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FEATURE

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Ode to Soil

Graeme Buchan

A PREAMBLE: THE MEANINGS OF SOIL

"Paradox" is truth spelt with seven letters instead of five. Water is a paradox (Buchan 1996). So also is soil—no other word attracts such opposites of meaning. At one extreme, its meanings include "filth," "dirty or refuse matter," and "excrement!" The verb "to soil" means "to bring disgrace or discredit upon." At the other extreme, it is reverently described as "The place of one's nativity" (Shorter Oxford Dictionary 1970). Indeed, our material nativity lies at the soil–root interface (figure 1): here begins the flow of minerals into plants and then on into animals. The human body contains about 70% water and 7% minerals, derived mainly from soil (table 1).

Figure 1

The soil-root interface: where human life begins. Nutrients flow along the soil–plant–animal supply chain. The root's absorption efficiency is greatly enhanced by rhizosphere microbes (fungi and bacteria). Roots absorb water partly by osmotic attraction because their cells contain solutes (including ions, proteins).

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Table 1

Composition of the human body (Data from Walker 1990).

	Percent
H_2O	65%–70%
Carbon (from air via plants)	18%
Nitrogen and other minerals (from soil)	7%

In agriculture and ecology, soil means the top 1 to 2 m (3 to 6 ft) of life-bearing material. To engineers, it is mainly inert (lifeless) material under structures; and to geologists, it includes deep sediments. Here soil is widely interpreted as earth surface materials: it is any particulate material containing sand, silt, or clay particles (figure 2), and with or without organic matter. Soil is the "fines" (i.e., particles <2 mm (0.079 in) in size) produced by the fragmentation and weathering of rock or volcanic emissions. While our most important soil is the plant-nourishing mantle on the land enriched by organic matter, buried soil materials (e.g., quarried sand or clay) are also vital resources for our technologies.

This article has two purposes: it summarises the key properties and natural functions of soil and then reviews our many uses of soil materials, including non-agricultural uses.

THE NATURE OF SOIL

Soil's Main Components: Complex Stuff! Soil is very complex. Its solid phase contains three main materials: (1) mineral particles; (2) organic matter (OM)—both living biota (roots and a rich array of microscopic life-forms) and a very complex array of organic materials; and (3) ions—either dissolved in water or stored on mineral and organic particles (figure 3). Soil is not just a skin on the land, but is also sediments found deeper in Mother Earth's complexion. On a geological time scale,

Figure 2

Relative sizes of soil particles and microbes. From Buchan and Flury (2007). Reproduced by permission of Taylor and Francis Group LLC.

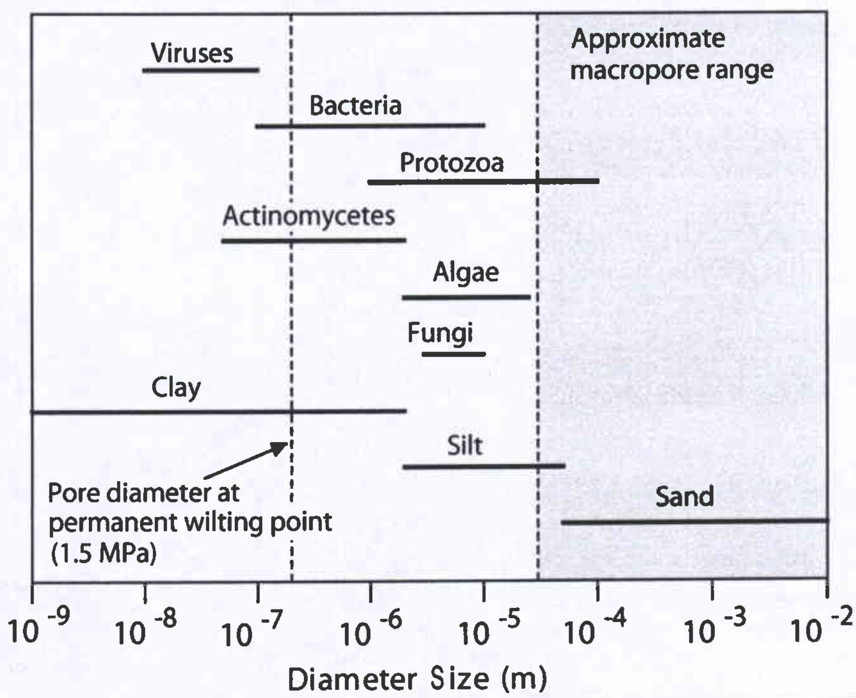

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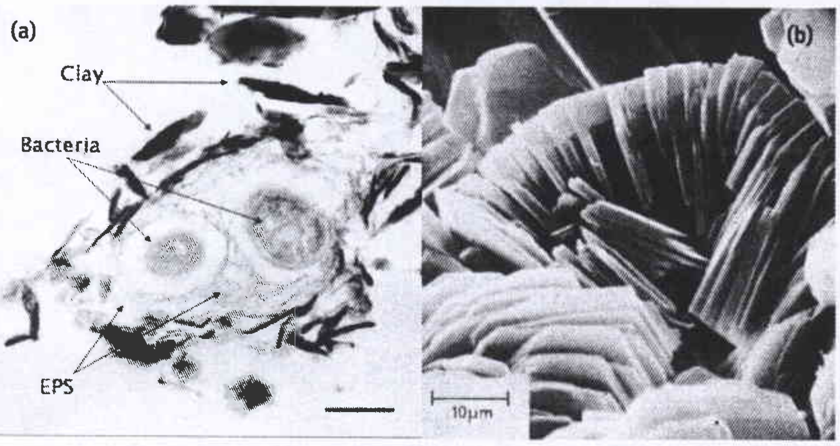
Figure 3

Clay particles and bacteria (both ~1 µm in size) seen with electron microscopes: (a) Bacteria and clay particles. The scale bar is 0.4 µm long. The bacteria produce extracellular polymeric substances (EPS), which help them stick together or to soil particles (Environment Canada 2004); (b) A domain of kaolin clay particles, showing their ordered stacking. The spaces between the particles contain water and ions. Added water is attracted into the interparticle spaces, causing swelling, or even total dispersion into a suspension. Firing the clay in an oven removes the water, bonding the particles into hard porcelain.



rising and falling sea levels intermittently flooded some land surfaces, forming complex layered systems (e.g., the Canterbury Plains in New Zealand) (figure 4).

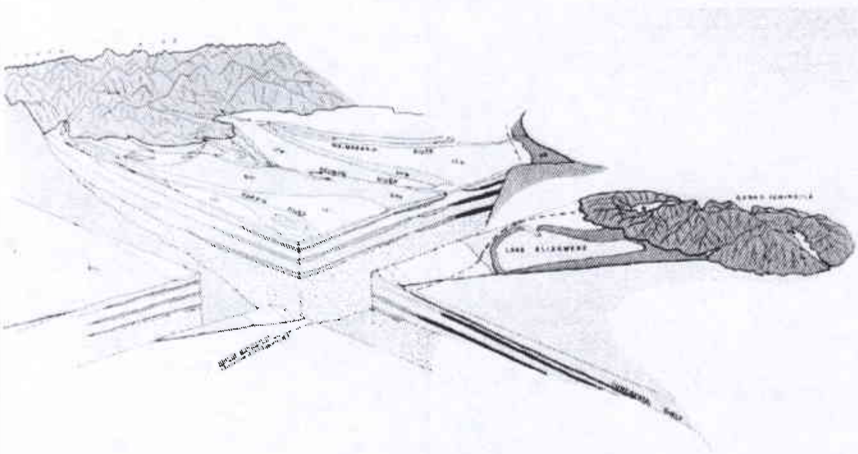
Soil looks highly disordered, but it has some order or structure (e.g., figure 3). Its components are bonded together by clays, OM, and mineral oxides, as well as by a living mesh of roots and fungi. These bonds are often easily broken or weakened by the remarkable softening power of water (Buchan 1996). Thus soil is physically alive, continuously reforming its structure, especially by wetting and drying cycles.

Soil Minerals. The mineral particles (figures 2 and 3) derive from rock or volcanic emissions. Sand and silt particles (primary minerals) are mainly fragments of rocks such as quartz or limestone. Clay particles (secondary minerals) are quite different: they result from complete chemical transformation of primary minerals, including slow dissolution and recrystallisation. The largest clay particles are about the same size as a bacterium (~1 µm (3.9×10^{-5} in) (figure 3a). Clay has two remarkable properties (figure 3b): (1) large surface area—a mere 0.1 gram (0.0035 oz) of clay (about 2% of the weight of a credit card) has a surface area of about 1 m^2 (10.8 ft^2), almost the body surface area of an adult); (2) most particles have strong surface charge (mainly negative). So, clay is the main colloid (i.e., surface active) soil component with strong stickability. It bonds soil particles and adsorbs water and nutrients, e.g., calcium (Ca^{++}) ions. Pure sand and silt particles have relatively inert (inactive) surfaces, giving very weak soil cohesion and poor adsorption of water or ions. However, Nature sometimes coats these particles with metal oxides or OM, enabling the particles to bond and retain nutrients (Adams and Gibbs 1994).

Organic Matter. Organic matter ranges from fresh deposits (e.g., leaves, roots) to almost fully decomposed humus. Humus, like clay, is a colloid with strong surface activity. A soil rich in OM (>70 %) is a peat. OM bonds particles and stabilises structure, contributing to the inner architecture of the pore space. In fact, it tends to open up soil porosity. It is the yeast of the soil, turning it into more holesome stuff! Decay of OM acidifies and accelerates the weathering of soils by adding complex organic acids and carbon dioxide (CO_2) gas (which dissolves to form carbonic acid).

Figure 4

Stratigraphy (i.e., layering) of the Canterbury Plains in New Zealand. Soil materials form a "layer cake" structure, overlying a bedrock basement at depths up to 500 meters. The layers are (a) permeable sands and gravels forming aquifers (water-carrying layers providing very pure groundwater for humans) and (b) impermeable marine clay layers, formed when ocean covered the land (Bowden 1983).



DID YOU KNOW?

A hyperactive soil caused the failure of Biosphere 2—a transparent, 1.2 ha (3 ac) enclosure in the Arizona desert, containing a closed, artificial ecosystem (including plants and humans). It was designed to simulate planet Earth (which is Biosphere 1). Why did it fail? It had excessive soil organic matter. Microbes decomposing this OM lowered oxygen levels in the atmosphere to life-unfriendly levels (Vergano 1996).

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Ions. The vital plant nutrients are either positive cations (e.g., Ca^{++}, potassium [K^+], sodium [Na^+], magnesium [Mg^{++}]) or negative anions (e.g., nitrate [NO_3^-] or phosphate [$(PO_4)^{3-}$]). Clay and organic particles, with their mainly negative surfaces, can adsorb large quantities of cations. A soil's cation exchange capacity (CEC) is a measure of its adsorption power, i.e., its ability to store and release nutrients. Ca^{++} is often a dominant cation, at the start of the soil–plant–animal supply chain which provides calcium for bones. By contrast, negative anions (e.g., NO_3^-) are repelled by soil's negative charges and are easily leached from soil. Hence, nitrate contamination of groundwater is a worldwide problem.

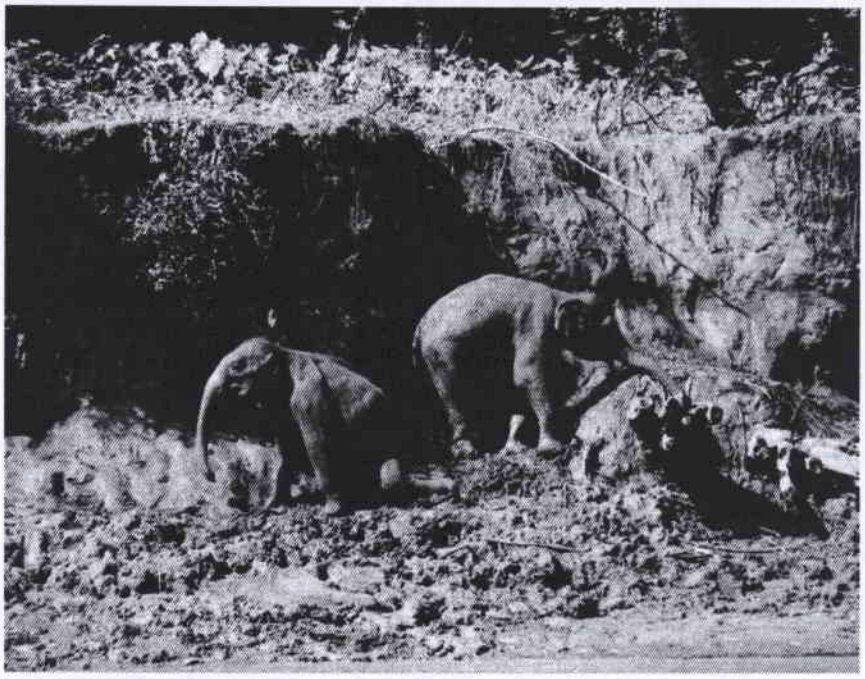
The Bonding and Separation of Soil Particles. The forces between colloid (i.e., clay and organic) particles are critical for their behaviour in (a) bulk soils in the field and (b) suspended material in water (e.g., rivers or oceans). The attraction or repulsion of particles is controlled by the degree of wetness and the types of cations in solution. If particles in a soil are weakly bonded, then when exposed to a very dilute solution (e.g., rainwater), the water invades the interparticle spaces, causing dispersion (see figure 3b). By contrast, if particles in a suspension are exposed to a highly concentrated solution such as seawater, the reverse attraction of water to the ions (osmosis) can reverse the dispersion, causing flocculation (i.e., the clustering of particles into flocs, similar to the domain in figure 3b).

DID YOU KNOW ?

River or swimming pool water containing suspended clay or organic particles (e.g., figure 5) can be clarified for human use by adding alum (aluminium sulphate) as a flocculating agent. In a similar process, blood clotting involves coagulation of blood platelets and can be speeded up by aluminium ions. Alum (in the form of a styptic pencil) dabbed on skin halts bleeding from minor (e.g., shaving) cuts.

Figure 5

Elephants in an orphanage in Sri Lanka enjoying riverbank mud bathing! By drinking the dirty river water with its suspended soil particles, they also ingest soil minerals.



So, Why are the Oceans not Muddy? Rivers and lakes typically carry fine particles in suspension (figure 5). Earth's hydrological cycle is a soil conveyor belt, sweeping soil material (silt, clay, and OM) into the oceans at the rate of about 15 billion t (~16 billion tn) per year (Ludwig and Probst 1998). Fortunately, the oceans remain clear, enabling sunlight to reach phytoplankton at the start of the ocean food chain. Why are the oceans clear? Answer: The high concentration of salts in seawater causes suspended particles to bind into groups (flocs) and settle out as ocean-bottom sediments. Some old marine clay layers, now under the land, are effectively watertight and form confining layers which trap and protect huge aquifers (groundwater lenses), conveniently available for use by humans (figure 4). So, salts in the sea make it self-clarifying.

PHYSICAL ASPECTS OF SOIL

Soil minerals have a density of about 2.65 g cm^{-3} (165 lb ft^{-3}) (similar to most rocks), about 2.5 times the density of water. This is slightly denser than common silica glass (2.2 g cm^{-3} [137 lb ft^{-3}]) due to heavier elements (such as aluminium).

DID YOU KNOW ?

The average density of planet Earth is 5.5 g cm^{-3} (343 lb ft^{-3}). Earth's thin continental crusts consist of rock material with density 2.65 g cm^{-3} (165 lb ft^{-3}) (similar to soil particles). They float on denser materials beneath (Buchan 1994).

A TRICK QUESTION

Which is denser—organic matter (e.g., wood fiber) or water?
Answer: organic matter is denser, with a material density about 1.3 g cm^{-3} (81 lb ft^{-3}). Hence, waterlogged wood or saturated tea leaves sink!

Water Storage. Water and soil are powerful partners supporting life on the land. Their strong mutual attraction makes soil a reservoir of water for plants, thanks to the wonder properties of water (Buchan 1996), including its strong polarity and large surface tension. This results in powerful absorption of water into soil pores, and adsorption onto particle surfaces.

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Soil Air Exchange. Soil is alive with microbes, roots, and other life-forms, which (like humans) need to respire, i.e., consume oxygen and release energy, giving out CO_2. So soil breathes through its surface layers. A square meter of a temperate soil may breathe in about 10 l or more (0.35 ft^3) of oxygen per day (Currie 1970). For comparison, a sitting adult requires about 500 l (17.6 ft^3) of oxygen per day (Keele et al. 1982).

Soil Degradation and Erosion. The loss of productive soil, mainly by erosion, is among our top few environmental threats. Civilisations have risen and fallen on their soils. A leading factor in the decline of Mesopotamia was the slow salinisation (accumulation of excess salts) in its once productive soils, leading to declining crop yields (Hillel 1998). Worldwide, about 12 billion ha (~30 billion ac) per year of arable land are degraded and abandoned by humans—about 0.8% of all cultivated land (Pimentel et al. 1995).

Erosion is either natural or accelerated (caused by humans). Natural erosion occurs on a grand scale and is vital—it has deposited and formed our soils. However, accelerated erosion now causes loss of about 10 million ha (24.7 million ac) of world cropland each year (Pimentel 2006).

DID YOU KNOW?

Erosion is estimated to remove from the land over 68 billion t (75 billion tn) of soil per year (Wilkinson and McElroy 2007; Pimentel et al. 1995). Much of this soil is redistributed and concentrated elsewhere on the landscape or in reservoirs or dams. Only about 15 billion t (16 billion tn) per year (i.e., about 20%) is discharged by rivers to the oceans (Ludwig and Probst 1998).

In the United States and Europe, erosion skims off the land about 1.7 mm (0.067 in) of soil per year, while new soil forms naturally at only about 0.1 mm (0.0039 in) per year (Pimentel et al. 1995). The World Clocks (http://tranquileye.com/clock/) has two digital displays: the population clock counts quietly upwards, while the second, showing Earth's productive land area, counts downwards. They tell a clear story of unsustainable practices.

Tiny soil particles, windblown into the high atmosphere, provide part of Nature's range of cloud condensation nuclei (CCN). These CCN are essential for seeding the formation of cloud droplets or ice crystals, and hence raindrops or snow. So again, water and soil are partners in the hydrological cycle.

CHEMICAL ASPECTS OF SOIL

Soils tend to resist rapid chemical changes, i.e., they are buffered. For example, soil acidity changes very slowly, thanks to soil's ability to adsorb ions onto its surfaces (Yong et al. 1992). Soil is like a giant chemical exchange material covering Earth's land surfaces, capturing and releasing ions and nutrients and buffering ecosystems against rapid changes, e.g., in the acidity of rainwater.

Soil: A Water Cleanser and Conditioner. Soils, buried sediments, and rocks also condition the state of waters on planet Earth. Deep groundwater (e.g., figure 4) has percolated through layers of soils and sediments, which filter out impurities and contaminants and also add dissolved minerals—hence the term "mineral water" (Snoeyink and Jenkins 1980).

Soil Color. Soil color originates from several components. Organic matter darkens soils. Sesquioxides (i.e., iron and aluminium-based minerals) impart other colors, e.g., haematite (iron based) is red, and goethite is yellowish brown.

DID YOU KNOW ?

Eating soil (geophagia) is a custom among some peoples (as well as wildlife and curious infants!). It can have several benefits: it supplements trace elements in the diet or detoxifies foods by adsorbing toxins onto particle surfaces (Oliver 1997). See figure 5.

BIOLOGICAL ASPECTS OF SOIL

Soil Microbes. The soil is densely populated with microbes (including protozoa, bacteria, fungi, and viruses). See figure 3. One tablespoon of agricultural soil has more organisms in it than people on Earth. Soil microbes help close several of Nature's cycles, including the nitrogen (N) and carbon (C) cycles. Soil is the great digester, decomposing and returning to the biosphere huge amounts of plant and animal wastes.

DID YOU KNOW ?

- Soil is also a reservoir of diseases. These include tetanus (figure 6), anthrax, and hookworms (Oliver 1997).
- Most clinical antibiotics, including penicillin, originate from soil microbes (Clewell 2008).

Plants. Plants are the main conveyors of the Sun's energy (and hence life!) to the soil "reactor," providing organic matter and food for microbes. Roots interact subtly with soil. Nitrogen-fixing bacteria live in symbiosis with roots of some plants, providing natural N fertiliser. In New Zealand, free nitrogen from clover (an example of an ecosystem service) is worth over one billion dollars per year to agriculture (~NZ $300 per person each year). Root-to-soil contact is enhanced by another symbiosis: the rhizosphere is a sheath of microbes (fungi and bacteria) surrounding root fibers, which enhances their uptake of water and nutrients (figure 1).

Worms. Worms are both gardeners and engineers of the underworld. Darwin recognised their huge role as biological cultivators. In a fertile soil, worms can digest as much as 90 t ha^{-1} (40 tn ac^{-1}) of soil each year, helping to intermix soil layers. For comparison, a good wheat crop yields 10 t ha^{-1} (4.5 tn ac^{-1}). Wormholes are Nature's ventilation shafts and drainpipes. They speed up soil's acceptance of surface water, reducing water runoff and erosion. Without worms, soils today would be more eroded, thinner, and less fertile.

DID YOU KNOW ?

In a fertile pasture, the weight of earthworms below the surface can exceed that of grazing animals above! (Yeates 1989).

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Figure 6

Most soil microbes are beneficial for soil activity or harmless to humans. However, soil also contains pathogens, e.g., for tetanus or legionnaire's disease. This painting shows a soldier dying from tetanus, a bacterial infection harboured in soil, contracted via a wound. Painting by Charles Bell. Reproduced by permission of the President and Fellows of the Royal College of Surgeons of Edinburgh.

NATURAL ROLES OF SOIL

Soil and Water: Clean-up Partners. Water entering soil can carry suspended material and contaminants, but is filtered as it percolates through the soil, cleansing it before it reaches groundwater. About one-third of all housing units in the United States dispose of wastewater via on-site septic tanks, with soil acting as the final receiver and cleanser of the treated wastewater.

While soil cleanses water, water also cleanses soils! As soil minerals slowly break down, they release salts. In dry climates, this results in salt-affected soils, i.e., soils with an excess of salts or sodium. Fortunately, Earth has a huge flushing system. Water evaporating from Earth's 70% ocean cover delivers excess rain to most of the 30% land, which leaches out excess salts from soil. This is Nature "doing its washing."

DID YOU KNOW?

Ninety percent of world soils are clean (free from salt problems). In suitable climates, they support productive crops. Only the remaining ten percent are salt affected (Szabolcs 1989).

Soil—The Climate Controller. Soils emit and absorb several greenhouse gases, including CO_2, methane (CH_4), and nitrous oxide (N_2O), and thus help regulate Earth's climate.

DID YOU KNOW?

- Earth's land cover (plants and soils) absorb about 29% of anthropogenic CO_2 emissions, helping reduce global warming (Global Carbon Project 2009).
- World soils contain about twice the total C in the atmosphere (Blum 2005; Wilding and Lin 2005).

Heat Storage. Soil is a powerful climate moderator. It prevents surface temperatures swinging to hostile extremes. The biosphere pulses with two rhythms: the daily and annual cycles of temperature. Soil plays two vital roles:

- Daytime. Soil is the vital water reservoir, supplying water to transpiring plants, whose evaporation helps cool Earth's "skin."
- Nighttime. Soil is a heat reservoir. It is Nature's "storage heater," storing solar heat in daytime and then releasing it at night. Without this, nighttime temperatures would plummet and freeze and kill all but the most basic life-forms.

Similarly, the soil moderates summer-to-winter temperature swings. Below about 8 m (26 ft) depth, temperature remains almost constant all year.

DID YOU KNOW ?

Soil is cool! The residents of Coober Pedy, a mining town in Australia, suffer stifling daytime air temperatures. So, they have built an entire town underground, where it stays tolerably cool.

USES OF SOIL

This section reviews nonagricultural uses of soil materials. Since most involve use of clays, these are reviewed first.

Uses of Clays. Globally, humans extract more than 135 million t (149 million tn) per year of different clays for industrial, construction, agricultural, and environmental purposes (Murray 1993).

In industry, clays are used widely as follows:

- Ceramics and porcelains. Firing clay at high temperatures drives out interparticle moisture, pulling particles together so that they bond to form strong materials, such as porcelain or pottery (figure 3b).
- Papermaking. Clays (e.g., kaolin) are used as fillers, closing the tiny gaps between cellulose fibers. This enables printing of higher resolution images, increases paper strength, and can also act as whitening pigment.
- Paint. Kaolin is used alongside titanium dioxide in water-based paints. Small particles give high-gloss finish, while larger particles give a "flat" finish. Clay also acts as a carrier for the coloring pigments (Velde 1995).
- The petroleum industry uses over 300,000 t (330,000 tn) of kaolin per year as a catalyst in the breakdown (or cracking) of larger hydrocarbon molecules.
- Montmorillonite clays (called bentonite in industry) are used in oil-well drilling muds.

Clays are also used in everyday products, including cleaning agents, and in the clarification of beer and wine (Murray 1993).

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In construction, huge quantities of soil are used for building materials (Allen 1997). See figure 7. Bricks are made from kiln-fired clay or silt. Mud can be moulded into bricks to build adobe houses, which have excellent heat insulation. Soil is also used to construct earth dams. During the Red River floods in Canada in 1997, 47 km (29 miles) of earth dikes were built over a few days, helping save Winnipeg and its surroundings from severe flooding.

DID YOU KNOW?

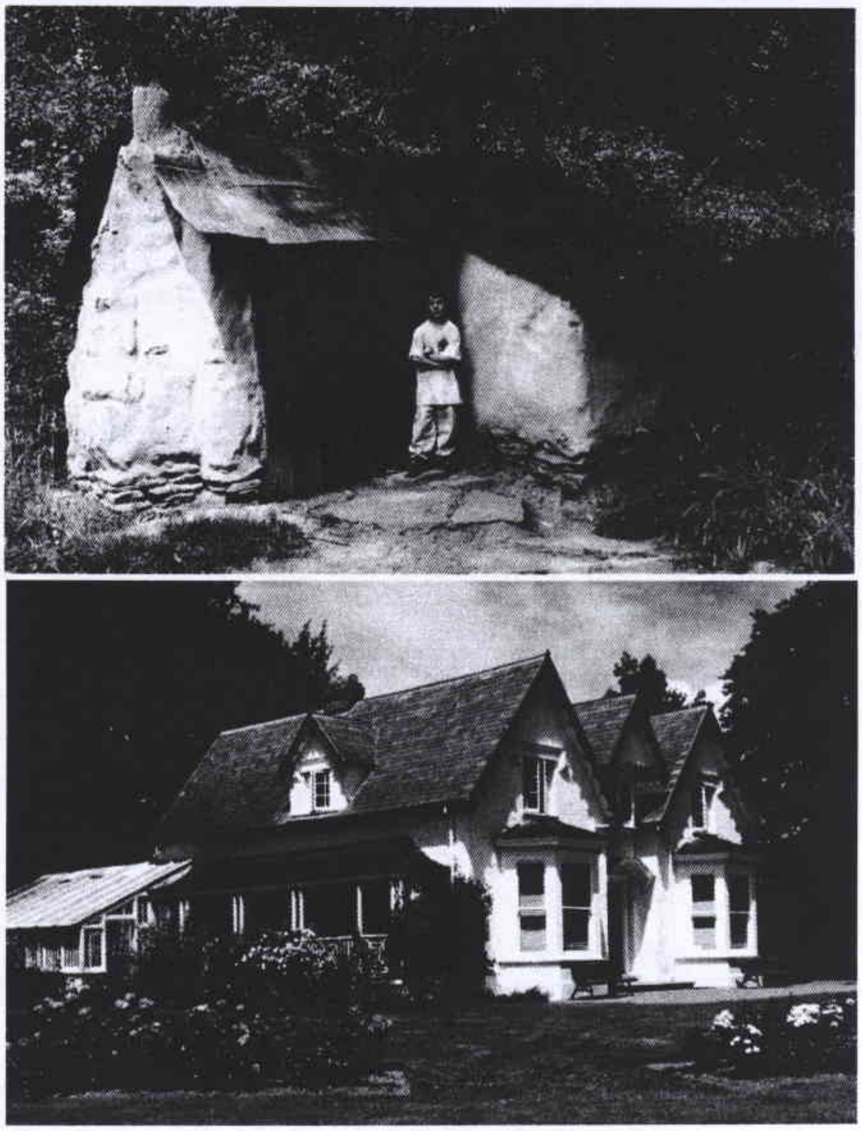
The bricks in Buckingham Palace, London, were made from loess (i.e., windblown silt) deposits from North Kent, England.

Compacted clay (e.g., montmorillonite) makes an excellent sealing or lining layer (e.g., in irrigation ditches, dams, and ponds). Clay can be used as a liner in modern waste landfills, making them watertight against water entry in and leaching losses out. Clays also have strong exchange capacity and hence can capture contaminants, blocking the migration of toxic or hazardous wastes out of the landfill.

Soils for Sports. Soil properties are critical for sports. For wet-weather surfaces (playing fields or golf greens), the best support is a sand or sandy soil. They are free draining and compact to provide a stable, nonsticky, nonpugging, nonslip surface for foot traffic. By contrast, for dry-weather cricket pitches or grassed tennis courts, the best surfaces are dry, compact clays, which provide good bounce for the ball (Adams and Gibbs 1994).

Figure 7

Soil for construction. Top: 19th century home in Chinese Village, Arrowtown, New Zealand. Bottom: Broadgreen House, Nelson, New Zealand. The walls of these houses are partly constructed from earth material. Earth-building of homes is increasingly recognised as a sustainable construction method.



CONCLUSIONS

Imagine being given this task: Design a life-enabling planet. One major subtask: you must invent a material to cover the land and support its life. Specifications include the following: it must store and release water and gases and drain away excess water; it must act as a chemical factory, generating, storing, and releasing nutrients, and as a bioreactor, cycling Nature's huge annual yields of dead organic material back into the biosphere; it must help regulate microclimate; it should be strong enough to support plants and animals and resist erosion, yet weak enough to enable penetration by roots and worms. You would surely design...... soil: that marvellous, "holesome" material, a myriad of tiny particles and pores. Crops can be grown in soil-less media: in hydroponics (roots dangling in nutrient solution) or even aeroponics (roots dangling in air, sprayed by nutrient solution). However, these high-tech methods suit only small-scale growth of high-value crops. Our major food stocks will always require large-scale cropping of field soils.

Soil is the terra incognita, the hidden half. We spend large resources exploring outer space, while much remains unknown of the "inner space" of the soil, especially at the soil–root interface. Soil is the very source of civilisation—Culture begins with cultivation. It is the beginning and end place for land-borne life, a vital link in the cycles of life: the digester of the dead and the birthplace of the new. Life should be a covenant between people and the land. Just as soil gives us life, we should be custodians of the life of the soil. Let us

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value and conserve soil, the place of our nativity.

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