



Glossary

accelerometer: a device used to measure acceleration.

actinides: natural, and/or artificial **radioelements**, of **atomic number** (i.e. the number of **protons** in the **nucleus**) ranging from 89 (actinium) to 103 (lawrencium).

activity: the number of **decays** per unit time within a **radionuclide**, or a mixture of radionuclides, expressed in **becquerels** (Bq).

advection: the transfer of a property solely through the motion of a fluid (e.g. the natural, horizontal motion of an airmass).

albedo: the ability of a surface to reflect light. The Earth has an albedo of 0.3, while that of a snowy surface may range from 0.6 to 0.8.

algology: the science concerned with algae, in particular microscopic algae (diatoms), making it possible, as with **palynology**, to reconstruct, on the basis of lacustrine **sediments**, past climate data.

algorithm: a sequence of logical-mathematical operations and operational rules required for the carrying out of a computation task.

ammonia (NH₃): a pyramidal, triangular-based **molecule**, comprising **nitrogen** (N), located at the center, while **hydrogen** (H) is positioned at three of the four apices, the fourth being occupied by 2 **electrons**.

analog system: a system similar to another one, one of these systems being simpler to investigate than the other.

analyte: a chemical substance undergoing detection, and measurement in the laboratory.

anode: an **electrode** where an electrochemical **oxidation** reaction takes place (resulting in production of **electrons**), as opposed to the **cathode**, where an electrochemical reduction reaction occurs (resulting in electron consumption).

anticyclone: an airmass involving high **atmospheric** pressure, subject to clockwise rotation in the Northern Hemisphere, anticlockwise rotation in the Southern Hemisphere; it is characterized by ascending air flows, precluding cloud formation, and is associated with dry, clear weather.

antigen: a **molecule** having the ability to induce an immune response (induction of antibodies).

atom: the basic constituent of ordinary matter, comprising a **nucleus** (made up of **neutrons** and **protons**) around which **electrons** orbit.

atomic number: the number of **protons** in the **nucleus**, for atoms of a given **element**.

backscatter gauge: a particular type of **nucleonic gauge**, for which the detector and radiation source are positioned on the same side of the object undergoing measurement; the detector measures the radiation scattering in the material.

basalt: a dark, near-black **volcanic** rock, yielded by **magma** cooling when in contact with water, or air, forming the main constituent of the **oceanic crust**. See **Focus A**.

bathymetry: the science concerned with measuring oceanic depths, to determine seafloor topography.

becquerel (Bq): named after French physicist Henri Becquerel. The unit of measurement for nuclear **activity** (1 Bq = 1 **atomic nucleus** decay per second). The becquerel is an altogether tiny unit! Nuclear activity was previously measured in curies: 1 **Ci** = 3.7·10¹⁰ Bq.

benzene: a monocyclic **hydrocarbon** (C₆H₆, also noted Ph-H, ϕ -H, or Ar-H); a natural constituent of crude oil, this is a carcinogenic liquid solvent, extensively used in the chemical industry.

beryllium (Be): the first representative of the alkaline-earth metals group, of **atomic number** 4, including ⁷Be, a **radioisotope** of this **element** having a **half-life** of 53.12 days.

biogen: a factor indispensable to the makeup of living matter; it is produced by, and within, a living organism, as e.g. the calcareous skeleton of corals, mother-of-pearl...

biomass: the total quantity of matter (mass) for all of the living species present in a given natural environment.

biome: each one of the main environments present across the globe (ocean, tropical forest, desert, tundra, savanna, prairie...).

biosphere: the ensemble of **ecosystems** on the planet, comprising all living beings, and the environments in which they live.

bromine (Br): a chemical **element**, a member of the halogen group, of **atomic number** 35.

calcium carbonate: a compound of **molecular** formula **CaCO₃**, comprising a **carbonate ion**, **CO₃²⁻**, and a **calcium ion**, **Ca²⁺**. It arises from **bicarbonate ions**, **HCO₃⁻**, and calcium ions: **Ca²⁺ + 2 HCO₃⁻ → CaCO₃ + H₂CO₃** (carbonic acid).

carbon (C): chemical **element**, at the head of the so-called crystallogenic group (carbon group), of symbol **C**, and **atomic number** 6, having an atomic mass of 12.0107. Carbon has two naturally occurring stable **isotopes** (¹²C, ¹³C), while ¹⁴C has a **half-life** of 5,730 years.

carbon cycle: the exchange of **carbon**, in a variety of forms (**carbon dioxide**, **methane**, organic matter...), between the atmosphere, the oceans, the terrestrial and marine **biosphere**, and the **lithosphere**. The lifetime of methane in the atmosphere is short (10 years); the same does not hold for carbon dioxide (several thousand years). See **Focuses A** and **C**.

carbon nanotubes: **crystal** structures, consisting of one or more rolled up graphene sheets (planes of **carbon** atoms, a single atom thick, stacks of which form graphite), involving **nanometer** diameters, with lengths however that may reach several, or even several hundred **micrometers**. Depending on the direction along which it is rolled, a carbon nanotube may be either metallic, or a **semiconductor**.

carbon sinks: this term refers to the process whereby **greenhouse gases** are extracted from the **atmosphere**, either by being destroyed by way of chemical processes, or by being stored in another form; for instance, **carbon dioxide** is often held in ocean water, plants, or subsoils. Forests and oceans absorb about one half of **carbon** emissions.

Carboxen: trade name for an absorbent **polymer**, used for the extraction of volatile **organic compounds**.

catechol (pyrocatechol): this is used as an anti-oxygen agent, as it inhibits chain **oxidation** reactions, by capturing radicals; it prevents, likewise, the spontaneous **polymerization** of some ethylene compounds, e.g. styrene. It arises as a degradation product from **naphthalene**.

cathode: the positive pole of an electric battery, or the negative pole in electrolysis.

centile: a term used in descriptive statistics, referring to each one of the 99 points (values) separating a set of ordered data into 100 equal parts, so that each part contains 1/100 of the population sample.

cesium: a chemical **element**, of symbol **Cs**, and **atomic number** 55.

chemical compound: a substance formed by the assembly of various kinds of **atom**, from distinct chemical **elements**, in definite proportions. The latter law was stated in 1794 by French chemist Joseph Proust.

chemiluminescence: a phenomenon arising in a chemical reaction, resulting in generation of light.

chemisorption: the adsorption of a **molecule** onto a surface, with concomitant setting up of a chemical bond.

chlorine (Cl): a chemical **element**, of **atomic number** 17, a member of the halogen group. **Dichlorine (Cl₂):** a **molecule** comprising two chlorine **atoms**; this is a gas in normal pressure and temperature conditions.

chloroform (trichloromethane): an organochlorine **chemical compound**, of formula **CHCl₃**.

chromium: a metallic chemical **element**, of symbol **Cr**, and **atomic number** 24.

chronostratigraphy: a branch of stratigraphy (the discipline concerned with the study of the succession in which the various geological layers, or strata, occur), concerned with investigating the age of rock strata, referred to a timescale, and having the purpose of classifying the various sequences and epochs of rock deposits, depending on the geological region, to draw up a complete geological record of the Earth.

climate: the more classical concept results from a spatial approach, whereby the Earth is divided into climate zones, depending on the **meteorological** conditions prevailing through the various seasons. Another concept corresponds to a global, temporal approach, whereby climatologists consider the changes arising in meteorological conditions, integrated across the entire planet.

climatology: the study of families of **meteorological** conditions, liable to have an effect on the various regions of the world, over extended time intervals. This draws on the various sciences concerned with nature, e.g. geography, geology, physics, chemistry...

cobalt (Co): a transition metal, of **atomic number** 27, and atomic mass 59. ^{60}Co (**half-life:** 5.27 years) is a gamma-emitter **radioactive isotope**, used in radiotherapy, and arises as an activation product, occurring in the waste from nuclear power plants. ^{57}Co , a short-lived isotope (271.79 days), is used as a radioactive tracer.

colloids: particles that occur naturally, of **nanometer** to **micrometer** size, of highly diverse types (clay, organic matter, quartz, bacteria, organic **macromolecules**), present in large quantities in soils. **Colloidal:** said of a system in which very fine particles are held in suspension in a liquid, a solid, or a gas, and involve a very high surface/volume ratio.

compartment: in a living organism or an **ecosystem**, this term refers to the biological space, in most cases of a virtual character, having however a measurable volume, occupied, in homogeneous fashion (concentration), by a substance or **molecular** population exhibiting a given behavior, and occurring in a single physico-chemical form.

complex systems: while there is no hard-and-fast consensus as to the definition, a system is said to be complex, first, if it comprises a large number of components, and if its behavior is not trivially predictable, and self-organization properties emerge from it; however, one and the same object may be seen as a complex system with regard to certain problems, and not be so considered in other problems: for instance, from the standpoint of celestial mechanics, the Earth is a point, whereas, if the scope narrows down to the sole **biosphere**, the Earth is seen to be a highly complex system.

complexation: the formation of a structure (a **complex**), electrically charged, or neutral, comprising a central **ion**, to which other **molecules** or ions are chemically bound.

computation code (or software): the assembly, in a computer software, in the form of coded mathematical expressions, of the simplified representation, in **numerical** form (**model**), of a system, or a process, for the purposes of simulation.

conductivity: the ability, exhibited by materials, to propagate heat, or electricity – being expressed, in the latter case, in siemens per unit length; semiconductivity arises in materials exhibiting electrical conductivity intermediate between that of conductor materials, and insulators.

convection: the ensemble of motions generated inside a fluid, due to density, temperature, or pressure gradients. This process contributes to heat transport.

convection current: an ascending, vertical motion undergone by air masses, due to heating up of the lower layers in the **atmosphere**.

cosmic radiation: a stream of charged particles (**protons**, helium and **heavy-element nuclei**) traveling through interstellar space at relativistic velocities. Some of these particles originate outside the solar system, while others come from the Sun, escaping through holes in the solar corona; they mostly interact with **atoms** in the upper atmosphere, before they reach the Earth's surface.

cosmology: the branch of astrophysics concerned with the study of the Universe as a physical system.

cryosphere (from the Greek *kryos*, meaning “icy cold, frost”): a term referring, collectively, to those parts of the Earth's surface where water occurs in the solid state (ice shelves, frozen lakes, and rivers, regions lying under snow, glaciers, inland ice, and frozen soils, whether temporarily or permanently [**permafrost**]).

crystal: an assembly of **atoms**, **ions**, or **molecules** arrayed in regular, periodic fashion across all three space directions.

Dansgaard-Oeschger event: this corresponds to a major, rapid warming event, followed by slower reversion to glacial conditions. Investigations of the variations in ice **isotopic** composition enabled two research scientists, one Danish, Willi Dansgaard, the other Swiss, Hans Oeschger, to identify, in 1984, very rapid changes in local temperatures during the last **glacial period**. The occurrence of 24 Dansgaard-Oeschger (D-O) events was confirmed in the 1990s and in the present decade.

Darcy's law: an empirical law, making it possible to relate the flow rate of a fluid through a porous medium to that medium's porosity, and the hydraulic gradient.

deglaciation: a major, generalized decrease in the area occupied by glaciers, resulting from **climate** changes.

depleted uranium: **uranium** having a content in **isotope** 235 – its only **fissile** isotope – lower than its natural level (0.71% by mass); this is mainly obtained, on the one hand, as the byproduct of an enrichment operation (with around 0.3% ^{235}U), and, on the other hand, as a byproduct (1% ^{235}U) of spent fuel reprocessing operations, subsequent to its in-reactor dwell time.

differential equation: in mathematics, a term referring to an equation defining the relation between one or more unknown functions, and their derivatives; the order of a differential equation corresponds to the highest degree of differentiation involved, for any one of the unknown functions; differential equations are used for the purposes of constructing mathematical **models** of physical and biological phenomena, e.g. for the investigation of **radioactivity**, or celestial mechanics.

dihydrogen (H_2): a **molecular** substance, occurring in the gaseous state under normal pressure and temperature conditions, its molecules comprising two **hydrogen atoms**; this is found in **trace** form (0.5 **ppmv**) in the atmosphere.

dioxin (polychlorodibenzo-*p*-dioxins or PCDDs): a generic name, also covering other families of **molecules** exhibiting common properties with PCDDs.

dioxygen (O_2): a **molecule** comprising two oxygen **atoms**; this occurs in the gaseous state, under normal pressure and temperature conditions.

Doppler shift (or Doppler effect): a shift in frequency undergone by an acoustic or **electromagnetic** wave, between its value as measured when emitted, and as received, when the distance between emitter and observer varies over time.

dosimetry: the determination, through measurement, or by way of an appropriate computation, of the quantity of energy absorbed within a given mass of material.

ecosystem: a grouping of biological communities, sharing a common physical environment; the atmosphere, the Earth, water, and living organisms, including humans, interact to form an ecosystem.

eddy correlation: a technique for the measurement of **atmospheric** fluxes, involving the statistical analysis of series of high-frequency fluctuations in wind velocity, and **carbon dioxide** concentration; the correlations (resp. anticorrelations) found allow the quantitative determination of a positive (resp. negative) carbon dioxide concentration flux.



El Niño: a warm marine current forming close to Ecuador, in the eastern Pacific Ocean, shortly after Christmas, owing to the very warm weather prevailing in the region at that time of year – hence the name El Niño, meaning “Christ Child.”

electrode: an **electron** conductor (in metal or **carbon**), or **ion** conductor (glass), either connected to the terminal of an electric generator, or forming part of a battery.

electromagnetic (radiation or wave): a radiation (or wave) that propagates, in a vacuum, at the velocity of light, through the interaction of oscillating electric and magnetic fields, and transports energy (**photons**). Light is an electromagnetic wave, characterized by its wavelength; the human eye is only able to perceive a limited segment of the electromagnetic wave spectrum, known as visible light (to each wavelength, the eye associates a specific color).

electron: a negatively-charged elementary particle. One of the constituents of the **atom**, orbiting around the **nucleus**.

element (chemical): the ensemble of all **atoms** having the same **atomic number** (i.e. all atoms having **nuclei** containing precisely the same number of **protons**, irrespective of the number of **neutrons**). A distinction is made between **light elements** (**hydrogen**, helium, lithium, **beryllium**, boron), and **heavy elements** (the others, from **carbon** to **uranium**, as far as natural elements are concerned – though more specifically those elements of atomic number equal to or greater than 80).

elution: a term used in **chromatography**, to refer to the migration of a substance across a porous solid medium, under the draining effect of a solvent. **Eluent:** a solvent used to effect the separation of substances **adsorbed** onto a substrate, in **liquid chromatography**, or thin-layer chromatography.

enzyme: a **macromolecule**, having the nature of a protein, acting as a catalyst for a biochemical reaction.

epidemiology: the science concerned with the study of the relationships between diseases, and various factors liable to influence their frequency, distribution, and evolution.

Euler's (or Eulerian) method: named after Swiss mathematician Leonhard Euler, this is a procedure used to solve, by way of approximation, first-order **differential equations** satisfying an initial condition. This is the most basic method used for the numerical solving of differential equations.

Eulerian model: a **model** that involves placing the observer in a fixed coordinate system, to observe the deformations arising in a medium.

femtogram: (10^{-15} g).

fission: the splitting of a **heavy nucleus** into two fragments, with concomitant emission of **neutrons**, radiation, and a considerable release of heat.

fluorescence: the emission of light, induced by absorption of an incident flux (of light, of **electromagnetic X-radiation** or of **electrons**), and subsequent rapid deexcitation of electrons in the outer **atomic** shells of the **luminescent** substance, this loss of energy taking the form of an emission of fresh electromagnetic radiation; should its wavelength lie in the visible part of the spectrum, **luminescence** occurs.

fluorine (F): chemical **element**, a member of the halogen group, of **atomic number** 9.

fluorophor (or fluorochrome): a chemical substance exhibiting the ability to emit light by **fluorescence**, after excitation.

foraminifera: single-celled organisms, appearing some 540 million years ago (during the Cambrian Period), characterized by a skeleton, or test, featuring one or more chambers, with one or more foramina (apertures). They lead an existence which is either benthic (on, or in seafloor **sediment**), or planktonic (suspended in water). Their size ranges, as a rule, from 38 μm to 1 mm, however some may reach a size of more than 10 cm.

fossil energies: energy produced from minerals formed by the fossilization of living organisms: petroleum, natural gas, coal; these occur in limited, nonrenewable quantities; burning such minerals results in formation of **greenhouse gases**.

Fourier transform: a complex mathematical formula, giving a measure of the relative “weight” of every frequency in a signal extending over time, in order to yield a spectral representation of that signal.

free electron: an **electron**, normally bound, at a distance, to the **nucleus** of an **atom**, which has broken from its bond with that atom.

gamma-measurement bench: a sounding device serving to effect the continuous measurement of emissions of gamma particles along a sample (a soil column); it may be used for two purposes: either to determine density, porosity, or water content, by measuring the absorption capacity of the sample, positioned between a **gamma radiation**-emitter source, and the detector; or to monitor the migration of a **radioactive** tracer within the sample, in the course of a tracing experiment.

gamma spectrometry: the measurement of **gamma radiation** energies, for the purposes of analyzing a mixture of **radioactive** substances.

geochemistry: the discipline making use of tools and concepts from chemistry for the purposes of carrying out an exhaustive scientific investigation of natural or anthropic processes in the Earth system.

geomorphology: the study of the topographical characteristics determining the shape, and formation, of terrestrial landforms.

glacial (period): a time interval standing both as a cold **paleoclimatic** phase, and a geological period of the Earth, during which a major part of the continents lay under ice.

glacial cycles: a sequence of **glacial** and **interglacial** stages. Over the past 800,000 years, these cycles have involved a period of 100,000 years, whereas earlier that period stood at 40,000 years.

glaciations: the return, at more or less regular intervals, of **glacial periods**, standing as one of the major characteristics of the Earth's history. The most recent glaciation occurred 21,000 years ago (in the **Pleistocene** Epoch), while the oldest ascertained goes back to the Precambrian (from about 2.3 billion years to 2.7 billion years ago).

grafted silica: chemically modified **silica** (SiO_2), bearing on its surface functional groups, **hydrocarbons** as a rule.

granulometry: the measurement of the grain size of the basic particles making up grain conglomerations (powders, sands, flours...), and determination of statistical frequencies for the various grain sizes in the ensemble being investigated.

graphitized carbon: an **adsorbent** phase, consisting of sheets of **graphite**, used in **liquid chromatography**, as a separation substrate.

hafnium (Hf): chemical **element** of **atomic number** 72, a transition metal.

half-life (radioactive): the time required for one half of the **atomic nuclei** of a **radioactive nuclide** to disappear through **radioactive decay**.

halide ion: a negative **ion** (anion), formed by an **atom** of a chemical **element** of the halogen group that has gained an **electron**.

halogenated solvents: these products chiefly involve **chlorine** compounds (trichloroethylene, perchloroethylene, dichloromethane), used for cleaning, and dilution purposes in basic chemistry, and metal treatment processes; they make it possible to dissolve, extract, or put in suspension many substances, without chemically altering them; they are, as a rule, hazardous compounds (in terms of their explosive character, toxicity, flammability) for humans and the environment.

heat conduction: the process whereby heat flows, within a medium, from a higher- to a lower-temperature region, or between two media coming into contact, from the higher- to the lower-temperature medium.

heavy metals: metals having a density higher than 4.5 g/cm³, e.g. zinc (7.14), cadmium (8.6), **lead** (11.35).

Heinrich event: an event corresponding to the release of large quantities of fresh water, and massive discharge of **icebergs** into the North Atlantic, due to glaciers melting. In 1988, while investigating North Atlantic marine **sediments**, German geologist Hartmut Heinrich found rocks eroded by glaciers. These had been released by icebergs in mid-ocean, as they melted. These events, thought to have occurred 6 times over the past **glacial period**, are noted H1 (the most recent one, 16,800 years ago) to H6 (the oldest, about 60,000 years ago). They are associated to global **climate** changes, on a worldwide scale. Millions of cubic kilometers of fresh water must have been released into the North Atlantic, resulting in considerable alteration to both oceanic surface water, and deepwater circulation.

hertz: a unit of frequency (**Hz**), equal to 1 cycle per second, for alternating phenomena. The chief multiples include the **megahertz** (1 **MHz** = 10⁶ Hz), and the **gigahertz** (1 **GHz** = 10⁹ Hz).

Holocene: the second epoch in the **Quaternary** Period, covering the past 11,400 years. This **interglacial period** comes after the **Pleistocene glacial phase**.

hydraulic conductivity: a quantity characterizing the ability of a porous medium to allow a flow of fluid to pass through, under the effect of a pressure gradient (see **Darcy's law**).

hydrocarbon: a **molecule** consisting solely of **carbon** and **hydrogen**.

hydrogen: a chemical **element** (H), having three **isotopes**, one of which is an **atom** simply comprising one **proton** and one **electron**; the other isotopes are **deuterium** and **tritium**.

hydrogen sulfide (H₂S): a gaseous compound of **hydrogen** and sulfur, released in the anaerobic (i.e. occurring in the absence of oxygen) fermentation of organic matter.

hydrogeology: the discipline, part of the Earth sciences, concerned with the study of groundwater, and, in particular, the quantity and quality of water resources.

hydrosphere: the ensemble of all water on the planet, including oceans, seas, lakes, waterways, and groundwater.

hydroxyl radical (OH): a radical comprising one oxygen **atom** and one **hydrogen** atom.

hygrometry: the measurement of the proportion of water held in air.

ice sheet: a mass of ice, extending across a large continental area, several thousand kilometers wide, lying near the poles. The thickness of an ice sheet ranges from 1 km to several kilometers.

iceberg: a block of freshwater ice that has broken away from an **ice sheet**, or glacier, and drifts across the ocean. Nearly 90% of its volume lies under water. Icebergs may float around the ocean for several months, or years, their thickness reaching, in some cases, several hundred meters.

infiltrometer: an experimental device, comprising a bottomless, cylindrical or annular reservoir; positioned at the surface of the soil, this measures the evolution, over time, of the constant-head infiltration rate, between an initial hydric state and a final, saturated state, when a permanent regime is set up, corresponding to the soil's saturation **hydraulic conductivity**.

interferometry: a measurement, or observation technique making use of interferences, making it possible to visualize the deformations arising in the **Earth's crust**, between two passes of a **radar** satellite. From two images obtained by radar satellites, an image of interference fringes (also known as an **interferogram**) is computed, from which variations in elevation may be reconstructed. See **Focuses A** and **D**.

interglacial (period): a period coming between two **glaciations**, during which average temperatures are relatively high. The present interglacial period is the **Holocene**, which began some 11,400 years ago. Such interglacial periods are short, lasting from 10,000 to 40,000 years, compared with **glacial periods**, which last about 100,000 years.

intertidal zone: the stretch of land that is covered at high tide, and exposed at low tide.

intertropical convergence zone (ITCZ): the zone, in the equatorial region, where trade winds from both hemispheres meet: those from the Northern Hemisphere being northeasterlies, those from the Southern Hemisphere southeasterlies.

ion: an **atom**, or **molecule** that has lost, or gained, one or more **electrons**, and is thus electrically charged (**cation**: positive ion; **anion**: negative ion).

ion-exchange resin: an **ion** exchanger is a solid having the ability to exchange ions held within itself, with other ions yielded by a solution, by effecting a shift in the prevailing equilibrium; if such exchanges are to be speeded up, allowing that equilibrium to be achieved, the solid must exhibit the largest possible contact surface area with the solution; initially, the first ion exchangers to be used were zeolites (natural inorganic compounds); nowadays, the substances used are synthetic **organic compounds**: an ion-exchange resin consists of a three-dimensional network, made of a high-mass **polymer**, most commonly polystyrene, onto which ionized, or ionizable functional groups are grafted, endowing it with an ion-exchange capability.

ionization: the process whereby charges are stripped from, or added to an **atom**, or a **molecule**, which, as it loses or gains these charges, ceases to be electrically neutral. It is then known as an **ion**.

ionizing radiation: radiation having the ability to generate, either directly, or indirectly, **ions** as it passes through a material.

iridium (Ir): chemical **element** of **atomic number** 77, a transition metal, and a member of the platinum group, occurring in the form of a hard, brittle metal, highly corrosion resistant, and exhibiting the properties of being a catalyst of hydrogenation, and synthesis reactions.

isoprene: a volatile, colorless, odorous liquid, readily flammable, and liable to form explosive mixtures with air; soluble in alcohol, acetone, **benzene**, it **polymerizes** into natural rubber, and may become a toxic **pollutant**, when occurring in large quantities.

isotopes: forms of one and the same chemical **element**, for which the **nuclei** have the same number of **protons** (and hence of **electrons** orbiting that nucleus), but different numbers of **neutrons**. **Heavy isotopes** involve high **atomic numbers**.

isotopic fractionation: the differential distribution of the various **isotopes** of an **element**.

isotropic: exhibiting identical physical properties in all directions (antonym: **anisotropic**).

jet stream: at the latitudes corresponding to Europe, the **atmospheric** general circulation is characterized by strong westerly winds, at altitude, arising as a permanent regime. These are commonly known as westerly jets.

kinetic: relating to the rate at which chemical reactions occur.

kriging with outer drift: named after South African mining engineer Daniel Gerhardus Krige, kriging is a spatial interpolation technique, originating in geostatistics, that includes a weighting rule for the variables subject to mapping, directly derived from the spatial distribution of their values. Kriging with outer drift further takes in the correlation that may prevail between the variables being mapped, and an external auxiliary value.

laboratory channel: a special instance of a physical **model**, corresponding to a simple case, as it involves a one-dimensional flow, making it possible to focus on more fundamental processes.

Lagrangian measurements: the principle of such measurements is to make a "snapshot" of a phenomenon, at a given point in time.



lanthanides: a chemical series of transition metals, including **elements** with **atomic numbers** ranging from 57 to 71.

laser: a light source yielding waves that are monochromatic (of a single wavelength), and spatially and temporally coherent (always in phase).

laser diode: an optoelectronic component, providing a source of coherent light, in which beam intensity may be varied by means of a variable voltage.

Laurentide and Fennoscandian Ice Sheets: **ice sheets** that covered parts of North America (**Laurentide Ice Sheet**), and parts of Northern Europe (**Fennoscandian Ice Sheet**) during **glacial periods**. Their existence resulted in a lowering of sea levels, which stood, during the Last Glacial Maximum, 21,000 years ago, some 110 m below present sea level (the Antarctic contributing a further 10 m). The last remnants of these ice sheets disappeared 7,000 years ago.

lead: chemical **element**, a member of the so-called crystallogen group (carbon group), of **atomic number** 82, having a number of natural **isotopes**, including ^{212}Pb and ^{210}Pb .

ligand: an **atom**, **molecule**, or **ion** featuring chemical functions enabling it to set up bonds with one or more central atoms, or ions, in a **complex**.

LMDZ code: a 3D general circulation **model**, developed at LMD, having the ability to “zoom” in onto a particular region, i.e. to cater for a finer-pitched grid for a given region.

luminescence: the process whereby certain substances, when subjected to radiation, emit visible radiation (light), of a wavelength, different from that of the incident radiation, characteristic of the substance involved. There are various kinds of luminescence: it may e.g. be prompt (**fluorescence**), or delayed (**phosphorescence**).

macromolecule: a very large **molecule**, formed by the reiterated concatenation of a large number of chemical groups, either identical, or different (known as repeating patterns), linked one to another by means of covalent bonds.

magnetic susceptibility: the ability of a material to become magnetized under the influence of a magnetic field.

Mascarene (or Mascarenhas): the ecoregion defined by the archipelago of that name, in the southwestern Indian Ocean.

mechanistic model: a **model** incorporating the laws, or mechanisms governing the evolution of a **complex system**, by contrast to descriptive, or statistical models.

mesoscale: in **meteorology**, and oceanography, this refers to a scale intermediate between the planet-wide circulation (depressions, and **anticyclones** covering an entire continent, marine currents, etc.), and very-small-scale phenomena, extending over a diameter of less than 2 km.

metal oxides: oxides serving as a base for ceramic pigments (**cobalt** oxide for blue, **chromium** oxide for green...).

metaphysics: the branch of philosophy that considers the principles involved in reality, going beyond any one particular, specific science; it further has the aim of unraveling the ultimate nature of being, the world, the Universe, and our interaction with that Universe.

meteorology: the study and prediction of atmospheric phenomena over short time intervals, and across well-defined geographical spaces. The data dealt with are thus of a point character. The feature that sets **climate** apart from meteorology is that climate **simulations** require integrations over extended intervals, in order to extract an average climate.

methane: a **hydrocarbon** of **molecular** formula CH_4 ; methane is the main constituent of natural gas, and biogas, yielded by the fermentation of organic matter of animal, or vegetal origin. It is naturally released over poorly oxygenated wetlands, e.g. swamps, and flooded land. It also arises in the rumen of cattle. Methane is one of the chief **greenhouse gases**. See **Focus C**.

MetOp: the first European meteorological satellite, put into a low-altitude (837-km) polar orbit around the Earth. It carries 11 instruments, making it possible to obtain a detailed picture of the changing **atmosphere** enveloping the Earth. Its purpose is the investigation of operational **meteorology**, global **climate**, and climate change, and to facilitate search and rescue operations, and the monitoring of charged particles present in the Earth's atmosphere.

micro-: a prefix (symbol μ) representing one millionth (10^{-6}). 1 **micrometer** (μm), or **micron** = 10^{-6} m; 1 **microgram** (μg) = 10^{-6} g.

modeling: the working out of a simplified representation (a **model**) for a system, or process, for the purposes of simulating it, which is then drawn up in a computation software (often referred to as a **code**), in the form of mathematical expressions. Mesh **cell** size, across space and time, yields the model's **resolution**.

molecular biology: a scientific discipline standing at the crossroads between genetics, biochemistry and physics, having the purpose of understanding the cell's operating mechanisms, at the **molecular** level; this term is also used to refer to the ensemble of techniques involved in the manipulation of nucleic acids (DNA, RNA), also known as genetic engineering techniques.

molecularly imprinted polymer: an absorbent **polymer**, specifically structured around a given **molecule**, or family of molecules, and exhibiting a selective **adsorption** capability with regard to that molecule, or family of compounds, through recognition of the relevant molecular imprint.

molecule: a group of **atoms**, held together by chemical bonds.

monsoon: a climatic phenomenon, arising in the intertropical region, and chiefly affecting India and Indonesia, but equally Africa, characterized by high temperatures, and, most importantly, heavy rainfall, which arrives abruptly, after a dry season.

Monte-Carlo computation: a method to obtain an approximate solution for an equation, using parameter values randomly drawn from within certain intervals.

morphogenesis: the process whereby relief formation occurs in the Earth's crust, making it possible to understand the origin, and shaping of landforms.

nano-: a prefix (symbol **n**) representing one billionth (10^{-9}). **Nanometer** (**nm**): 1 nm = 10^{-9} meter. **Nanotechnologies** are the ensemble of processes used for the fabrication and handling of nanometer-scale structures, devices, and material systems.

naphthalene: a bicyclic aromatic **hydrocarbon**, of formula C_{10}H_8 .

Navier-Stokes equations: named after two 19th-century physicists, Claude Navier and George Stokes; used in fluid mechanics, these are nonlinear partial differential equations, describing the motion of fluids, in accordance with the continuous media approximation. These equations govern, for instance, the motions of **atmospheric** air, ocean currents, the flow of water inside a pipe, and many other fluid-flow phenomena.

Neolithic (from the Greek *neos*, meaning “new,” and *lithos*, meaning “stone;” literally: **New Stone Age**): a period of major changes in the evolution of human societies, corresponding to the domestication of plants and animals, the taking up of sedentary lifestyles, and the widespread use of polished stone implements and ceramic pottery.

neutron: an electrically neutral particle, 1,839 times heavier than an **electron**. Neutrons are, together with **protons**, the constituents of atomic **nuclei**.

nitrate (formerly known as niters, often used as a synonym for saltpeter): the salts yielded by nitric acid; the chemical formula for the nitrate **ion** is NO_3^- .

nitric oxide (or **nitrogen monoxide**) (**NO**): a **chemical compound** comprising one oxygen **atom** and one **nitrogen** atom; this is a gas under normal pressure and temperature conditions, and it acts as one of the few gaseous neurotransmitters in mammals.

nitrogen: chemical **element** of symbol N, and **atomic number** 7.

nitrogen dioxide (NO₂): this compound arises in the **atmosphere**, from **nitric oxide (nitrogen monoxide) (NO)**, this being chiefly released by fossil fuel burning, as occasioned by road traffic, for instance. Nitrogen dioxide transforms, in the atmosphere, into **nitric acid**, this falling down to the ground, and onto vegetation. This acid contributes, together with other pollutants, to the acidification of natural environments.

nitrogen oxides (NO_x): a family of compounds, including **nitric oxide**, or **nitrogen monoxide (NO)**, **nitrogen dioxide (NO₂)**, **nitrous oxide (N₂O)**, dinitrogen trioxide (N₂O₃), and dinitrogen tetroxide (N₂O₄).

nitrous oxide (N₂O): also known as laughing gas; this compound has many applications: as an anesthetic, as oxidant in certain rocket propulsion systems, and even in canisters of Chantilly whipped cream.

noble gases (or rare gases, inert gases): gases belonging to a group of chemical **elements**: group 18 in the periodic table. This group includes helium, neon, argon, krypton, xenon and **radon**. Ununoctium, a recently synthesized artificial element, is likewise seen as a member of this group. Elements in the noble gas group exhibit a specific characteristic: they are very weakly reactive, since they feature a complete outer electron shell (valence shell). This shell, saturated as it is in terms of **electrons**, is very stable, and the **atom** consequently neither yields, nor accepts further electrons. Chemical bonding thus proves virtually impossible with noble gases, with the result that, by contrast to other gases, they are monatomic.

North Atlantic Drift: a powerful warm ocean current, a northeastward extension of the Gulf Stream (the latter originating in the area between Florida and the Bahamas, and diluting itself into the Atlantic Ocean around the longitude of Greenland). This current splits in two, west of Ireland.

nucleonic gauge: a measuring device (physical parameter measurement), relying on radiation-matter interaction. See also **backscatter gauge**, **transmission gauge**.

nucleonic techniques: measurement techniques relying on **ionizing radiation**-matter interactions; the measurement of the radiation involved, subsequent to its interaction inside the material subject to investigation, allows information on that material to be obtained.

nucleus (atomic): the chief constituent in an **atom**, bearing a positive charge and comprising **protons** and **neutrons** (except in the case of **hydrogen**), and around which **electrons** orbit.

nuclide: a nuclear species, characterized by its number of **protons** *Z* (i.e. its **atomic number**), number of **neutrons** *N*, and mass number *A*, this being equal to the sum of the number of protons and number of neutrons ($A = Z + N$).

numerical simulation: a method involving the mimicking, by way of computation, of the functioning of a system, as described by a **model**, or an ensemble of models.

ocean ridge: a submarine chain of **volcanoes**, extending continuously over more than 60,000 km, rising to a depth, on average, of ~2,500 m, and corresponding to the boundary between **divergent tectonic plates**, between which **magma** wells up, and flows out, to form the **oceanic crust**. See **Focuses A** and **D**.

organic compound: a **chemical compound** is said to be organic when it contains at least one **carbon atom**, bound to at least one **hydrogen** atom.

orography: that part of physical geography which is concerned with the formation and structure of mountains, and, more broadly, the disposition of relief on the Earth's surface.

oxidation: a chemical reaction whereby the oxidized constituent loses one or more **electrons**.

oxidation-reduction: a process whereby **electrons** are transferred from one species to another; the term "oxidizing agent" (or "oxidant") refers to the species that captures the electrons, while "reducing agent" (or "reductant") refers to the species that releases them in this chemical reaction.

paleo- (from the Greek *palaios*, meaning "ancient"): prefix indicating, in Earth sciences, that the term relates to past geological times.

paleoclimatology: the science concerned with the study of the **climatology** of past ages, going back over thousands, or millions of years. By providing global, or local indicators of past climate, paleoclimatology feeds into the debates on a variety of topics of current concern, e.g. global warming.

palynology: the study of pollens, and spores, making it possible to reconstruct, from core samples of **sediments**, data relating to past vegetation, and **climates**; the analysis of charcoals of vegetal origin in sediments is known as "anthracology."

Pangea (from the Greek *gê*, meaning "land, earth," and *pan*, meaning "all," literally: "All Lands"): a supercontinent bringing together virtually all of the present continents, forming between 360 and 250 million years (Ma) ago, following the collision of *Protogondwana* with *Laurussia* (also known as Euramerica). The vast ocean surrounding Pangea, *Panthalassa*, was the ancestor of the present Pacific Ocean, while the great ocean extending eastward from that continent was the **Tethys Ocean**. Pangea started breaking up about 200 million years ago, yielding two new supercontinents: *Gondwana* (bringing together present-day South America, Antarctica, Africa, India, and Australia), and *Laurasia* (Europe, North America, Asia without India).

pascal: the international unit of pressure (**Pa**). Its multiples include the hectopascal (1 **hPa** = 100 Pa).

pedology: the branch of Earth sciences concerned with the study of soils, their formation, and evolution.

petrography: the science concerned with the description of rocks, and analysis of their structural, mineralogical, and chemical characteristics.

pH (hydrogen potential): a measure of the acidity, or alkalinity of a solution.

phase transition diagram: a classical representation, in statistical physics, setting out the various states (phases) a system may take on, as a function of a number of parameters. One well-known example is the phase diagram for water (ice, liquid, vapor), as a function of pressure, and temperature.

photochemistry: the study of the chemical effects generated by light radiation.

photon: the quantum of energy of an **electromagnetic radiation**. An elementary particle, having zero mass and no electric charge, associated to such radiation.

photosynthesis: the process whereby plants, and certain bacteria, use solar energy to carry out the synthesis of organic **molecules**, from **carbon dioxide**, and water.

physical model: a scaled-down model of a given site, with the representation of the physical characteristics of that site, to scale, including **sediments** liable to be transported to the site.

piezometric: relating to a height of water, as measured in a well; at any given point in a porous medium, this corresponds to the elevation of the free surface of the static column of liquid that would balance hydrostatic pressure at that point.

plasma: a state of matter in which it consists solely of charged particles (**ions**, and **electrons**).

Pleistocene: the epoch in the **Quaternary** Period beginning 1.806 million years ago, and ending about 11,400 years ago. It includes most of the recent **glaciations**. The end of the Pleistocene coincides with that of the Paleolithic, as recognized in archeology.



plutonium: element of **atomic number** 94, and symbol Pu, having **isotopes** ranging from ^{232}Pu to ^{247}Pu . Five of these isotopes are important, from ^{238}Pu to ^{242}Pu , especially ^{239}Pu , a **fissile** element, generated inside nuclear reactors from **uranium-238**.

polarography: a special form of **voltammetry**, using as working **electrode** a dropping mercury electrode; this method is used for the analysis of **oxidations**, and reductions occurring in solutions: it thus belongs to the field of electrochemistry, the science concerned with the description of chemical reactions involving **electron** transfers.

polyacrylate (or acrylic resin): an absorbent **polymer** phase, widely used for the purposes of extracting **organic compounds**.

polymer: a **macromolecule** involving the repetition of an identical structural pattern, known as a monomer (from the Greek *monos*, meaning "solitary, single," and *meros*, meaning "part").

potassium–argon and argon–argon dating: the potassium–argon (K–Ar) dating method, and the derived argon–argon (^{40}Ar – ^{39}Ar) method rely on the natural **radioactive decay** of ^{40}K into $^{40}\text{Ar}^*$. In a closed **crystalline** system, as e.g. rocks, or volcanic minerals, parent **isotope** (^{40}K) content decreases. Conversely, daughter isotope ($^{40}\text{Ar}^*$) content rises over time. A K–Ar, and Ar–Ar age is thus obtained by measuring the numbers of parent isotopes remaining, and daughter isotopes formed, building up within the system. The ages that may be determined by way of these methods lie in a range from a few thousand years to one billion years.

ppm: part per million; **ppmv:** part per million by volume (for concentration measurements); **ppb:** part per billion (10^9).

precipitation: in a solution, the formation of an insoluble, solid substance, as a result of a reaction between two liquids, or gases.

principal components analysis (PCA) (statistical): a mathematical method used for data analysis, involving seeking the spatial directions best accounting for the correlations prevailing between n random variables.

proton: a particle – a constituent of the **atomic nucleus** – bearing a positive electric charge, equal to that of the **electron**, and of opposite sign. A proton is 1,836 times heavier than an electron.

Quaternary: the latest geological period, beginning around 2.4 million to 1.5 million years ago, and continuing through to the present, characterized by repeated **glacial cycles**. The Quaternary Period includes the **Pleistocene**, and **Holocene** Epochs. In paleontological terms, this period is marked by the evolution of the genus *Homo*, of which humans are a species.

radiation budget (or radiation balance): the difference between the energy received from the Sun, and that reemitted by the Earth into space. There is **radiation equilibrium** when the amount of energy received is equal to the amount of energy reemitted.

radiative forcing: a variation in energy, expressed in **watts** per square meter (W/m^2), due to a change in the **radiative equilibrium**; any contribution to modifications in the amount of energy received, or emitted by the Earth in the form of radiation. For instance, a doubling of preindustrial **carbon dioxide** levels ($280 \rightarrow 560$ **ppm**) corresponds to a further radiative forcing of $4 \text{ W}/\text{m}^2$.

radio wave (or radioelectric wave): an **electromagnetic wave** of a frequency lower than 3,000 **GHz**, i.e. of wavelength longer than 0.1 mm.

radio-frequency identification (RFID): a method used to hold, and remotely recover data, through the use of labels known as "RFID tags."

radioactive decay: the spontaneous transformation of a **nucleus**, through **radioactive disintegration**, or emission of a particle; the falloff, over time, of the **activity** exhibited by a radioactive substance, owing to radioactive decay of its constituent nuclei.

radioactive disintegration: the process whereby a **nucleus**, or particle undergoes **fission**, i.e. splits into several fragments (particles, and nuclei, forming *fission products*, **photons**), corresponding to lower-energy, and thus more stable states, the characteristics of that transformation depending only on the initial state of the nucleus (or particle), not on the process that brings it about.

radioactivity: the property, exhibited by a **nuclide**, of transforming spontaneously into another nuclide, this involving an emission of radiation (particles, **X-radiation**, **gamma radiation**...), or of undergoing spontaneous **fission**, with a concomitant emission of particles, and gamma radiation.

radiometry: the measurement of energy fluxes associated to **electromagnetic radiation**; radiometers are devices serving to carry out such measurements.

radionuclide: a **radioactive nuclide**. The various radionuclides corresponding to one and the same **element** are referred to as **radioisotopes** of that element.

radium: a white, shiny metal, a member of the alkaline earth group. ^{226}Ra : one of the 25 **radioactive isotopes** of radium, forming part of the **decay** line of **uranium-238**. By way of emission, ^{226}Ra transforms into ^{222}Rn , which has a **half-life** of 3.8 days.

radon: a natural **radioactive element** (^{220}Rn , and, most abundantly, ^{222}Rn), yielded, in gaseous form, within rocks, and construction materials, by the **decay** of **uranium**, and **radium**, present in the Earth's crust. ^{222}Rn : the most stable **isotope** of radon.

reaction–diffusion equations: equations used to represent diffusion and reaction mechanisms, between the components of a system; these exhibit complex behaviors (chaos, self-organization...), and may be applied to highly diverse phenomena: population dynamics, chemical waves, ecology, **epidemiology**...

regression: a statistical tool, making it possible to extract a trend from a set of experimental data.

resilience: the ability exhibited by an **ecosystem**, or a species to recover, and return to normal functioning, or development, after being subjected to an aggression.

resistivity: the specific resistance (resistance per unit volume) of a material to **electron** travel.

scalar parameter: a quantity that may be described by a single number, and the relevant unit, in any given point in space.

scintillation detector: in this type of radiation detector, the sensitive element consists in a **crystal**, within which **ionizing radiation** enters into interaction, yielding light; this light is then captured at a **photocathode**, to be turned into **electrons**, these subsequently undergoing amplification inside a photomultiplier tube; an electric signal is thus obtained, proportional to the quantity of incoming radiation.

sediment: an initially unconsolidated deposit, brought by water, wind, and other erosion agents, and which, depending on its origin, may be marine, fluvial, lacustrine, or glacial sediment.

seismotectonics: the branch of **geodesy**, and geophysics concerned with the study of **tectonic** structures, and motions, through the investigation of **earthquakes**, and the relationships prevailing between earthquakes, and tectonics. See **Focus D**.

semiconductor: a solid exhibiting, at ambient temperature, a **conductivity** intermediate between that of insulators, and conductors, its conductivity thus increasing with temperature; depending on the doping agents employed, a semiconductor may be of the "p" type (conductivity arising by way of holes), or of the "n" type (the doping **atom** yielding **electrons** taking part in conduction).

silica (or silicon dioxide) (SiO_2): an insulating material, used in **semiconductors**.

silver (Ag): chemical **element** of **atomic number** 47, one of the transition metals.

sol-gel process: a chemical synthesis process, using a solution holding reactive precursors, such as alkoxides or metal salts, involving two steps: hydrolysis and condensation (formulation of a covalent network); the **colloidal** suspension (*sol*) consists of a solid phase, involving grain sizes ranging from 1 **nm** to 1 **µm**, dispersed in a liquid; after condensation, the solution evolves to form a system of higher molecular complexity, imprisoning the solvent: the *gel*.

sorption: an interaction process between a solid surface and an **atom** (whether **ionized** or not), or a **molecule**; as a rule, this is characterized by the solid material's ability to set up chemical bonds at its surface with the compound involved. **Adsorption** involves the bonding of molecules, by various means, onto a solid surface, by way of a process that is, as a rule, passive, and nonspecific (e.g. by way of an electrostatic effect, in a gaseous or liquid medium). **Desorption** is the reverse process.

space geodesy: the science concerned with measurement of the Earth, using ground-based and spaceborne systems (using, for example, artificial satellites, e.g. GPS, DORIS).

spallation reaction: a nuclear reaction whereby **nuclei** are exploded, yielding constituent particles.

spatial resolution: the smallest angular, or linear separation between two objects, characterizing in particular the ability of an optical system to distinguish, or reproduce details in a scene, or its image.

speciation: the determination of the various forms in which a given chemical species occurs, in a given environment.

spin: the intrinsic angular momentum of a particle.

stable isotopes: **isotopes** that occur in a constant, known proportion in the natural state. For instance, oxygen has three such stable isotopes (¹⁶O, ¹⁷O, ¹⁸O), and carbon two (¹²C, ¹³C), while hydrogen has two (¹H, ²H).

subduction: the process whereby a tectonic plate plunges under another plate, of lower density.

sulfate: a salt of sulfuric acid.

supercritical fluid: the term "supercritical" refers to the state of matter when subjected to high pressure, or high temperature: a fluid is thus supercritical when it is brought beyond its critical temperature and pressure; the physical properties (density, **viscosity**, diffusivity) of a supercritical fluid are intermediate between those exhibited by liquids and gases.

tantalum (Ta): chemical **element** of **atomic number** 73, one of the transition metals.

terbium (Tb): chemical **element** of **atomic number** 65, a member of the **lanthanide** series, and of the rare earth group.

terrestrial geodesy: the science concerned with the measurement, and representation of the Earth's surface.

Tethys Ocean: a **paleo**-ocean that opened up, from east to west, from the Upper Permian to the Middle Jurassic. It formed across **Pangea**, dividing it into two continents, Gondwana to the south, Laurasia to the north. The western termination of this ocean corresponded to present-day Southern Europe and North Africa.

thermodynamics: the branch of physics and chemistry relating to the study of the thermal behavior of bodies, and the investigation of energy, and its transformations (in particular, with regard to internal energy).

thermohaline (from the Greek *thermos*, meaning "hot," and *hals*, *halos*, meaning "salt"): the thermohaline circulation is the deep oceanic circulation driven by differences in temperature and salinity between water masses.

thorium: chemical **element** of **atomic number** 90, and symbol Th, fairly abundant in nature, having **isotopes** ranging from ²²³Th to ²³⁵Th. ²³²Th is a natural isotope.

traces and ultratraces: a **trace** is an **element** occurring at a low concentration; there is no definite rule, setting a threshold concentration, below which the term "trace" must be used; the notion of trace has varied with the evolving sensitivity of the techniques employed, nor does it have the same meaning for a geochemist, a biologist, a metallurgist... In practice, analytical scientists speak of traces when the element subject to measurement occurs at concentrations ranging from a few tens of milligrams per kilogram (mg/kg) to a few tens of **micrograms** per kilogram (**µg**/kg), and of **ultratraces** for concentrations lower still.

transmission gauge: a particular type of **nucleonic gauge**, for which the detector stands on one side of the material undergoing measurement, while the radiation source is positioned on the other side; the detector measures radiation transmitted through the object.

tritium: the heaviest **isotope** of **hydrogen**, and the only **radioactive** one. Its **nucleus** comprises one **proton**, and two **neutrons**.

turbidity: for a liquid, its degree of cloudiness, or its content of materials causing it to cloud over; this is due to suspended particles that absorb, scatter, and/or reflect light.

ultrasound: a sound wave having a frequency higher than 20,000 **Hz**.

ultraviolet (UV) radiation: a segment of the electromagnetic spectrum covering radiation of wavelengths ranging from 400 nm to 10 nm (1 nanometer = 10⁻⁹ meter). A large proportion of UV radiation is absorbed by the **Earth's atmosphere**. See **Focus A**.

unsaturated zone (USZ): a compartment of the environment, extending between the soil surface, and an underground aquifer; rock porosity, in the unsaturated zone, is filled with water, and air, whereas it is entirely filled with water in the **saturated zone**.

uranium: a chemical **element** of **atomic number** 92, and symbol U, occurring naturally (**natural uranium**), in the form of a mixture of three **isotopes**: ²³⁸U, a fertile isotope (99.28%), ²³⁵U, a **fissile** isotope (0.71%), and ²³⁴U (traces). See also **depleted uranium**.

valence: the number of possible bonds an **atom** may set up.

vertical density profile: the curve plotting the density e.g. of a water-silt mixture, as a function of depth.

vertical profile: the variations in concentration, for a constituent of the **atmosphere**, as a function of elevation, yield its vertical profile.

very-long-baseline interferometry (VLBI): an **interferometry** process, involving the recording, and subsequent analysis, at a later time, of signals received by antennas that may be several thousand kilometers apart. VLBI makes use of extragalactic radioelectric sources, e.g. quasars.

viscosity: the ability of a fluid to flow.

voltammetry: ascertaining the fundamental characteristics of an electrochemical reaction is achieved by way of the measurement of variations in current intensity, as a function of the voltage applied to the terminals of an electrolytic cell; the general principle of voltammetry thus involves obtaining a response (a current flow) from the system being investigated to the excitation (the voltage) causing the desired chemical reaction.

watt: a unit of power (**W**), corresponding to production (or consumption) of one joule per second.

Younger Dryas: a short, very cold, very dry climate interval, lasting around 1,200 calendar years (12,700–11,500 years before present), preceded by the *Bølling-Allerød interstadial*, and marking the end of the **Pleistocene** Epoch, followed by the *Preboreal*, ushering in the **Holocene**. This period takes its name from the white dryad, or mountain avens (*Dryas octopetala*), the pollen of which made, at that time, its last appearance in plains and valleys.

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-

Skip to page 22

(1) Granite: a dense, magmatic rock consisting of crystals visible to the naked eye, mainly quartz (silica [SiO₂]), micas (minerals chiefly consisting of aluminum silicate, and potassium), alkali feldspars (KAlSi₃O₈), and sodium plagioclases (NaAlSi₃O₈).

(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.



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

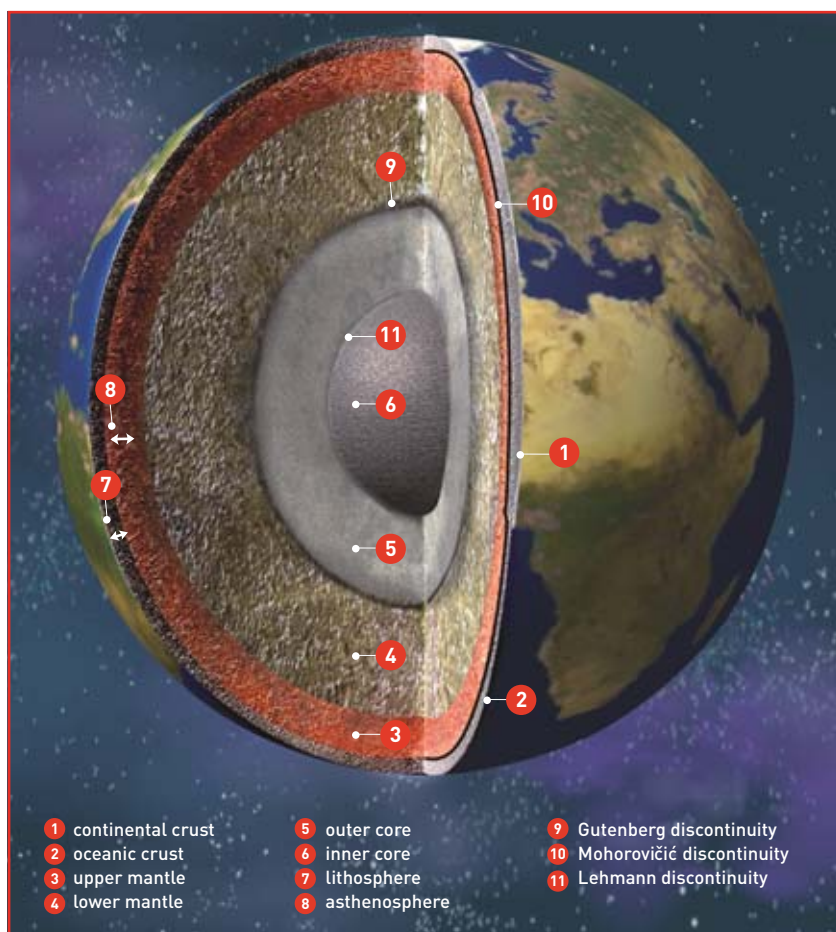


Figure 1.
The Earth's internal structure.

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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 **crys-**

tallization 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 $[\text{Si}_4\text{O}_{11}(\text{OH})]^{7-}$ 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 $-18\text{ }^{\circ}\text{C}$, rather than the $15\text{ }^{\circ}\text{C}$ 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 $1,013.25\text{ hPa}$. 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 $6.4\text{ }^{\circ}\text{C}$ per kilometer. Temperature varies, on average, from $20\text{ }^{\circ}\text{C}$ at ground level to $-60\text{ }^{\circ}\text{C}$ at the upper boundary of this region. As this layer holds $80\text{--}90\%$ 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 $8\text{--}15\text{ km}$ to 50 km), temperature stays constant over the first few kilometers, then rises slowly, and far more swiftly thereafter, increasing with altitude up to $0\text{ }^{\circ}\text{C}$. 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 ₂ O)	0.30	
ozone (O ₃)	0.04	
water vapor (H ₂ O)	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. CO₂ concentrations stood at 280 ppmv in 1800, 345 ppmv in 1998.

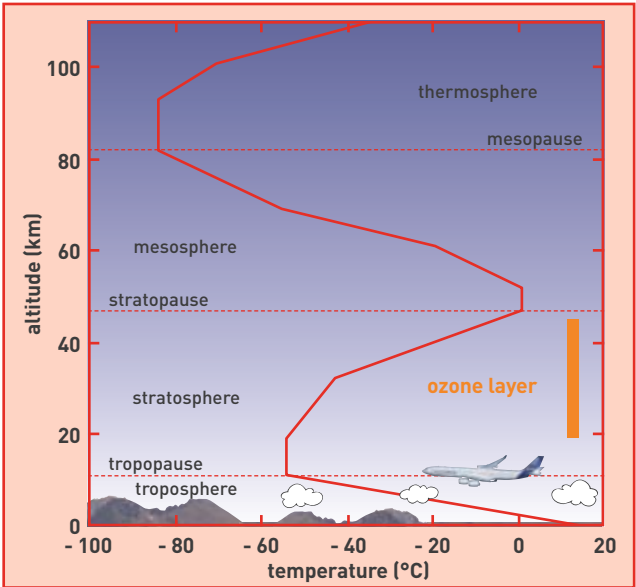


Figure 2.
The layers in the atmosphere. Their boundaries are determined on the basis of discontinuities in temperature variations, as a function of altitude.



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



StockTrek



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.

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

Page 23 cont'd

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 $1,000^{\circ}\text{C}$. 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 protonosphere). 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**.

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

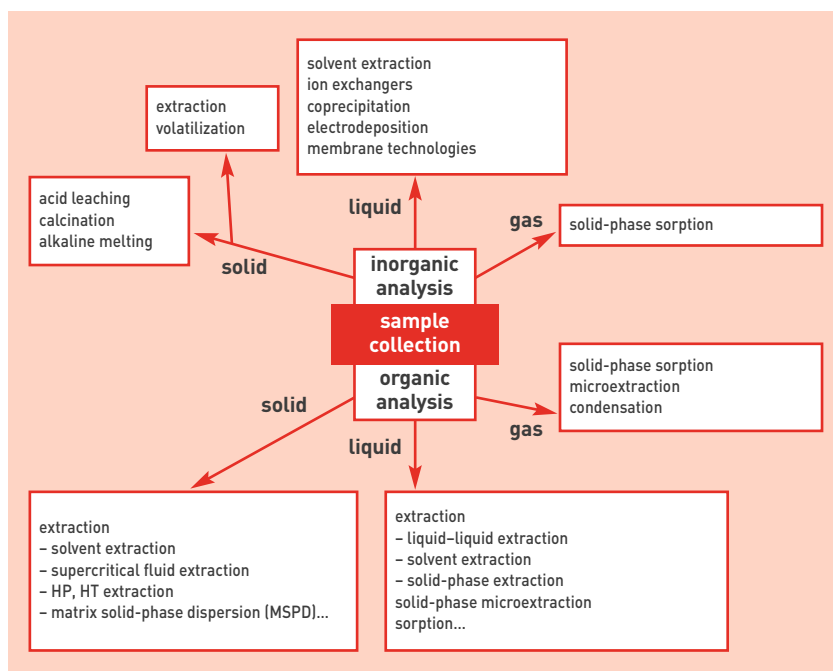


Figure 1.
Examples of pretreatment techniques for environmental samples

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.

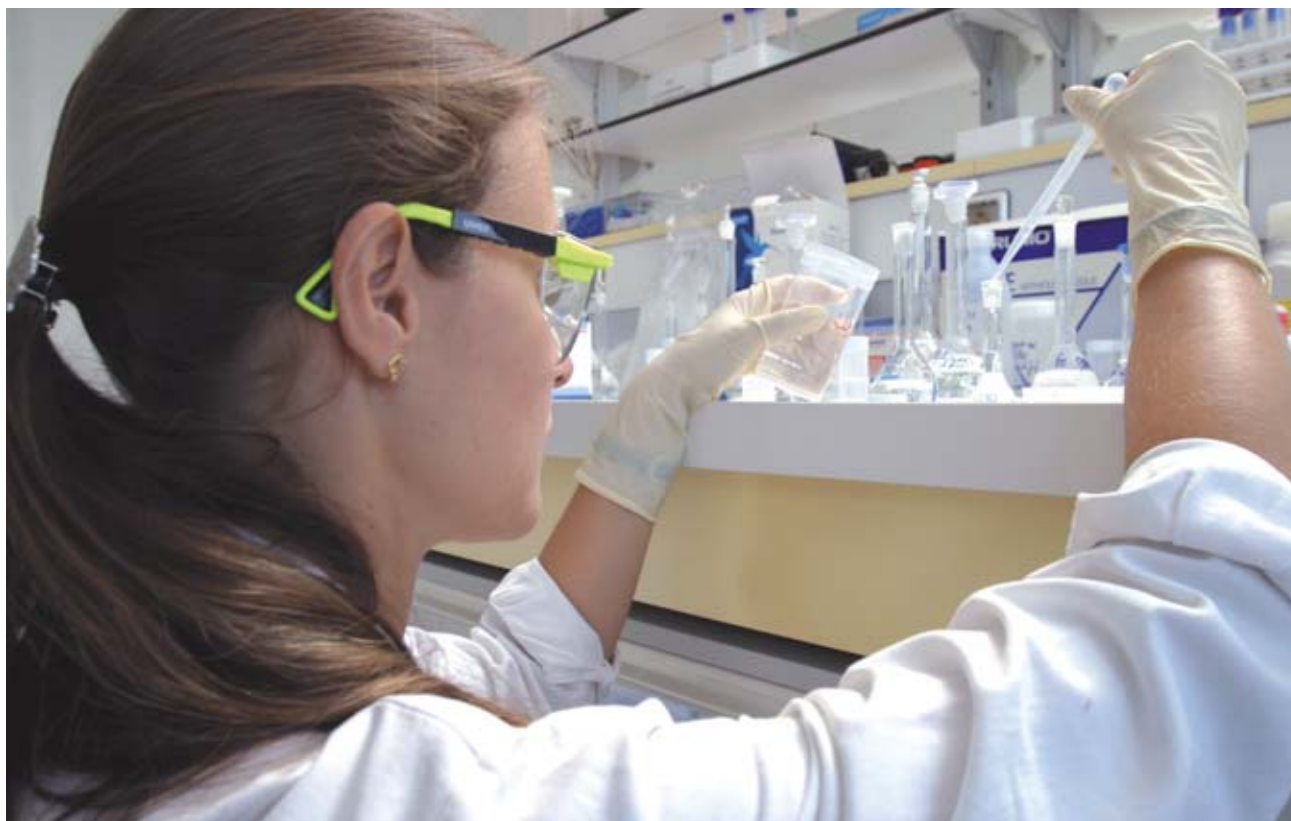
- **Solvent extraction** – this as a rule involving a volatile solvent, sparingly soluble in water (a light alkane, ethyl acetate...) – allows the extraction of **molecules** from aqueous media. Solvent–water separation is effected simply, through settling.
- **Preparative ion chromatography**, which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

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 invol-

ves 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 physico-chemical 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 of analytical 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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Continued from p. 53

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

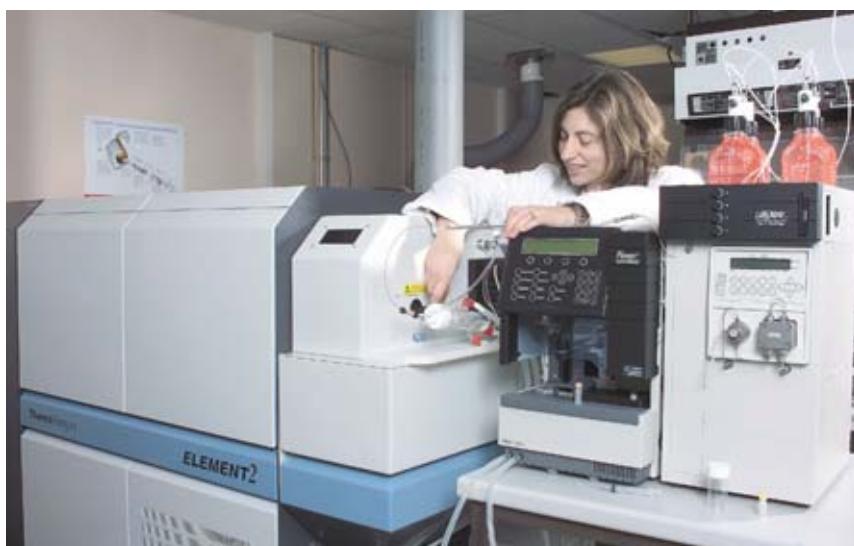
pulse), allowing the elimination of unwanted, short-lived fluorescence signals. Current developments involving this technique concern **speciation** (i.e. the determination of chemical species), and remote measurement via optical fiber in the nuclear industry, and for environmental analysis.

- **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.



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 mul-

tiple 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 (**ultra-violet** radiation), or a **radioactive** (alpha- or beta-emission) source.

Continued p. 56

Continued from p. 55



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.

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



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.

The greenhouse effect, a natural phenomenon

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

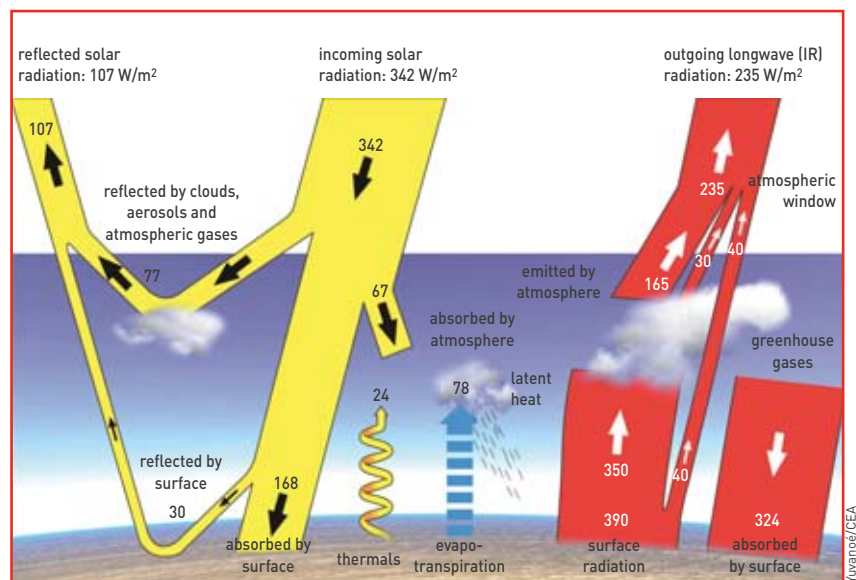


Figure 1. Energy fluxes within the climate system (IPCC diagram).

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 ave-

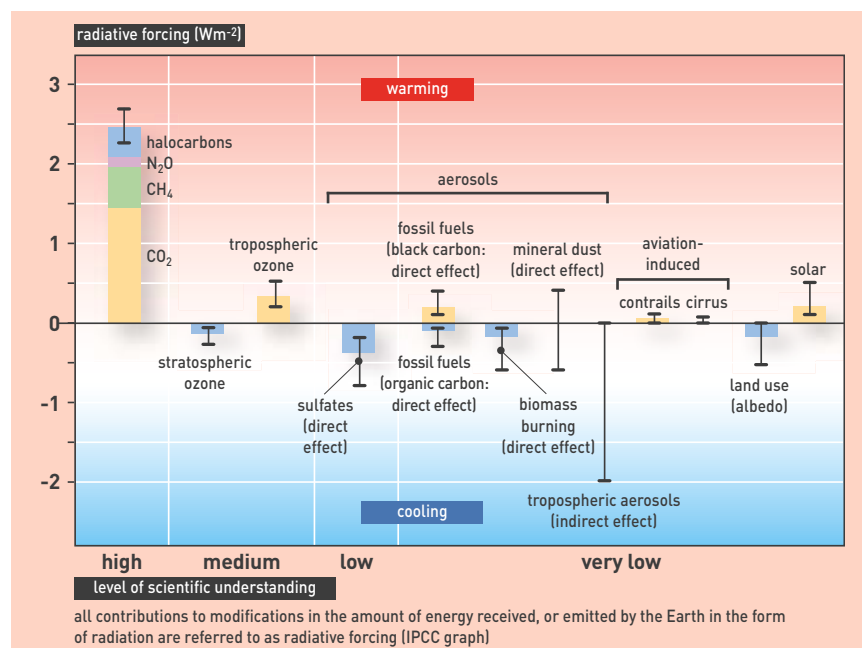


Figure 2.
Changes in **radiative forcing** between 1750 and 2000.

rage 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 **photo-synthesis** to counterbalance, at this stage, the releases that may be attributed to human activities.

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

Followed p. 68

Followed from p. 67



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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 **anti-cyclonic** 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.

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



Digital Vision Ltd.

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.

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 emis-

sions. 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 CO₂ 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).

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,

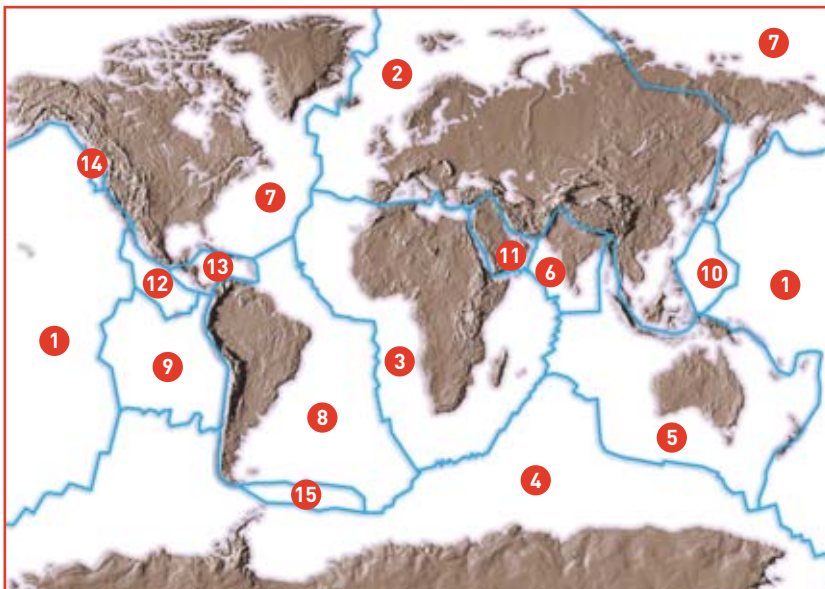


Figure 1. The Earth's outermost layer is subdivided into a number of rigid plates, slowly moving across the underlying viscous material in the asthenosphere, while rubbing one against the other. Certain plates may in turn be subdivided into several plates, involving smaller relative motions.

	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

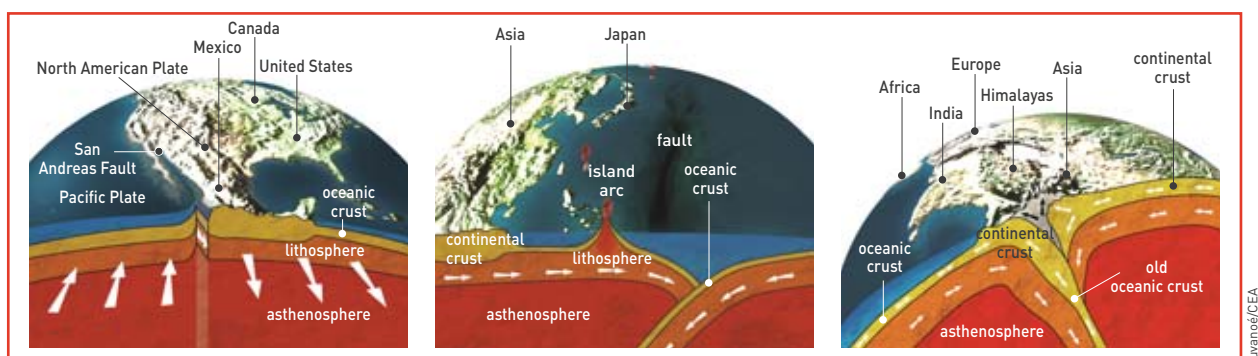


Figure 2.

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

Skip to page 92



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.



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.

Page 91 cont'd

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 **hydro-carbon** 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 sur-

face 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

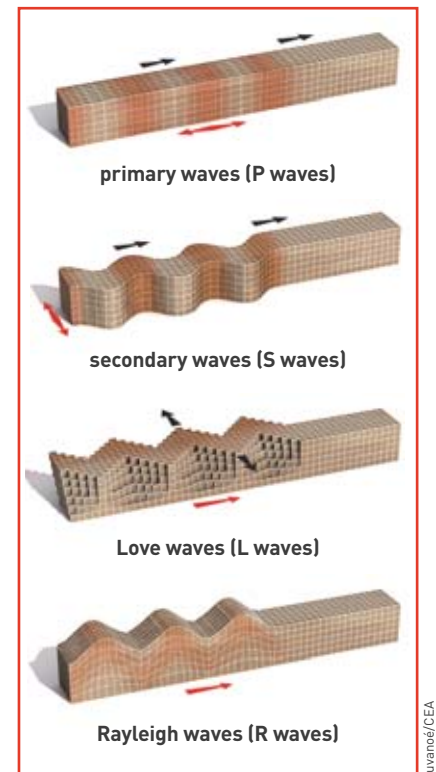


Figure 3.

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.

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.

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 character-

(1) Currently, seismologists use magnitudes such as **moment magnitude**, for the purposes of estimating the size of very strong earthquakes. This magnitude, noted **M_w**, introduced in 1977 by Hiroo Kanamori, from the California Institute of Technology, is defined by the relation $\log M_o = 1.5 M_w + 9.1$ (where M_o 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 under-sea 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 \mathbf{x} (latitude, longitude, depth, event origin time), and data subsumed under a vector \mathbf{t} covering the various measurements (e.g. wave arrival times). The direct problem, as noted by vector $\mathbf{t}(\mathbf{x})$, involves computing, from \mathbf{x} , the theoretical values associated to the data involved. Solving the **inverse problem** involves finding the vector \mathbf{x}_0 that minimizes the differences between \mathbf{t} , and $\mathbf{t}(\mathbf{x}_0)$.

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-

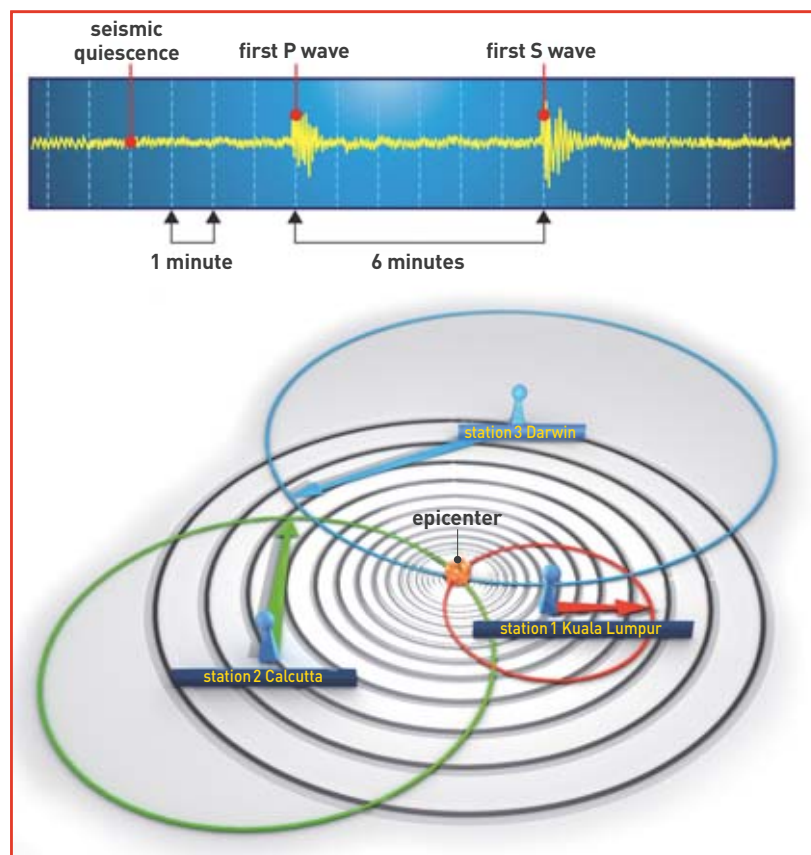
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(2) In France, as in most European countries, the intensity scale adopted is the EMS-98 scale (European Macroseismic Scale, as established in 1998), which features 12 degrees.



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.



Yvanoff/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.

Page 93 cont'd

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), headquartered 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.

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.

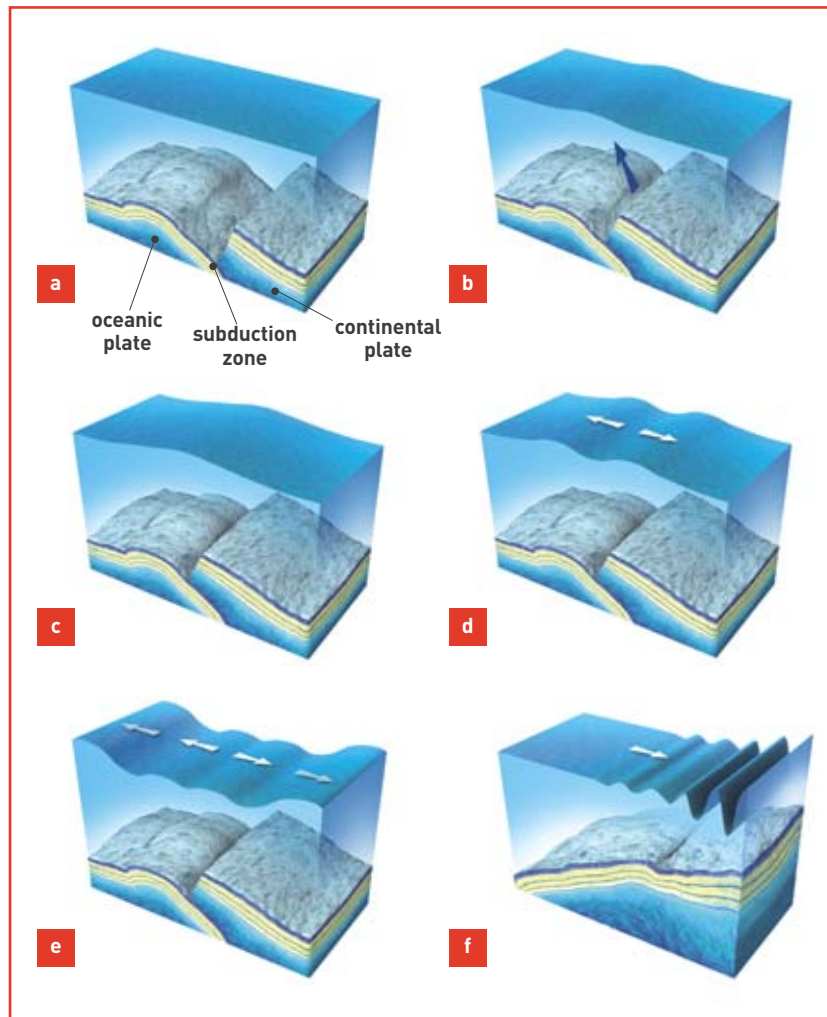


Figure. A situation involving a subduction zone, where an oceanic plate is slipping under a continental plate (a). In a strong earthquake, the overthrusting continental plate is abruptly uplifted by several meters, pushing upward the overlying volume of water (b). The surface bulge (c) begins to propagate 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**.