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Sustainability of the Earth's surface environment: a European geoscience perspective

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Research Report RR/00/05

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BRITISH GEOLOGICAL SURVEY

Research Report RR/00/05

Sustainability of the Earth's surface environment: a European geoscience perspective

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Cover illustration
Soufrière Hills Volcano, Montserrat. A new lava dome is seen steaming in the centre of this picture taken in early April 2000.
Gill Norton, BGS © *NERC*

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Sustainability of the Earth's surface environment: a European geoscience perspective

Recent population growth and economic advances are extending the problems associated with land degradation, pollution, urbanisation and the effect of climate change over large areas of the Earth's surface, giving increasing cause for concern about the state of the environment.

According to some authors (e.g. McMichael, 1993), the threat of global ecological disruption due to the speed and scale of the impact of human activities is now so great that the fabric of life-support systems is beginning to unravel. *Homo sapiens* has existed for less than one two-hundredth of the Earth's history, but is causing serious damage to the self-sustaining mechanisms which have evolved over a very long period of time. If the environment changes gradually, survival depends on biological evolution, but the fossil record shows several periods when change has been so rapid that the pace of evolution has been overwhelmed, with mass extinction of species. Concern that human activities are unsustainable has led to statements like that of the World Commission on Environment and Development that humanity should ensure that 'it meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland, 1987) and to the call by the 1992 Rio Declaration on Environment and Development for states to 'reduce and eliminate unsustainable patterns of production and consumption'.

Too often, issues such as biodiversity or water quality are treated in isolation, ignoring the fundamental fact that it is the Earth and Earth processes that provide the essential basis for all life-support systems and that they need to be considered as part of a holistic approach to the environment.

The Gaia hypothesis (Lovelock, 1987), which takes the view that life, the environment and the planet are part of a single system, provides a realistic model for understanding the interactions between human activity and the many chemical, physical and biological processes that take place on the Earth's surface. Gaia forces a planetary perspective: it is the health of the whole planet that matters, not that of individual species or organisms.

A shorter version of this article (Plant and Haslam, 1999) has been published in the official magazine of the British Geological Survey, *Earthwise*.

The solid Earth

Over aeons, the Earth has been transformed by a complex interplay of physico-chemical and biological processes from a hot, lifeless mass spinning through space more than 4500 million years ago into a planet with a cool and varied surface environment, where abundant water and an oxygenated atmosphere are capable of supporting complex and diverse life forms. Over time, Earth processes have also led to the accumulation of metallic, energy, industrial and construction minerals, which are used by man to provide shelter and food and to support an ever-increasing material standard of living.

Unlike other planets in our solar system, the Earth has an active surface across which continents migrate and over which there is mass transfer of rock, soil, fluids, air and energy. The Earth's crust, on which we live, comprises a thin (approximately 6 km thick) iron-magnesium-silicate crust beneath the oceans and a thicker (average 35 km), lighter crust, dominated by silicates of aluminium, iron, calcium, sodium, potassium and magnesium, forming the continents. The outer layer of the Earth is divided into huge plates, moving on million-year time scales in a complex inter-relationship with convection currents deep within the Earth (Figure 1). These currents are fuelled by heat, produced partly by natural radioactive decay (Figure 2) and partly by the cooling of the metallic core.

New crust is formed where plates are pulled apart, for example across the mid-Atlantic ridge, which extends from 75° N north of Iceland to about 52° S. Away from spreading ridges, plates cool and increase in density before being destroyed as they descend beneath the continental crust to the Earth's interior (e.g. Himalayas, Indonesia). These destructive plate margins are associated with some of the most intense earthquakes and life-threatening types of volcanic activity, together with tsunamis and landslides. Damaging earthquakes also occur where plates move laterally against each other, as along the San Andreas fault in California. These spectacular geological phenomena can cost many lives.

In Europe, crustal movements associated with a major boundary between the European and African plates cause frequent earthquakes in Portugal, Spain, southern France, Italy, Cyprus and Greece (Figure 3). Although the 1997 earthquakes in central Italy were only of magnitude 6.0, the damage to the Basilica of St Francis at Assisi highlighted the risk to heritage sites. The greatest impact from the 1755 earthquake off the coast of Portugal (magnitude greater than 8.0) was the tsunami which inundated Lisbon and other coastal settlements with the loss of 60 000 lives. Even areas of low seismicity in Europe need to be protected against earthquakes, because of the high population densities and the engineering and industrial infrastructure such as nuclear facilities, dams, chemical plants, long bridges and tunnels.

The remnants of long-extinct volcanoes are common in the landscapes and geology of Europe. Currently active volcanoes are largely confined to Iceland (where several volcanoes erupt frequently), Italy (where Etna is in a state of almost continuous eruption) and the Aegean islands of Greece (where Santorini was last active in 1956). Active volcanoes require constant monitoring and surveillance, as they can pose a considerable threat (e.g. in the Bay of Naples where there are huge urban areas close to the active volcano of Vesuvius). In recent years, volcanic activity on the island of Montserrat in the eastern Caribbean has rendered a large part of the island uninhabitable (see cover illustration). On the other hand, circulation of fluids through active volcanic areas can create useful geothermal energy, as at Larderello (Italy) and in Iceland.

On a global scale, volcanic activity can result in the emission of large amounts of fine ash or dust together with volcanic gases which can rise to great altitudes above the Earth's surface and encircle the globe, causing short-term lowering of global temperatures. Conversely, volcanoes can emit large amounts of CO_2, adding to the Earth's store

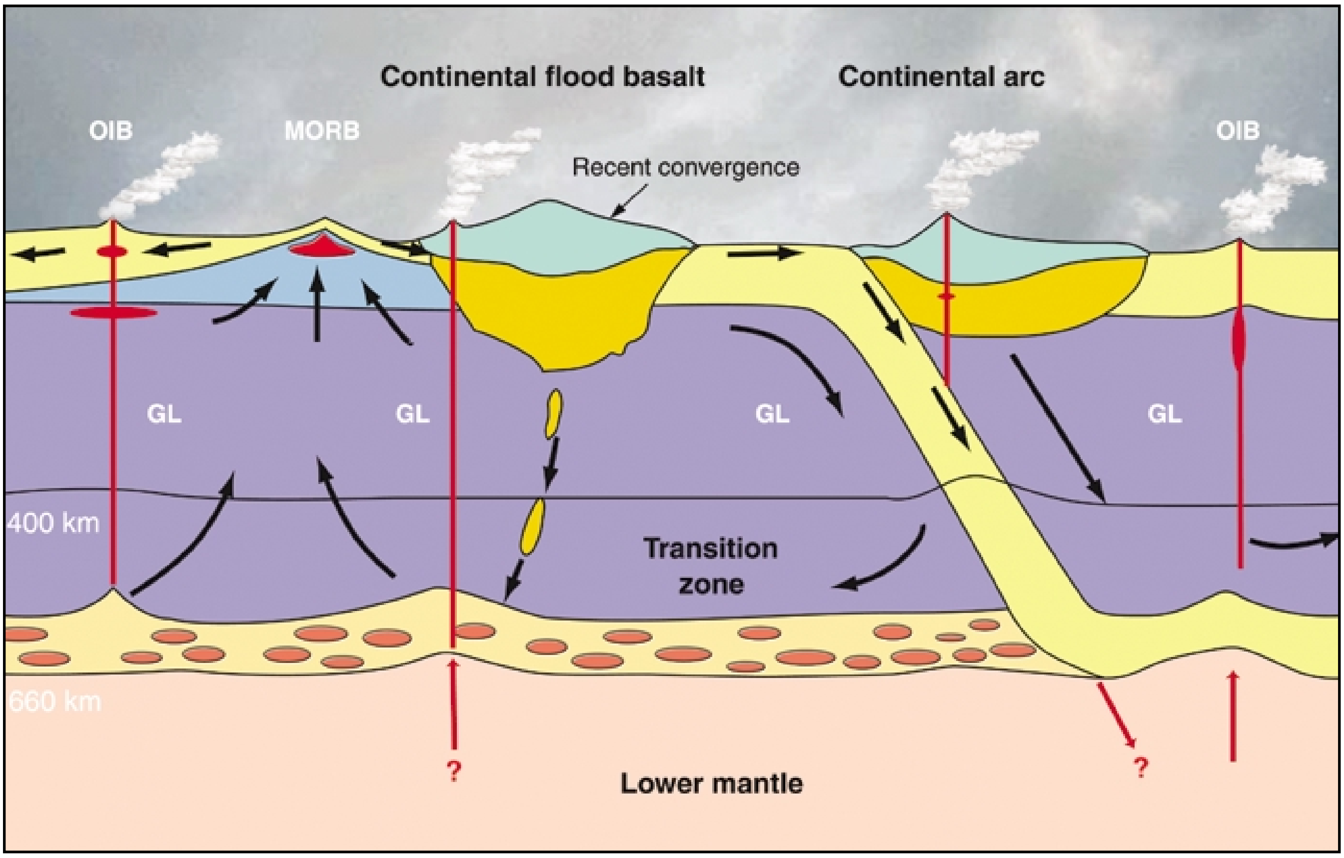

Figure 1 Illustration of the upper 800 km of the Earth (after Brown and Mussett, 1993). GL, garnet lherzolite; MORB, mid-ocean-ridge basalt; OIB, ocean-island basalt.

of greenhouse gases which increase global warming; emission of CO_2 at Lake Nyos, in an inhabited region of Cameroon, West Africa in 1986, resulted in considerable loss of life. Volcanic gases are also responsible for a significant proportion of acid precipitation. Prolonged periods of intense volcanic activity in the past may have had a profound and long-lasting effect on the Earth's climate. The geological record indicates that from time to time the rise of large plumes of hot material from deep in the Earth have generated vast outpourings of volcanic lava and emissions of dust and gas.

The continental crust began to form about 4000 million years ago (Brown and Mussett, 1993; Windley, 1995) and now constitutes about 30% of the Earth's surface. During that time continents have formed, fragmented, migrated across the globe, and reformed (Figure 4). Europe itself consists of a complex assemblage of ancient fragments of continental crust (e.g. in northern Fennoscandia and Scotland) and younger mountains such as the Alpine ranges which developed as Africa moved north against the European plate. The Earth's surface, and Europe in particular, shows an amazing diversity in the age, structure, composition and disposition of rocks — geodiversity — with implications for the evolution of its landscapes, environment, natural resources and biodiversity.

At mid-ocean ridges, where spreading rates range from 1 to 18 cm per year and extensive fracture systems create high permeability in the ocean crust, enormous volumes of sea water pass through the rocks, stripping them of metals such as copper and zinc. On discharge at submarine hot springs, known as black smokers, the sulphurous and metal-rich water has temperatures of up to 350°C and is highly acid (pH <1). Despite the apparently inhospitable conditions, complex ecosystems exist near these vents, including tube worms and crabs not seen elsewhere. These and similar processes, over geological time scales, have given rise to some of the Earth's major base-metal deposits, such as the Troodos copper deposit in Cyprus and the pyrite belt of Iberia. In the past two decades, more than 135 sites of extinct and active hydrothermal vents have been found on the ocean floor. Deposits of metal-rich material on the ocean floor provide natural analogues to guide any responsible offshore disposal of metallic waste such as that from decommissioned drilling rigs.

Over geological timescales, large-scale fluid movement through the Earth's crust has generated other types of mineral and fossil-fuel deposits, including petroleum, natural gas, base and precious metal and uranium ore deposits. North Sea oil is an important fuel for Europe, while several countries in Europe have significant uranium deposits. Some uranium ore deposits in Gabon are so radioactive that they formed natural nuclear reactors. Understanding uranium ore deposits as natural analogues of nuclear-waste repositories is crucial to developing procedures for the safe containment of nuclear wastes.

The Earth's surface

The Earth is a water-cooled planet. The Earth's hydrosphere and atmosphere have evolved gradually over time, initially as a result of outgassing of the primitive Earth, then by interaction with volcanic systems and subsequently with continental crust and river systems comparable to those of the present day. The geological record shows that the Earth has been through many cycles of global climatic change. During the last 600 million years there have been four cool and four warm climatic periods, reflecting complex interactions between geological, biological and climatic processes. Cool periods were characterised by high-latitude glaciation. Towards the end of each cool period, decreasing levels of biological productivity and/or the oxidation of organic matter caused an increase in CO_2 levels in the atmosphere and climatic warming, which terminated glaciation. During the warm periods, increased deposition of organic matter and carbonate sediments locked up carbon in the lithosphere, but high levels of atmospheric CO_2, and consequent global warming, were maintained by volcanic outgassing. An example of how circulation deep within the Earth can influence the circulation patterns of the atmosphere is provided by the rise of the Tibetan plateau over the last 5–10 million years, caused by collision between India and Asia, which has disturbed the circulation cells of the atmosphere, causing the Indian summer monsoons. More recently, and since the appearance of *Homo sapiens*, there have been four major glacial to interglacial cycles since 450 000 years BP; some scientists predict that there will be a fifth glacial period in about 20 000 years time (Cogeoenvironment Working Group on Geoindicators, 1995; Larsen, 1998). The alternation of glacial and interglacial periods has a profound effect on sea level. In northern Scandinavia, for example, the land surface is still rising in response to the removal of the ice, reflected by the silting up of ports and harbours. Elsewhere, rising sea levels could threaten to flood low-lying areas such as the Netherlands and eastern England.

At the Earth's surface, rocks that were formed at high temperatures and pressures break down into minerals which are stable in the presence of air, water and, frequently, biological activity. The weathered material may be transported by water, glaciers or wind and redeposited as rocks such as sandstones, limestones (made of the remains of calcitic organisms) or coal beds (the remains of once-great forested swamps).

Soil forms by similar processes acting on rock: it is a complex mixture of rock and mineral fragments, mineral nutrients, organic matter, live microbes, worms, insects and other organisms. When soil is denuded of plant cover, overgrazed, chemically polluted, depleted of nutrients, or made saline by over-irrigation, it 'dies' and turns to dust which is readily eroded by water or wind. In 1993 the UN estimated that in the last 45 years, approximately 17% of all potentially arable and pastoral land had suffered some degree of degradation (UNEP, 1993); for Europe the figure is about 23% (Oldeman et al., 1991). The chemical composition of soil and its ability to absorb pollution or withstand depletion depends very much on the chemical composition of the underlying rocks. For example, the effects of acid deposition are buffered in soils rich in calcium and magnesium, such as those developed over limestone, while soils deficient in these elements, such as those developed over granites or slates, release aluminium ions which are potentially toxic to humans, animals and crops.

The mineral composition of soils, which reflects bedrock and climatic conditions, determines how they respond to weathering agents and human activity. Some clay soils are prone to swelling and shrinking as they become wetter or drier, causing severe problems for the stability of building foundations. Wind-blown silts have unstable internal structures which can collapse with significant reduction in volume when they become wet or are compressed by a load

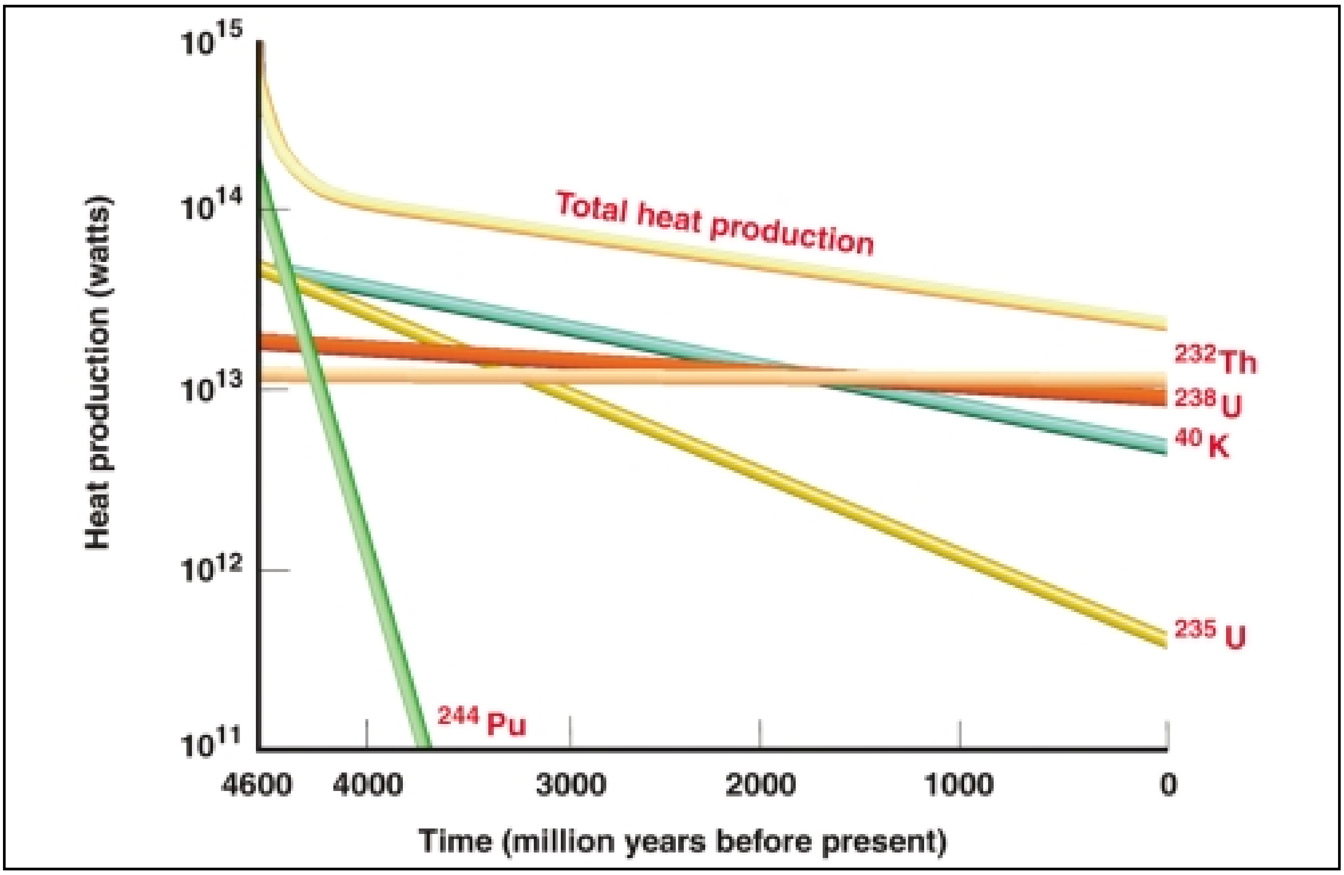

Figure 2 Amount of heat produced through time from the more important radioactive isotopes (after Brown and Mussett, 1993).

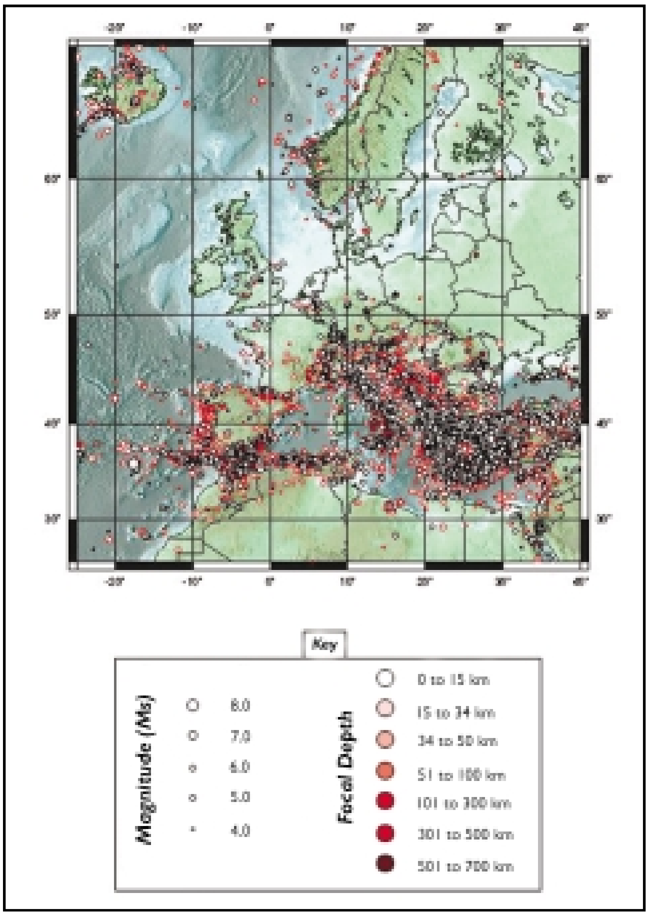

Figure 3 Seismicity of Europe 1900–2000, magnitude 4.0 and above. The plot shows earthquake activity along the mid-Atlantic ridge (Iceland) and the Europe-Africa plate boundaries. Seismicity data from the BGS World Seismicity Database.

such as a building. Other types of soil lose chemical bonding when wet so that they are rapidly dispersed by erosion. Intense rainfall on sloping ground can trigger landslides, which can cause further erosion. Soluble rocks and minerals, such as limestone, salt and gypsum, can be dissolved, leading to the formation of underground voids, followed by roof collapse.

The earliest life forms were simple micro-organisms living in the sea (Windley, 1995). Oxygen, released by photosynthesis, began to build up in the atmosphere between about 3000 and 2000 million years ago. It was not until about 550 million years ago (in the last 10% of the Earth's history) that there were any land plants or animals. There are complex interactions between life and Earth processes: for example, rocks made up of the fossilised carbonate remains of marine creatures now form part of the High Alps, while coal and hydrocarbon resources are made, respectively, from the remains of plants and microscopic animals. Like carbon, oxygen, sulphur and nitrogen, most chemical elements follow cycles with exchange between the lithosphere, hydrosphere, atmosphere and biosphere.

Human activity and its influence on the environment

Since human societies changed from groups of hunter-gatherers to settled communities who modified their environment, mineral materials have been extracted from the Earth for building, manufacturing (becoming increasingly sophisticated) and energy production. Today's industrialised society depends on the ready availability of energy, metallic and non-metallic minerals (Plant, Turner and Highley, 1998). Europe consumes nearly a third of the world's mineral production. It hosts mineral deposits that have been, and in some cases still are, very important by world standards (e.g. the Navan deposit in Ireland), and its metallurgical industry is also very important by world standards. However, there is increasing concern about the environmental impact of extraction, despite the fact that the land area used is relatively small. In England, the area of planning permissions for surface mineral workings is only about 0.7% of the total land area, and about half of this has been restored. The concept of sustainable development requires that the most efficient and effective use is made of minerals, to maximise the value of the resource and minimise waste and environmental impact; full life-cycle analysis in relation to economic well-being is therefore essential (Figure 5).

Within the last 1000 years, the combustion of fossil fuels, whereby carbon is oxidised to CO_2, has been increasingly used as a source of energy, and the emission of CO_2 is of concern because of the contribution it makes to global warming. The principle of sustainability requires that the products of fossil-fuel combustion and nuclear fission, which has also been used as a source of energy in recent decades, should be returned to the geosphere, and Earth scientists are currently working on methods of disposing of CO_2 into oilfields and nuclear waste into safe repositories in bedrock.

Full life-cycle analysis should also be applied to land (Figure 5). Although modern industry seeks to minimise contaminating discharges, there remains a stock of land affected by previous use, much of it in urban areas. A large proportion of the population of Europe lives in towns and

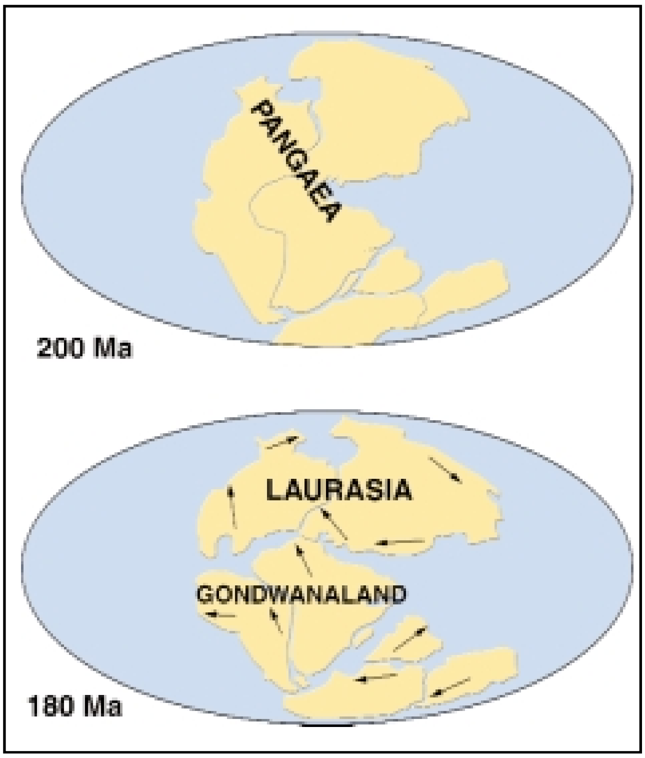

Figure 4 Distribution of the modern continents 200 million years ago (when they formed a single landmass, the supercontinent of Pangaea) and 180 million years ago when Laurasia and Gondwanaland had formed, as a consequence of the fragmentation of Pangaea (after Windley, 1995).

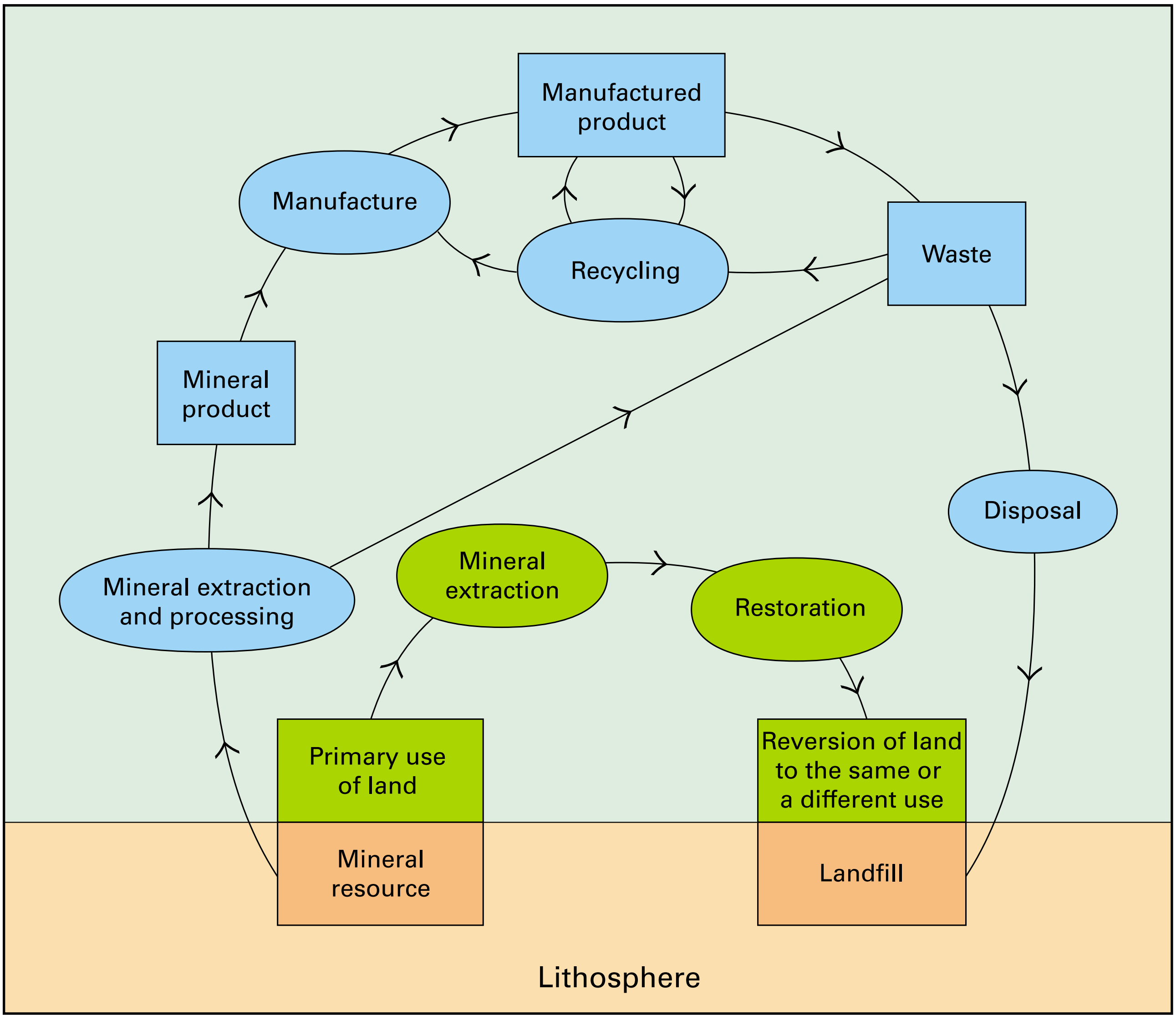

Figure 5 Life cycle of mineral-bearing land (green) and minerals.

cities, many of which have grown up around heavy industry and mining. The legacy of these activities includes landfill and man-made and contaminated ground, as well as abandoned mines, quarries and waste tips. In addition, low-level pollution from sources such as vehicle exhausts and household waste is more damaging in areas of high population density. Affected land should be recycled and re-used as far as possible, and planning permission for the extraction of mineral resources should be conditional on land being restored to a state suitable for beneficial after-use, in consultation with local communities. Potential uses include leisure activities, agriculture, nature conservation and landfill. In the case of landfill, variations in the local geology affect the behaviour of contaminants, and the extent of natural attenuation (which largely reflects microbiological processes) and thus the impact on the environment. Geochemistry, hydrogeology and engineering geology, used together with microbiology, have a particularly important part to play in remediating contaminated land.

Contaminated land is of increasing concern across Europe, but too often sites are considered in isolation. It is important that anthropogenic heavy-metal contamination and radioactivity should be assessed in the context of natural, geogenic, levels. In the case of radioactivity, it has been estimated that approximately 65% of the total dose of ionising radiation received by the average UK citizen is from gamma rays and radon released naturally from rocks and soils, compared with 1% from all non-medical artificial sources (National Radiological Protection Board, 1989). Geological surveys are increasingly involved in the mapping of radioactivity (Figure 6) and the preparation of radon-potential maps, to enable the risk to human health to be minimised.

Serious health problems to man and animals can be caused by chronic deficiencies of micronutrients such as iron, selenium, and iodine, which tend to be extracted from the soil by modern agricultural practices and the failure to recycle waste back to the land. Iodine deficiency, for example, gives rise to goitre and, more seriously, to severe mental impairment (cretinism) in babies born to mothers who are deficient in iodine.

The body burden of toxic chemicals reflects input from many sources, including soil, dust, air and water. Multi-element geochemical surveys based on different media including soil, water and stream sediment are the most powerful tools for providing a baseline against which to identify areas of potential toxicity and deficiency of chemical elements (Figure 7), as well as areas at high risk from natural radioactivity. Systematic surveys using a combination of different sample types are much more effective than separate surveys based on soils or groundwaters conducted by different organisations and are essential for the preparation of GIS-based decision-support systems. They are particularly important in Europe, which has a long history of mineral extraction, industrialisation, intensive agriculture and forestry, and urbanisation, and which remains one of the most densely populated and utilised land areas on Earth. The geological surveys of Europe are presently collaborating to prepare a multi-element, multi-media environmental geochemical reference for Europe (Plant et al., 1996; Salminen et al., 1998), as their contribution to the preparation of a global geochemical reference network (Darnley et al., 1995).

About 70% of the Earth's surface area is covered by water, but most of it is salt water in the oceans and seas. Today, fresh water, which comprises only 2.5% of the world's water, is our most vital Earth resource. Most of this fresh water (99.975%) is bound in glaciers and permanent snow fields. More than 95% of the remaining fresh water is groundwater and less than 5% is surface water. Increasing demand for water for agriculture, industry and domestic consumption globally, and in Europe in particular, is leading to over-extraction of groundwater and salination of water supplies. In contrast, areas of abandoned mine workings and the rebound of water tables in contaminated urban areas where water is no longer extracted also threaten the environment. Groundwater in its natural state is generally of excellent quality because rocks act as filters. However, population pressure and intensive agriculture are leading increasingly to contamination with pathogens and, since the industrial revolution, chemical contaminants from industrial production and waste-disposal sites. An improved understanding and awareness of hydrogeology is essential in the assessment of the vulnerability of aquifers to contaminants and in the responsible management and protection of potable water supplies in Europe.

Human activity can cause erosion over large areas. Excavations and building on steep terrain can induce landslides and ground failures, possibly resulting in substantial loss of life. Underground mining has often been the cause of subsidence, while landscaped mine waste is prone to landslip. In the coastal zone, considerable efforts are being made to develop strategies to protect against marine erosion and flooding. The protection of cliffs from erosion may save communities and valuable land, but the disruption to the natural system of sediment movement can result in the reduction of deposition elsewhere, resulting, for example, in the disappearance of beaches. Offshore, the dredging of sand and gravel for use by the construction industry has led to concerns about the effects on shoreline stability, the degradation of marine habitats and reduced productivity of fisheries.

The role of geosciences and geological surveys

Sustainability requires a non-declining capital stock (the aggregate of produced, human and natural capital), including raw materials, waste receptors, landscape and amenity assets, accompanied by economic efficiency. It also involves fairness across different interest groups. In the past, one of the ways in which mankind has coped with environmental degradation has been to migrate to new territory. Present population levels and life styles require that every part of the globe should be subject to a sustainable management regime: we can no longer afford to destroy tracts of land and leave it to nature to rehabilitate them. Europe must recognise its responsibility to the environment and to mankind globally. The environment of Europe can remain healthy only as part of a healthy global environment. The European Community Fifth Environmental Action Programme *Towards Sustainability* (CEC, 1993) is a commitment to these principles.

Europe's geological surveys together prepare and maintain authoritative, systematic, quality-assured information on the geology, geophysics, geochemistry and hydrogeology of Europe, onshore and offshore, as a basis for the sustainable management of the environment and its resources (Annells, 1996). The information is recorded in digital form and can be interacted using sophisticated computer technology. Such data presented on Geographical Information Systems or 3D or 4D models can be used to

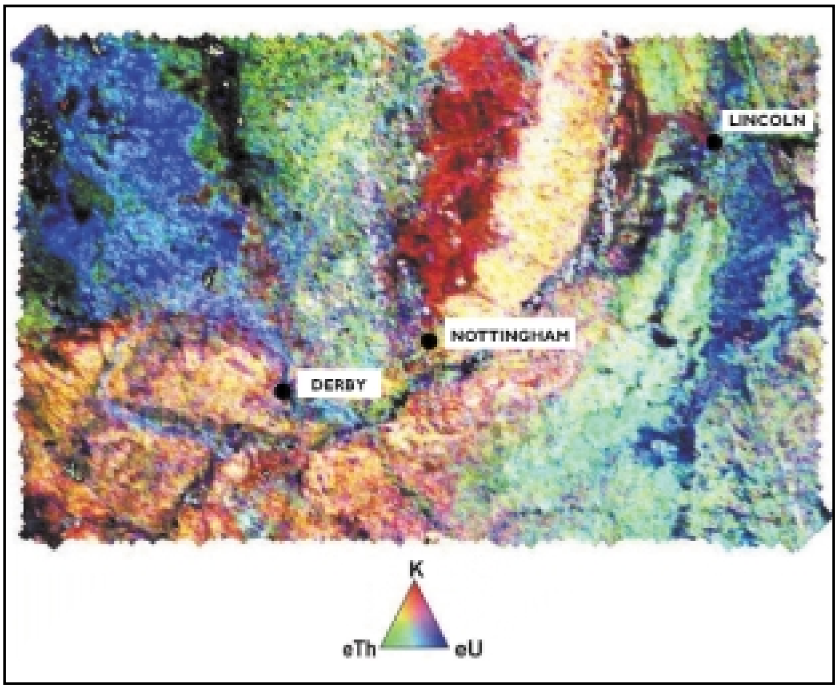

Figure 6 Ternary gamma-ray (potassium–equivalent uranium–equivalent thorium) image of part of central England, showing features related to solid geology and overlying superficial deposits. The red and yellow areas north-north-east of Nottingham represent the differing signatures of the Sherwood Sandstone and Mercia Mudstone groups, while the predominantly blue area north-west of Derby largely reflects the Carboniferous limestones of the White Peak, an area affected by higher than average levels of the radioactive gas radon, a uranium decay product.

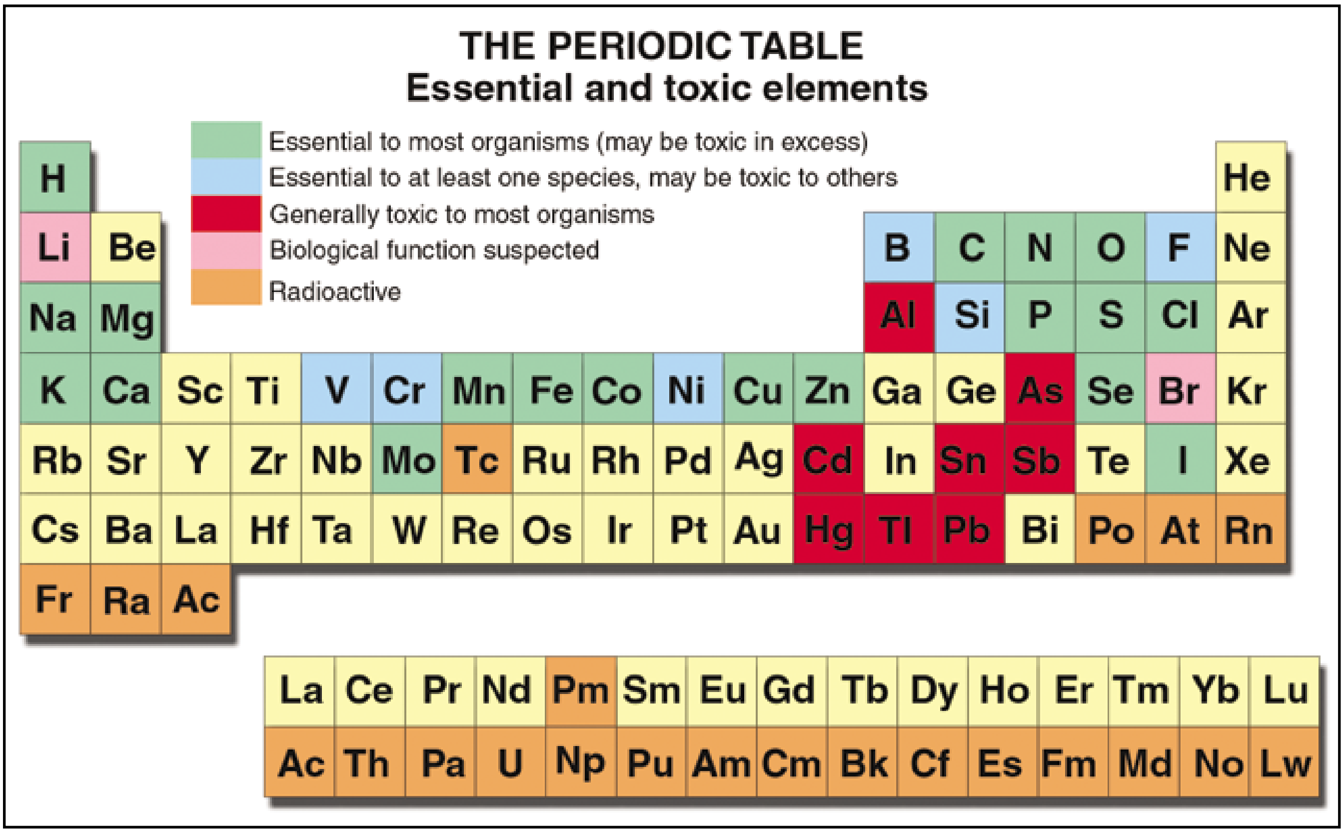

Figure 7 Periodic table of elements, showing elements with known and possible biological effects.

inform policy and to help to achieve economic development while sustaining the environment. They can be made available to the wider public in attractive and easily understood forms, empowering the citizens of Europe to understand their environment and to contribute to improving it.

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GLOSSARY

attenuation The process by which a chemical substance is reduced in concentration through absorption, adsorption, degradation, dilution, and/or transformation.

body burden The amount of radioactive material or other potentially harmful chemical substance present in the body of a human or animal.

hydrosphere The waters of the Earth, as distinguished from the rocks (lithosphere), living things (biosphere) and the air (atmosphere).

geochemical baseline The present pattern of distribution of chemical elements over the Earth's surface which is a function of geogenic and historical land use, and against which change can be measured.

lithosphere The solid portion of the Earth, as distinguished from the atmosphere, the biosphere and the hydrosphere.