1 • Introduction

Palaeontology incorporates several, overlapping, areas, the principal of which are:

- Systematic palaeontology, or taxonomy, that is, the documentation, description and classification of new species and higher-level taxa of fossils
- Phylogenetics, that is, the analysis and interpretation of their evolutionary relationships
- Palaeobiology, that is, the documentation, analysis and interpretation of their relationships to evolving earth and life processes and environments, and their application to the elucidation thereof
- Biostratigraphy, that is, the documentation, analysis and interpretation of their ordered succession, their relationships to evolving earth and life history, and their application to the elucidation thereof.

The former two areas of study, systematics and phylogenetics, interfacing with life science, constitute pure palaeontology; the latter two, palaeobiology and biostratigraphy, interfacing not only with life science, but also with earth and environmental science and other disciplines, applied palaeontology (Fig. 1.1).

There is a logical progression from pure to applied aspects through the course of the book. The purer parts will perhaps be of most value to earth and life science undergraduate and postgraduate students and professionals in academia (and also to interested amateurs). The applied parts will be of value to professionals in industry, including not only applied palaeontologists, palaeobiologists and biostratigraphers, but also petroleum, minerals, mining and engineering geologists, environmental scientists and environmental archaeologists.

Chapter 2 ('Fossils and fossilisation') essentially deals with what fossils are, how they form, how they are collected, and how they are classified and identified, described and illustrated, and curated. It includes sections on fossils, on the fossilisation process (taphonomy), on collection of fossils, on classification and identification (systematic palaeontology or taxonomy), on description and illustration (palaeontography), and on preparation, conservation and curation (museology). The section on the fossilisation process contains sub-sections on the representativeness of the fossil record, and on exceptional preservation of fossil assemblages. The section on collection contains sub-sections on surface collection of macrofossils, and collection of surface samples for microfossil analysis, and contains a code of conduct. It also covers equipment and safety.

Chapter 3 ('Principal fossil groups') deals with the principal fossil groups. It includes sections on bacteria, plant-like protists or algae, animal-like protists or 'protozoans', plants, fungi, invertebrate and vertebrate animals, and trace fossils. The section on bacteria covers cyanobacteria and stromatolites. The section on plant-like protists or algae contains sub-sections on: dinoflagellates; silicoflagellates; diatoms; calcareous nannoplankton; calcareous algae; and Problematica (acritarchs and *Bolboforma*). The section on animal-like protists or 'protozoans' contains sub-sections on foraminiferans, radiolarians and calpionellids. The sub-section on foraminiferans covers, in some detail, '*Rhabdammina*' or 'flysch-type' or 'deep-water arenaceous foraminiferan (DWAF)' faunas, and larger benthic foraminiferans. The section on plants covers plant macrofossils, spores and pollen, and phytoliths. The coverage of plant macrofossils includes mosses and allied forms (bryophytes), club mosses, ferns, horsetails and allied forms (pteridophytes), seed-plants, that is, seed-ferns, tree ferns, conifers and allied forms (gymnosperms), and flowering plants (angiosperms). The section on fungi covers fungal spores and hyphae. The section on invertebrate animals contains sub-sections on sponges, archaeocyathans and stromatoporoids (poriferans), corals (cnidarians), brachiopods and bryozoans (lophophorates), bivalves (including, in some detail, rudists), gastropods, ammonoids, belemnites and tentaculitids (molluscs), trilobites, ostracods and

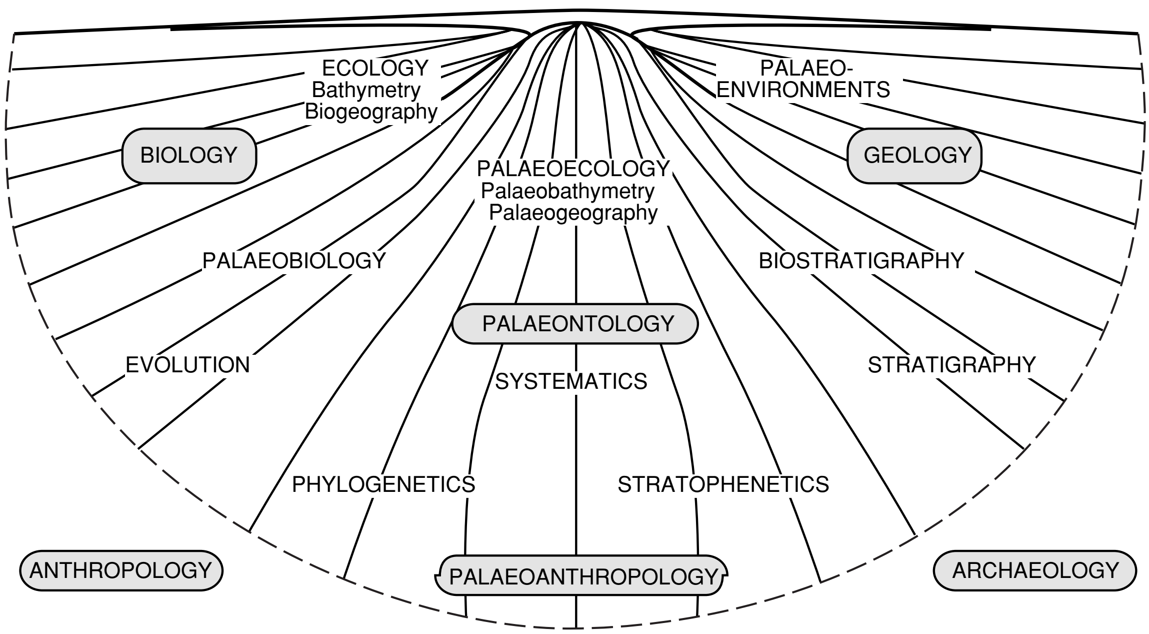

Fig. 1.1. Schematic representation of the relationship of palaeontology to biology and geology ('-ologies').

insects (arthropods), and crinoids and echinoids (echinoderms). It also includes sub-sections on 'ediacarians', 'small shelly fossils', tentaculitids, graptolites and chitinozoans. The section on vertebrate animals contains sub-sections on fish; and on amphibians, reptiles and birds, and mammals, collectively known as tetrapods. The sub-section on fish covers conodonts, ichthyoliths and otoliths, collectively colloquially known as 'fish bits'. Emphasis has been placed on the palaeobiological and biostratigraphic significance of the various groups, and their proven and potential applications in the interpretation of earth and life history and processes.

Chapter 4 **('Palaeobiology')** deals with applications of fossils in the interpretation of earth and life processes (excluding evolution), and environments. It includes sections on palaeoecology or palaeoenvironmental interpretation, on discrimination of non-marine and marine environments, on palaeobathymetry, on palaeobiogeography, on palaeoclimatology, and on quantitative and other techniques. The section on palaeoenvironmental interpretation contains sub-sections on palaeoenvironmental interpretation on the basis of analogy and palaeoenvironmental interpretation on the basis of functional morphology. The sub-section on functional morphology covers life strategy, life position and feeding strategy. The section on palaeobathymetry contains sub-sections on marginal marine environments, shallow marine environments and deep marine environments. The sub-section on shallow marine environments covers shallow marine clastic and carbonate environments. The sub-section on deep marine environments covers: oxygen minimum zone sub-environments; submarine fan sub-environments; and hydrothermal vent and cold (hydrocarbon) seep environments, including, in some detail, observations on benthic foraminiferans associated with hydrocarbon seeps. The sections on palaeobiogeography and palaeoclimatology each contain sections on the Palaeozoic, the Mesozoic and the Cenozoic. The section on quantitative and other techniques contains sub-sections on palaeobathymetry, palaeobiogeography and palaeoclimatology.

Chapter 5 ('Key biological events in earth history') deals with the generalities and specifics of the evolutionary and extinction events and trends that have controlled past and present, and will control future, biodiversity on Earth. It includes general sections on evolution and extinction events, and on Proterozoic, Palaeozoic, Mesozoic and Cenozoic events. The section on evolution and extinction contains sub-sections on evolution and extinction. The sub-section on evolution covers evolutionary events and evolutionary biotas (including the Cambrian, Palaeozoic and Mesozoic–Cenozoic, or modern, evolutionary biotas). It also covers, in some detail, foraminiferal diversity trends through time. The sub-section on extinction covers mass extinction events (including causes, periodicity, selectivity and recovery). The section on the Proterozoic contains sub-sections on the origin of life (prokaryotes), on the evolution of complex life (eukaryotes), and of multicellularity, and on the Late Precambrian mass extinction. The section on the Palaeozoic contains sub-sections on the Cambrian evolutionary diversification, the evolution of reefs, the Early and Late Cambrian mass extinctions, the Ordovician evolutionary diversification, the evolution of vertebrates, the End-Ordovician mass extinction, the evolution of life on land, the Late Devonian mass extinction, the evolution of forests, and of flight, and the End-Permian mass extinction. The section on the Mesozoic contains sub-sections on the Mesozoic evolutionary diversification, the End-Triassic mass extinction, the evolution of flowering plants, and the Late and End-Cretaceous mass extinctions. The section on the Cenozoic contains sub-sections on the End-Palaeocene and End-Eocene mass extinctions, the evolution of grasses and grassland animals, the evolution of humans, and the Pleistocene and Holocene mass extinctions. It also covers, in some detail, firstly, new evidence for land mammal dispersal across the northern North Atlantic in the Early Eocene; and, secondly, aspects of the palaeogeography and palaeoclimate of the Oligocene–Holocene of the Old World, and consequences for land mammal evolution and dispersal – including that of *Homo sapiens*.

Chapter 6 ('Biostratigraphy and sequence stratigraphy') deals with applications of fossils in the interpretation of earth and life history. It includes sections on biostratigraphy, on biostratigraphic technologies, on allied disciplines, on stratigraphic timescales and on sequence stratigraphy. The section on biostratigraphy contains sub-sections on the Proterozoic, the Palaeozoic, the Mesozoic and the Cenozoic. The section on biostratigraphic technologies contains sub-sections on graphic correlation and on ranking and scaling. The section on allied disciplines contains sub-sections on chemostratigraphy, cyclostratigraphy, heavy minerals, magnetostratigraphy, radiometric dating and Quaternary dating methods. The sub-section on chemostratigraphy covers carbon, oxygen and strontium isotope stratigraphy, and trace element stratigraphy. The section on stratigraphic timescales covers global stratigraphic (boundary) sections and points (GSSPs). The section on sequence stratigraphy contains subsections on general and clastic sequence stratigraphy, carbonate sequence stratigraphy, mixed clastic–carbonate and carbonate–evaporite sequence stratigraphy, and seismic facies analysis. It also covers, in some detail, palaeontological characterisation of systems tracts.

Chapter 7 ('Case histories of applications of palaeontology') deals with how our knowledge of fossils and earth and life history is applied in industry and elsewhere. It includes sections on petroleum geology, mineral exploration and exploitation, coal mining, engineering geology, environmental science and archaeology. The section on petroleum geology contains sub-sections on the principles and practice of petroleum geology, and on applications of biostratigraphy and palaeobiology in petroleum exploration and in reservoir exploitation, each with case histories. The sub-section on the principles and practice of petroleum geology covers: play components (petroleum source-rocks and systems, reservoir-rocks and cap-rocks (seals) and traps), and stratigraphic control on their distribution; petroleum exploration; and reservoir exploitation (drilling, petrophysical logging and testing). It also covers, in some detail: palaeontological inputs into petroleum systems analysis; micropalaeontological characterisation of mudstone cap-rocks; and palaeontology and health, safety and environmental issues in the petroleum industry. The sub-section on applications of biostratigraphy and palaeobiology in petroleum exploration covers chronostratigraphy and palaeoenvironmental interpretation, and operational biostratigraphy, with accompanying case histories selected from the central and northern North Sea and the Middle East. The sub-section on applications in reservoir exploitation covers integrated reservoir description, and biosteering, with accompanying case histories selected from Cusiana field

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in Colombia, the Andrew field in the North Sea, the Sajaa field in Sharjah in the United Arab Emirates and the Valhall field in the North Sea. The section on mineral exploration and exploitation includes a sub-section on case histories from the La Troya mine in Spain (mineral exploration), and the Pitstone and East Grimstead quarries in the UK (mineral exploitation). The section on engineering geology includes a sub-section on case histories from the Channel tunnel, Thames barrage and 'Project Orwell' site investigations in the UK. The section on environmental science contains sub-sections on environmental impact assessment and environmental monitoring. The section on archaeology contains sub-sections on archaeostratigraphy and environmental archaeology, and case histories. The sub-section on environmental archaeology covers, in some detail, the palaeoenvironmental interpretation of the Pleistocene–Holocene of the British Isles, as determined by proxy benthic foraminiferal distribution data. The sub-section on case histories covers Westbury Cave, Somerset (Palaeolithic), Boxgrove, Sussex (Palaeolithic), Massawa, Eritrea (Palaeolithic), Goats Hole, Paviland, Gower (Palaeolithic), 'Doggerland', North Sea (Mesolithic), Mount Sandel, Coleraine, Co. Derry, Northern Ireland (Mesolithic), the Black Sea (Mesolithic/Bronze Age), the Tyrolean Alps (Neolithic), Littleton, Co. Tipperary, Ireland (Neolithic–Medieval), Skara Brae, Orkney (Neolithic) and the City of London (Medieval).

2 • Fossils and fossilisation

This chapter essentially deals with what fossils are, how they form, how they are collected, and how they are classified and identified, described and illustrated, and curated.

2.1 Fossils

The word 'fossil' derives from the Latin *fodere*, meaning 'to dig'. Its usage is in reference to any and all physical remains or other direct physical indications of past life. The physical remains of past life include not only what are often termed 'body fossils', that is, 'hard parts' of skeletons such as bones (Denys, in Briggs and Crowther, 2001) and shells (Meldahl, in Briggs and Crowther, 2001), but also, under exceptional circumstances, 'soft parts' of animals (Stankiewicz and Briggs, in Briggs and Crowther, 2001), parts of plants (van Bergen, in Briggs and Crowther, 2001), bacteria (Liebig, in Briggs and Crowther, 2001), and biomolecules such as fats, proteins and DNA (Briggs *et al.*, in Erwin and Wing, 2000; Collins and Gernaey, in Briggs and Crowther, 2001; Evershed and Lockheart, in Briggs and Crowther, 2001; Poinar and Paabo, in Briggs and Crowther, 2001; Jones, 2001). Other direct physical indications of past life include 'trace fossils' (see separate section in Chapter 3).

2.2 The fossilisation process (taphonomy)

The fossilisation process, whereby living individual organisms or communities are transformed after death into fossils or fossil assemblages, is termed taphonomy (Fursich, in Briggs and Crowther, 1990; Allison and Briggs, 1991; Donovan, 1991; Martin, 1999; Behrensmeyer *et al.*, in Erwin and Wing, 2000; Wilson, in Briggs and Crowther, 2001; Holz and Simoes, in Koutsoukos, 2005). In fact, a range of biological, physical and chemical processes is involved, from decomposition (Allison, in Briggs and Crowther, 2001), through disarticulation, fragmentation and transportation (Anderson, in Briggs and Crowther, 2001), to compaction, thermal alteration and dissolution on burial (Briggs, in Briggs and Crowther, 1990; Tucker, in Briggs and Crowther, 1990; Jones, 1996; McNeil *et al.*, 1996), and reworking. For a living organism to become fossilised requires that it can withstand the combined effects of these processes. In general, its chances of becoming fossilised are enhanced if it becomes buried immediately after death (and/or is otherwise protected from decomposition, perhaps by anoxic bottom conditions), and/or is and remains resistant to the destructive physical and chemical effects of the so-called diagenetic processes that enter into operation after burial (see also Sub-section 2.2.2). The rate of burial relative to that of destructive processes, and hence the likelihood of fossilisation, varies considerably from place to place, and indeed from time to time (Brett and Speyer, in Briggs and Crowther, 1990). However, fossilisation potential is generally best in marine environments. The processes by which living plants and animals become fossilised in terrestrial environments can be extremely complicated, and remain comparatively poorly understood. Preservation of fossils is typically in the form of mineralised hard parts such as bones and shells, or casts or moulds of shells, in the case of marine and terrestrial animals; and in the form of flattened two-dimensional impressions in the case of plants (but see also Sub-section 2.2.2).

Importantly, the palaeobiological and biostratigraphic usefulness of (micro)fossils can be impaired by alteration to the specific composition of the living community by natural taphonomic processes such as – selective – transportation, and diagenetic thermal alteration, dissolution and destruction (Jones, 1996; McNeil *et al.*, 1996; Murray and Alve, in Hart *et al.*, 2000; Reinhardt *et al.*, 2001; Ruiz *et al.*, 2003).

Readers interested specifically in the taphonomy of plants are referred to Scott, in Briggs and Crowther (1990), Spicer, in Briggs and Crowther (1990) and Gastaldo, in Briggs and Crowther (2001). Those interested specifically in the complex taphonomy of terrestrial vertebrates are referred to Andrews (1990), Behrensmeyer *et al.* (1992), Behrensmeyer and Kidwell (1993), Lynam (1994), Behrensmeyer, in Briggs and Crowther (2001) and Trueman *et al.* (2003).

2.2.1 *Representativeness of the fossil record*

In view of the destructive nature of the fossilisation and preservation process (see above), legitimate questions have been asked as to the likely completeness and representativeness of the fossil record, and as to the meaningfulness of attempts to analyse same (Holland, in Erwin and Wing, 2000; Foote, in Briggs and Crowther, 2001; Kidwell, in Briggs and Crowther, 2001; Smith, in Briggs and Crowther, 2001). It may be equally legitimately argued that sufficient exceptionally preserved fossil assemblages are now known, providing 'windows on the world' at every level, that this is no longer such a serious issue.

2.2.2 *Exceptional preservation of fossil assemblages*

As intimated above, a number of examples are now known from the fossil record of exceptionally preserved fossil assemblages or 'fossil-Lagerstatten' (Briggs, in Briggs and Crowther, 2001; Bottjer *et al.*, in Bottjer *et al.*, 2002; Selden and Nudds, 2004). The word 'Lagerstatte' derives from the German mining tradition, and its usage is in reference to deposits containing sufficient constituents of economic interest to warrant exploitation (Seilacher, in Briggs and Crowther, 1990). The nature of the preservation in fossil-Lagerstatten is exceptional in terms of quality and/or quantity. Exceptional quality preservation, or conservation – in 'Konservat-Lagerstatten' in marine environments typically arises through the process of obrution, whereby living communities become smothered and buried extremely rapidly, perhaps by an effectively instantaneous event (Brett, in Briggs and Crowther, 1990). The Burgess shale, the Hunsruck slate, and the Lithographic limestone are all interpreted examples of obrutionary stagnation deposits, in which preservation was enhanced by the protection from decomposition provided by anoxic bottom conditions (see also below). These examples are all characterised by exceptional quality soft-part as well as hard-part preservation, albeit only in two-and-a-half dimensions. Exceptional quality preservation in terrestrial environments typically arises through deep-freezing, pickling, or desiccation (Seilacher, in Briggs and Crowther, 1990). It can also arise through encapsulation in amber (Martinez-Delclos *et al.*, 2004; Poinar and Poinar, 2004), as in the case of Baltic amber (Schluter, in Briggs and Crowther, 1990; Janzen, 2002; Selden and Nudds, 2004) and Dominican amber (Poinar and Poinar, 1999; Poinar, in Briggs and Crowther, 2001). Exceptional quantity preservation – in 'Konzentrat-Lagerstatten' – typically arises through concentration by physical processes (Seilacher, in Briggs and Crowther, 1990). Concentration can also arise in so-called 'traps', such as the Pleistocene Rancho La Brea tar pit in Los Angeles in California (Selden and Nudds, 2004).

The most important of the exceptionally preserved fossil assemblages or fossil-Lagerstatten are those that provide insights into key biological events in earth history (see below; see also Chapter 5).

Proterozoic

Exceptionally preserved 'ediacarians' are known from the Late Precambrian of the Ediacara Hills in South Australia and elsewhere (see Sub-section 3.6.1). The 'ediacarian' biotas provide important insights into the evolution of multicellularity.

Palaeozoic

Exceptionally preserved Cambrian biotas are known from, for example, the Early Cambrian, Atdabanian/Botoman, *Nevadella* Zone, of Sirius Passet in Greenland (Conway Morris, 1998), and the Early Cambrian, Qiongzhusian, *Eoredlichia–Wutingaspis* Zone, Ya'anshan member of the Heinlinpu formation of Chengjiang in eastern Yunnan Province in southwest China, part of the South China micro-plate (Hou Xian-Guang and Bergstrom, 1997; Bergstrom, in Briggs and Crowther, 2001; Hagadorn, in Bottjer *et al.*, 2002; Hou Xian-Guang *et al.*, 2004). Further exceptionally preserved faunas are known from the Middle Cambrian, Albertan, Burgess shale of British Columbia in Canada (Conway Morris, in Briggs and Crowther, 1990; Gould, 1990; Briggs *et al.*, 1994; Conway Morris, 1998; Hagadorn, in Bottjer *et al.*, 2002; Selden and Nudds, 2004). These faunas provide important insights into the 'Cambrian evolutionary diversification', and information on rare groups. Although it is not as prolific or as famous as the Burgess shale biota, the Chengjiang biota is perhaps more important, as it is older (although not as old as the – comparatively less well-known – Sirius

Passet biota). The Chengjiang biota is characterised by hard-bodied calcareous algae, 'small shelly fossils', poriferans, cnidarians, brachiopods, phoronids, arthropods, vetulicolids and chordates, occasionally with their soft parts preserved, and, significantly, by soft-bodied nematomorphs, priapulids, chaetognathans and enigmatics.

Exceptionally preserved eurypterids and conodont parent animals are known from the 'Late' Ordovician Soom shale member of the Cedarberg formation of the area around Keurbos in southwestern Cape Province in South Africa (Aldridge *et al.*, in Briggs and Crowther, 2001; Selden and Nudds, 2004). The Soom shale fauna provides important insights into the 'Ordovician evolutionary diversification' and into the evolution of vertebrates.

Exceptional preserved conodont assemblages and articulated remains attributed to a polychaete worm are known from the 'Early' Silurian Birkhill shales formation of southern Scotland (Wilby *et al.*, 2003). Exceptionally preserved ostracods and starfish are known from serial thin-sections of nodules from the Herefordshire Lagerstatte from the heart of England (Sutton *et al.*, 2003). The ostracods are preserved with their soft parts intact, including their penes, as pruriently reported in the popular press in the UK! These Silurian faunas provide further important insights into the evolution of vertebrates, and/or information on rare groups.

Exceptionally preserved Devonian biotas are known from the Early Devonian Hunsruck slate of Hunsruck in the Rheinisches Schiefegebirge in Germany (Bartels *et al.*, 1998; Raiswell *et al.*, in Briggs and Crowther, 2001; Etter, in Bottjer *et al.*, 2002; Selden and Nudds, 2004), from the Early Devonian Rhynie chert of Rhynie in Scotland (Trewin, in Briggs and Crowther, 2001; Rice *et al.*, 2002; Anderson and Trewin, 2003; Kelman *et al.*, 2003; Trewin *et al.*, 2003; Selden and Nudds, 2004). The Rhynie biota of primitive land plants and rare invertebrate animals such as arthropods provides important insights into the evolution of life on land.

Exceptionally preserved Carboniferous biotas are known from, for example, the Late Carboniferous, Pennsylvanian of Mazon Creek in Illinois (Nitecki, 1979; Baird, in Briggs and Crowther, 1990; Schellenberg, in Bottjer *et al.*, 2002; Selden and Nudds, 2004). The Mazon Creek biota of land plants, invertebrate animals and primitive tetrapod vertebrates provides further important insights into the evolution of life on land, and into the evolution of forests.

Mesozoic

Exceptionally preserved Triassic faunas are known from, for example, the Middle Triassic Grès a *Voltzia* of France and the Middle Triassic of Monte San Giorgio in Switzerland (Etter, in Bottjer *at al.*, 2002; Selden and Nudds, 2004). The Grès a *Voltzia* and Monte San Giorgio faunas provide important insights into the 'Mesozoic evolutionary diversification' or 'Mesozoic marine revolution' in marginal and fully marine environments, respectively.

Exceptionally preserved Jurassic biotas are known from, for example, the Late Jurassic Morrison formation of the Mid-West of the USA (Selden and Nudds, 2004; Turner and Peterson, 2004), and the Late Jurassic, Tithonian lithographic limestone or 'Plattenkalk' of Solnhofen in Bavaria in Germany (Barthel, 1978; Barthel *et al.*, 1990; Viohl, in Briggs and Crowther, 1990; Etter, in Bottjer *et al.*, 2002; Selden and Nudds, 2004). The Morrison formation biota of land plants and animals, including spectacular dinosaurs, provides important insights into the 'Mesozoic evolutionary diversification' on land. The Solnhofen biota provides further insights into the 'Mesozoic evolutionary diversification' on the margins of the land, and important insights into the evolution of flight among reptiles, and in the early bird *Archaeopteryx*.

Cenozoic

Exceptionally preserved Cenozoic biotas are known from, for example, the Middle Eocene of Messel near Frankfurt in Germany (Franzen, in Briggs and Crowther, 1990; Schaal and Ziegler, 1992; Franzen, in Gunnell, 2001; Selden and Nudds, 2004). The Messel biota provides important insights into, among other things, the evolution of flight among mammals (bats).

2.3 Collection of fossils

Collection of fossils is required to constrain surface and subsurface geological mapping and correlation, and to build up collections for reference and for academic research purposes (Croucher and Woolley, 1982; Tucker, 1996; Goldring, 1999; Green, 2001). The roles of the palaeontologist in the field are to provide age assignments and palaeoenvironmental interpretations based on fossils, and to ensure that only appropriate ages and facies of sediments are sampled for palaeontological analysis, and that the stratigraphic and geographic location of every sample is recorded. Incidentally, it is worth noting that field age assignments can be made by means not only of macrofossils but also of macroscopically visible microfossils, such as the larger benthic foraminiferans or LBFs of the Permo-Carboniferous and 'Middle' Cretaceous through 'Middle' Tertiary of the Tethyan realm (author's unpublished observations).

Surface collection of macrofossils and collection of surface samples for microfossil analysis are discussed in turn below. Collection of subsurface samples for microfossil analysis is discussed in Section 7.1.

Code of conduct

Field collection of fossils has to be responsible and sustainable, so as to conserve or preserve what is a finite natural resource for future generations, preferably in place, or at least in publicly accessible institutions such as museums and universities (King, in Bassett *et al.*, 2001; Weighell, in Bassett *et al.*, 2001). Occasionally, though, it is necessary to undertake more drastic salvage operations, as when active quarries are becoming worked out (Thompson, in Bassett *et al.*, 2001). In the UK, fossil collecting in designated Sites of Special Scientific Interest or SSSIs is restricted to that for genuine and justifiable scientific purposes only, otherwise it would constitute an 'operation likely to damage' (OLD) the resource (King and Larwood, in Bassett *et al.*, 2001; MacFadyen, in Bassett *et al.*, 2001). Elsewhere in the UK, it is restricted by recommendation or voluntary code of conduct (Edmonds, in Bassett *et al.*, 2001; Munt, in Bassett *et al.*, 2001; Reid and Larwood, in Basssett *et al.*, 2001; Simpson, in Bassett *et al.*, 2001). In Germany, fossil collecting in so-called 'geotopes' ('parts of the geosphere clearly distinguishable from their surroundings in a geoscientific fashion') is restricted by nature conservation and by national monument protection legislation (Wuttke, in Bassett *et al.*, 2001).

The Geologists' Association 'geological fieldwork code' of conduct recommends the following actions (Robinson, in Bassett *et al.*, 2001): Firstly, 'Students should be encouraged to observe and record, and *not hammer indiscriminately*.' Secondly, 'Keep collecting to a minimum. Avoid removing *in situ* fossils, rocks and minerals unless they are *genuinely* needed for serious study.' Thirdly, 'For teaching purposes, the use of replicas is recommended. The collecting of actual specimens should be restricted to those localities where there is a plentiful supply, or to scree, fallen blocks and waste tips.' Fourthly, 'Never collect from walls or buildings. Take care not to undermine fences, walls, bridges or other structures.'

Equipment

The – more-or-less – technical equipment required or useful for the palaeontologist in the field is as follows: a global positioning satellite (GPS) system; a topographic map or aerial photographs or satellite images of the area of interest; a compass/clinometer; an altimeter; a range-finder; a pair of binoculars; a digital camera or video; a portable laptop computer on which to upload digital images; a portable solar panel with which to recharge electronic equipment; a measuring tape; a $\times 10$ to $\times 20$ magnifying glass or a pocket microscope; a bottle of dilute hydrochloric acid to test for carbonates; a sledge or 4-lb (2-kg) lump hammer; a 2-lb (1-kg) hammer; a set of chisels; a set of dental tools; a pickaxe; an entrenching tool; an auger; a supply of sample bags; a supply of indelible pens for labelling them; a waterproof notebook and a supply of pencils for recording observations.

Safety

Safety equipment should include clothing and footwear appropriate to the season and terrain; suncream; personal protection equipment, including a hard hat or climbing helmet, and goggles for use when hammering; sufficient food and water to see out an emergency, such as becoming benighted; fire-lighting equipment; a survival blanket; a torch (flashlight); a whistle, for attracting attention; and a first-aid kit.

Recommended safety procedures are as follows (from Goldring, 1999):

> Listen to the daily weather forecast (including wind direction), which may determine where it is prudent to work. Take account of the time and height of tides when planning coastal work. Write down each day your approximate route, working

area and time of return, and leave it for others to see. In worsening conditions, do not hesitate to turn back if it is still safe to do so. If you get lost, disabled, benighted, or cut off by the tide, stay where you are until conditions improve or until you are found. Supposed short cuts can be lethal.

Distress codes are as follows (also from Goldring, 1999):

On mountains: 6 long blasts, flashes, shouts or waves in succession, repeat(ed) at minute intervals. At sea: 3 short then 3 long, then 3 short blasts or flashes [Morse code for SOS],repeat(ed). Rescuers reply with 3 blasts or flashes repeated at minute intervals.

2.3.1 *Surface collection of macrofossils*

Macrofossils are generally sufficiently large to be seen in surface outcrops or in float. However, careful observation may be required in order that they may actually be seen. The angle of the sun is important in this regard. Early mornings and late afternoons, when the sun is low and the shadows long, are often the best times for searching for fossils. (Similarly, tilting slabs can cast shadows that throw previously unseen and unsuspected fossils into unexpected relief.) Intensive searching can commence once extensive searching has revealed a fossiliferous horizon. Hard rocks can be broken open using a lump hammer, or split along bedding planes using a hammer and chisel, in both cases carefully, so as not to damage specimens. Contained fossils are typically harder than containing rocks, and can be readily extracted. In the event that the fossils are softer than the rock, they can nonetheless still be extracted, carefully, using dental tools, a process often started in the field and finished in the laboratory (see Subsection 2.6.1). Especially fragile specimens such as long bones may need to be protected against damage during excavation – and/or transportation – by first being 'consolidated', that is, wrapped in hessian or jute (burlap) soaked in plaster of Paris and allowed to dry (Longbottom and Milner, in Whybrow, 2000; Milner, in Whybrow, 2000). Collecting fossils from certain hard rocks, such as massive limestones, can be effectively impossible. Specimens are probably better photographed than removed from these rocks. Soft rocks can be trenched and samples removed for laboratory preparation (see Subsection 2.6.1).

2.3.2 *Collection of surface samples for microfossil analysis*

The overall objectives of the fieldwork should be considered when determining the appropriate strategy for sampling. For example, if the objective is reconnaissance mapping, spot sampling might be all that is required, whereas if the objective is detailed logging, targeted or close systematic sampling would be required. As a general comment, the biostratigraphic or palaeoenvironmental resolution of the analytical results will depend as much on the sampling density as on the fossils themselves. Partly on account of this, and partly on account of the logistical effort and financial cost of mobilising field parties, it is always advisable to collect what might be thought of as too many rather than too few samples. However, any restrictions on access or sampling imposed by the landowner should be respected, as should the code of conduct (see above). The particular microfossil groups to be expected in the ages and environments of the rocks expected to be encountered should also be considered, together with any sampling requirements specific to those groups (see below).

Size of sample

The size of sample required depends to an extent on the fossil group targeted (see below). For example, for microfossils, it varies from approximately 1 cm^3 in the case of calcareous nannofossils to up to several kilograms in the case of conodonts.

Lithology

The lithology of sample required also depends to an extent on the fossil group targeted (see below). However, some generalisations can be made, as follows. The lithologies most likely to be productive for microfossils are fine-grained clastics such as shales and mudstones, especially where calcareous, and limestones such as lime mudstones, wackestones and packstones. Those least likely to be productive are coarse-grained clastics such as sandstones, limestones such as grainstones, rudstones and framestones, and altered dolomites. Those most likely to be unproductive are coarse-grained continental clastics, especially 'red beds', and evaporites. Weathered rocks of any lithology are unlikely to be productive for organic-walled microfossils, on account of the likelihood of oxidation, which, it is worth pointing out, can occur not only at the surface but also in the subsurface, for example, at the junction between permeable and impermeable beds or along joints. They are also less likely than unweathered rocks to be productive for calcareous microfossils, on account of the likelihood of leaching. Where weathering pervades some distance into the rock, unweathered samples should be obtained by digging, augering or trenching, using appropriate tools. Unweathered rocks can be recognised by their generally blocky rather than slabby, platy, fissile or earthy texture. If it is simply not possible to access unweathered rocks, because the effects of weathering have pervaded so deep, it is worth sampling any calcareous concretions that might be present, since experience has shown that these can be productive for calcareous microfossils. Thermally altered rocks of any lithology are less likely than unaltered rocks to be productive, particularly for organic-walled microfossils. The effects of thermal alteration can be either local or regional.

Sampling for specific microfossil groups

Calcareous microfossils are locally so abundant in rocks of the appropriate age-range and facies as to be rock-forming, as in the case of '*Globigerina*' or planktonic foraminiferal oozes. They are common in essentially all marine limestones and marls, especially in finer-grained ones, and even in indurated ones, which cannot be easily disaggregated and which are therefore best studied in thin-section, although they may be difficult to identify in altered dolomites. Calcareous microfossils are also common in essentially all marine calcareous mudstones, and, in the case of arenaceous foraminiferans, in non-calcareous mudstones. Even non-marine, lacustrine calcareous mudstones can contain calcareous microfossils, in the form of ostracods. The contained ostracods may be sufficiently large to be discernible on bedding planes with the aid of a hand-lens. Samples are best collected by chiselling along bedding planes rather than hammering, so as to avoid damage to specimens. Sandstones are generally poorly productive in terms of *in situ* calcareous microfossils. One large sample bag is generally sufficient to ensure recovery of calcareous microfossils, especially if the material is fresh and unweathered. It is invariably worth the effort ensuring that this is so!

Siliceous microfossils are locally so abundant in rocks of the appropriate age-range and facies as to be rock-forming, as in the case of diatomites, radiolarian cherts or radiolarites, and spiculites. Diatomites often resemble volcanic tuffs when weathered. Diatoms can be common not only in diatomites but also in siliceous mudstones, such as those of the Miocene of California, or in so-called 'opokas', such as those of the Miocene of Sakhalin. Radiolarians can be common not only in radiolarites but also in shales and in calcareous rocks of marine origin. Unfortunately, the silica of which diatoms is composed is an unstable variety (Opal-A), which converts to a more stable variety (cristobalite or Opal-CT) under the sort of pressure and temperature conditions encountered at burial depths of the order of 2 km, often resulting in the destruction of diagnostic morphological features. Even under these conditions, though, diatoms can be preserved, with their diagnostic morphological features intact, through recrystallisation, replacement – typically by pyrite or calcite – or entombment in concretions. Radiolarians are generally more robust, and more resistant to diagenetic alteration.

Phosphatic microfossils such as conodonts are at least locally common in most marine rocks of the appropriate age-range and facies. They are perhaps most common in limestones, especially bioclastic wackestones or packstones. The occurrence of macrofossils such as crinoids or brachiopods in a rock is an encouraging sign that it will be productive for conodonts. Cherts are also sometimes productive for conodonts on treatment with hydrofluoric acid. Conodonts are generally resistant to chemical attack, and also to diagenetic dolomitisation and thermal alteration. They can occasionally be seen on bedding planes with the aid of a hand-lens. They can be concentrated in lag deposits such as bone beds. The abundance of conodonts varies through time, such that sample sizes need to be adjusted accordingly. Ordovician faunas from the mid-continent of the USA contain abundant specimens, and samples need only be 0.5 kg. In contrast, Devonian faunas contain only rare specimens, and samples need to