizing, on the other hand, the *effects felt* by human beings, and the *amount of damage observed* at a particular location, subsequent to the event.[2] The largest earthquake to have occurred since 1900 took place in Chile, in 1960, with a magnitude of 9.5. However, the earthquake taking the lar-

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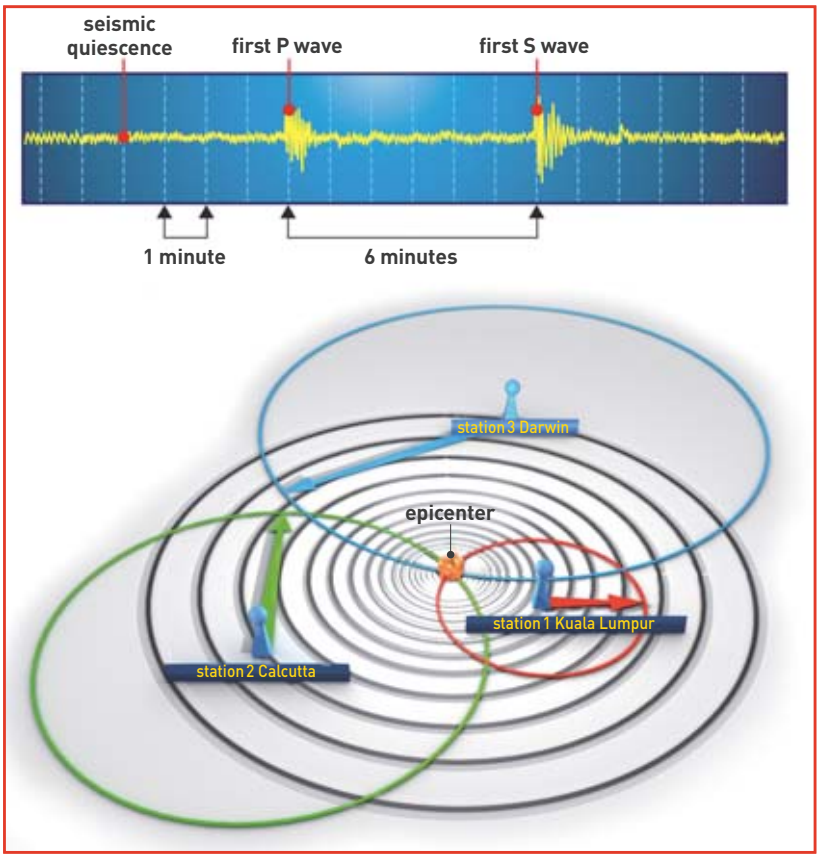
(2) In France, as in most European countries, the intensity scale adopted is the EMS–98 scale (European Macroseismic Scale, as established in 1998), which features 12 degrees.

C. Dupont/CEA

The short-period seismic detector allows measurement of ground motions involving periods shorter than 2 seconds. It is particularly suitable for the purposes of studying body waves generated by nearby earthquakes.



Yuvanoé/CEA

Figure 4.
The triangulation method has long been used for the purposes of locating a seismic event. The time difference between arrivals of P waves, and S waves allows the distance of the detector from the epicenter to be derived. On the basis of a number of seismic stations, each yielding a value for distance, the epicenter is located at the intersection of the circles centered on each station, of radius equal to the distance found at that station.

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gest toll in lives (some 250,000 casualties) was the Tangshan earthquake, in China, in 1976, with a magnitude of 7.5. The earthquake that affected Sichuan Province (southwestern China) on 12 May 2008, with a magnitude of 7.9, caused at least 90,000 casualties. One and the same earthquake, of a given magnitude, as defined by the energy released at its focus, will be experienced at varying intensity levels, depending on focus depth, distance from the epicenter, and the local characteristics of the observation location.

The concept of **seismic moment** was introduced, fairly recently, in an endeavor to provide a description of an earthquake in mechanical terms: the value of the seismic moment is obtained by multiplying an elastic constant by the average slip generated at a fault, and the area of that fault. This is complemented by the description of the rupture mechanism involved, specifying the parameters of the fault along which the rupture propagated (direction, length, depth...), the sections that have failed, their displacement, and rupture velocity, on the basis of wave recordings made by a number of detectors.

Nowadays, data from stations are directly transmitted via satellite to an analysis center, where every event is studied. Networks with a global coverage, such as the US World-Wide Standardized Seismograph Network (**WWSSN**), or Incorporated Research Institutions for Seismology (**IRIS**), or France's **Géoscope**, chiefly bring together equipment recording all the components of ground motion, across a wide band of frequencies. At the European level, the European–Mediterranean Seismological Center (**EMSC**) gathers all the findings from more than 80 institutions, in some 60 countries (from Iceland to the Arabian Peninsula, and from Morocco to Russia). In France, alongside the National Seismic Monitoring Network (**RéNaSS**: Réseau national de surveillance sismique), headquarted in Strasbourg, which covers all of mainland France, the global monitoring remit is entrusted to CEA, more precisely to the Detection and Geophysics Laboratory (LDG: Laboratoire de détection et de géophysique), coming under the Environmental Assessment and Monitoring Department (DASE: Département analyse, surveillance, environnement), part of CEA's Military Applications Division (DAM). LDG, based at Bruyères-le-Châtel (Essonne *département*, near Paris), seeks to detect, and identify, in real time, every seismic event, while advancing knowledge of the Earth's motions. The ensemble of data collected makes it possible to draw up a catalog of seismicity, a reference serving as the basis for the seismic zoning of mainland France, which was revised in 2007, for the implementation of the European Eurocode 8 (EC 8) seismic design standard, due to supplant existing French seismic design regulations (PS92, PS–MI) from 2010.

Finally, the French Permanent Accelerometer Network (**RAP**: **Réseau accélérométrique permanent**) – comprising more than one hundred stations, run on behalf of a scientific interest group, bringing together **CNRS**/**INSU**, CEA, **BRGM**, **IRSN**, **IPGP**, the Civil Engineers Central Laboratory (LCPC: Laboratoire central des Ponts et chaussées), and a number of universities – has the remit of providing the scientific, and technological community with data, allowing an understanding to be gained of phenomena related to ground motion during earthquakes, and arrive at estimates of such motion, in future earthquakes. The high sensitivity achieved makes it possible to investigate scaling laws, and nonlinearity phenomena. RAP should thus assist in the determination of reference spectra, allowing structural dimensioning to be carried out.

C. Dupont/CEA

DASE's geophysical signals analysis room. In this room, all signals are centralized, as they are detected by monitoring stations set up all around the world. Analysis of these signals makes it possible to alert instantly government agencies, in the event of a strong earthquake, a nuclear test, or exceptional events.

S. Poupin/CEA

Tests carried out on vibrating tables, in CEA's Tamaris laboratory – shown here, a test involving a structure of about 20 tonnes – have contributed to the drawing up of European seismic engineering standards for buildings.