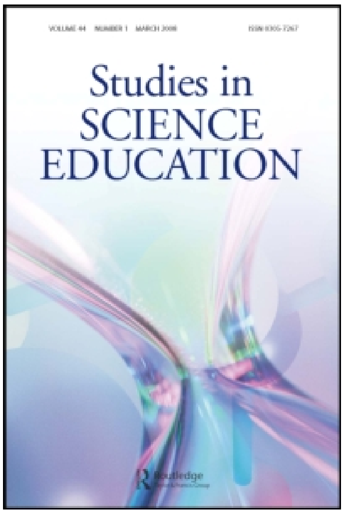

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Geoscience education: an overview

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Geoscience education: an overview

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Geoscience educational publications are reviewed in seven areas to identify future directions for curriculum development, professional development and research. The review shows that: effective teaching methods encompassing broad geoscience study still need extensive research; whilst some valuable materials have been developed for the teaching of systems approaches to geoscience, these need to be evaluated in different curriculum contexts; different methodologies for teaching spatial awareness in geoscience need to be more widely applied and researched; approaches for the effective teaching of geological time should be further developed and tested; there is much scope for the development and evaluation of approaches to geoscience fieldwork; geoscience misconceptions are widespread and need further identification and review; and studies of the effectiveness of professional development in geoscience education should be implemented more widely, including their impact in the classroom. The review indicates that geoscience education will progress most effectively through: extending geoscience learning to all children; educating teachers in effective implementation of new curriculum initiatives; evaluating the progress of the initiatives and using the results to refine them; and researching the whole process to demonstrate its effectiveness and to ensure wide dissemination on the basis of well-founded research findings.

Keywords: geoscience; geology; Earth science; education; school-level; research

1. Objectives

This paper reviews a wide range of research literature related to geoscience education. Geoscience education is gaining increasing prominence within school science education in a number of countries worldwide. Given this growth of interest, there is an urgent need for a detailed scholarly analysis of research in this area.

The review focuses on five strands that make geoscience a distinctive curriculum subject area – those of:

- the particular methodologies of geoscience thinking;
- the holistic systems perspective;
- geoscientific spatial abilities;
- the understanding of geological time; and
- the methodologies and attributes of geoscientific fieldwork.

The following issues are also encompassed:

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- an analysis of misconceptions in geoscience; and
- studies of professional development for teachers of geoscience.

Each of these areas provides particular issues for geoscience education. Therefore, for each area, the research is outlined and suggestions are made for future directions in curriculum development, professional development and research. The review focuses largely on formal geoscience education for students of age 5–19 years within schools and colleges.

2. Context

2.1. Geoscience

'Geoscience' is a relatively new term for the Earth sciences and is used as the focus of this paper. Broader elements of Earth science study, such as those of the atmosphere and oceans, geomorphology and soils, are largely excluded from this review.

The debate about the name and character of the geoscience taught in schools is an ongoing one. In the 1960s and 1970s, in the West at least, it was generally called 'geology' although there were discussions even then about a broader brief for the subject to include 'Earth science' (American Geological Institute, 1967; Heller, 1962; Thompson, 1979). Later, the perceived need to change from a narrow 'geology' perspective to a broader approach was reflected by the change in name of the UK 'Association of Teachers of Geology' to the 'Earth Science Teachers' Association' in 1989 and the change of the US 'National Association of Geology Teachers' to the 'National Association of Geoscience Teachers' in 1995. In the past few years educational arguments have favoured going beyond geoscience and Earth science to encompass Earth system science – a study of the whole Earth system, as discussed below.

Reviews of geoscience education and geoscience educational research have been undertaken only relatively recently. One of the first overviews was provided by Ault (1993). The first international conference of geoscience education took place in 1993 (Stow & McCall, 1996), with just a small component of research-based presentations. Since then the research component of the international conferences held in 1997 (Fortner & Mayer, 1998), 2000 (Clark, 1999), 2003 (GeoSciEd VI, 2003) and 2006 (Hlawatsch, Obermaier, & Martin, 2006) has been growing, whilst some research-based presentations in geoscience education have also been made at the International Geological Congresses held in 2000 and 2004. Meanwhile, some areas of geoscience educational research have been presented at conferences of the National Association for Research in Science Teaching in the USA.

2.2. Five distinctive attributes of geoscience and of geoscience education

The study of geoscience, and of geoscience education, requires a set of thinking and investigative skills that are not commonly found in other areas of the science curriculum or within the curriculum in general. In particular, it has five educational attributes that play a key role in science education and in 'education for life' that are not well developed elsewhere:

- Geoscience is '… an interpretive and historical science' (Frodeman, 1995, p. 960) involving a wide range of methodologies including those required for retrodictive thinking ('prediction' of the past), for large-scale thinking and for integrating large and incomplete data sets.

- Geoscience plays a crucial role in the development of holistic systems thinking, involving consideration of major Earth systems, such as the water and carbon cycles and their interactions and positive and negative feedback loops.
- Geoscience requires high-level spatial ability thinking (three dimensional thinking).
- In geoscience the development of time perspectives is crucial, particularly those of geological time.
- Geoscience fieldwork has particular strategies and methodologies that must be acquired (which range from particular observational and recording skills to the high-level analysis and synthesis skills necessary for understanding the multi-faceted field context). These strategies and methodologies involve development of all the attributes listed above, in field contexts.

The five attributes listed above provide the structure for the research review. An overview of the teaching of geoscience worldwide provides the context for these discussions.

2.3. The teaching of geoscience worldwide

The attributes that geoscience can bring to school-level education have been discussed in the UK since at least 1977 (Schools Council Geology Curriculum Review Group, 1977). The First International Geoscience Education Conference took place in 1993, providing a forum for the different approaches to geoscience education across the world to be discussed – and revealing a wide range of different approaches to implementing a geoscience curriculum, summarised by King, Orion and Thompson (1995). A review of the curriculum changes that had taken place in England, Israel and the USA in the 1990s (Orion, King, Krockover, & Adams, 1999a, 1999b) showed that in each case there had been 'a move from discipline-based science to integrative science' (1999b, p. 24) and, where there was a national curriculum (England, Israel), this included geoscience.

The current position of geoscience education at school level across the world can be summarised as follows:

- Geoscience as a small compulsory part of a national science curriculum, for example:
  - in southern Europe, where it is part of 'natural sciences' and generally taught by biology specialists;
  - in the UK, where it has mostly become allied to the chemistry part of the science curriculum and is generally taught by chemistry specialists;
  - in Japan, Korea and Taiwan, where it is taught by Earth science and general science teachers;
  - in New Zealand and South Africa where it is normally taught by general science teachers.
- Geoscience as a small compulsory part of a national geography curriculum, e.g. in many Northern European countries, such as Germany.
- Additional optional geoscience courses, of a year or more duration, available to some students following compulsory science/geography courses containing some geoscience, e.g. in Brazil, Japan, New Zealand, Portugal, South Africa, Taiwan and the UK.
- Optional geoscience-only courses, a year or more long, available to some students, e.g. in the USA and Canada.

In some countries, such as many African countries, little geoscience is taught through any area of the curriculum.

2.4. Strategies for teaching Earth science

A number of different geoscience teaching strategies have been evaluated for their effectiveness in schools. Chang and Mao (1999) tested the effectiveness of inquiry-based teaching (based on gathering information, collecting and interpreting data, formulating hypotheses and drawing logical conclusions) in geoscience compared with traditional didactic teaching, finding ‘that students in the inquiry group had significantly higher achievement scores and significantly more favourable attitudes toward the subject matter …’ (p. 340). Chang (2001) went on to investigate the effectiveness of a problem-based computer-aided-instruction programme on learning in the geoscience classroom, compared with direct interactive teaching, showing that the problem-based, computer-aided approach produced significantly greater improvements in both achievement and attitude of the students involved (Chang, 2003a). Teacher-directed students using this problem-based computer-aided approach had significantly higher achievement and attitude measures than students who used the approach without teacher direction (Chang, 2003b). Meanwhile Gudovich and Orion (2003) showed that a computerised distance learning unit based on lab and web-based activities was effective in distance learning, with most students improving their independent learning skills as well.

The importance of using activities as part of geoscience teaching was emphasised by the findings of Chang and Weng (2002) who concluded:

> ‘it is suggested that not only problem-solving skills but also process skills, especially those of observation and hypothesis formulation skills, be infused throughout all earth science curricula.’ (p. 449)

Recent studies into the interests of pupils in different aspects of geoscience (Trend, 2004, 2005) have shown:

> ‘that children have high interest in major geo-events set in the geological past, present and future and in current environmental changes which have direct implications for the future of humanity. They also have coherent topic interest in gradual (i.e. uniformitarian) change in the geological past. Girls have a preference for phenomena perceived as aesthetically pleasing and boys have a preference for the extreme and catastrophic.’ (p. 271)

The interests of pupils in the environment and humanity are confirmed by Hemmer et al. (2006): ‘The most prominent result was the lively interest in issues related to human activities, everyday life and environmental hazards’ (p. 71). Clearly, therefore, effective Earth science teaching strategies will relate to these pupils’ interests.

Moves to include scientific investigation in the science taught to all children, as exemplified by the inclusion of ‘scientific enquiry’ in the English National Curriculum for Science (Qualifications and Curriculum Agency [QCA], 1999) and ‘how science works’ in the most recent versions (QCA, 2004; QCA website), together with the publication in the USA of *Inquiry and the National Science Education Standards* (National Research Council [NRC], 2000), provide good opportunities for the methods of geoscientific investigation to be included in the curriculum. However, this will only happen if teachers have strong geoscientific backgrounds, which is not the case for most teachers of broad science.

2.5. Support for teachers of Earth science

The mandatory National Curriculum for Science was launched in England in 1989 and reached all pupils by 1992. It contained a small element of geoscience and this has remained, whilst fluctuating in amount, through all subsequent modifications. A survey in the late 1990s (King, 2001) of the science teachers teaching the geoscience component, which was relatively new to them:

> 'revealed that their background knowledge of Earth science from their own education was generally poor … they reported that their main sources of Earth science knowledge and understanding were broad science textbooks (with their small and variable Earth science content) and science colleagues (who often have poor Earth science backgrounds too). The low levels of practical, investigational and fieldwork recorded may be a reflection of their poor Earth science backgrounds. Most teachers indicated that they needed more support in this area.' (p. 636)

Subsequent surveys showed that the mean error level in the geoscience components of the 51 science textbooks being used in English secondary schools at the time was one error per page, with much of the geoscience content being variable or of poor quality (King, Fleming, Kennett, & Thompson, 2003, 2005). The quality and error-level of the geoscience component of syllabuses and examinations for 14–16 year olds was also poor (King, Brooks, Gill, Rhodes, & Thompson, 1999) although more recent surveys of syllabuses have shown improvements in quality (King & Hughes, 2007; King, Edwards, & Hughes, 2004).

Meanwhile, a review of US science textbooks was undertaken as part of the American Association for the Advancement of Science, Project 2061 educational initiative. This showed a wide usage of, and reliance on, the textbooks by teachers, that the textbooks evaluated were generally poor (Kesidou & Roseman, 2002) and that 'assessment scores of life and earth sciences are almost uniformly poor' (Stern & Ahlgren, 2002, p. 897). The ratings of the Earth science elements of the textbooks as published on the Project 2061 website (American Association for the Advancement of Science [AAAS] Project 2061 website), found the texts examined to be almost universally poor when measured against a range of instructional categories. That this issue is prevalent in other areas of the world is indicated by Sellés-Martinez (2006) for Argentina: 'A survey through introductory science books designed for children yielded alarming results' (p. 75) concerning the physical state of the mantle, citing examples from seven Spanish textbooks (Sellés-Martinez, 2007). Since science textbooks are so important to science teachers and therefore to science education (Council for Science and Technology [CST], 2000; Kesidou & Roseman, 2002, p. 522; Stern & Roseman, 2004, p. 556), it is crucial that the geoscience component of science textbooks is kept under review, increasing the pressure on the publishers to improve.

The educational contexts outlined in the sections above should be taken into account as geoscience education is reviewed below. The greater the amount of geoscience taught through a curriculum, the greater the scope for development of the distinctive geoscience attributes discussed below.

3. Geoscience education involving distinctive methodologies

The methodologies required for effective study of geoscience are diverse and difficult to summarise briefly. Frodeman (1995) attempted to review the scientific reasoning involved in studying geology and initially stated that geology is considered by many to be 'lacking a distinctive methodology of its own' (p. 960) (a perspective supported by the findings of Bezzi [1999, p. 675] for university students who considered that, whilst physics was 'objective and rigorous', geoscience was 'subjective and approximate'). But Frodeman (1995) then went on to tease out the distinctive features of geological reasoning as an interpretive and historical science that 'offers the best model of reasoning for confronting the type of problems we are likely to face in the twenty-first century' (p. 960), listing examples such as global warming, resource assessments (supply and demand of natural resources) and risk assessments, e.g. of sites suitable for nuclear waste disposal. Baker (1996), in attempting to summarise geoscience methodologies, said:

> 'The science of geology has long concerned itself with the real-world natural experience of the planet we inhabit. Its methodology more directly [than that of some other sciences] accords with the commonsense reasoning familiar to all human beings. Because its study focuses on the concrete particulars of nature rather than on abstract generalisations, its results are also more attuned to the perceptions that compel people to take action, and to the needs of decision makers who must implement this action.' (p. 43)

Bezzi (1999) refutes the idea that geoscience is 'subjective and approximate' and concludes:

> 'Geologists and earth science educators have the great responsibility to transform geoscience education into a process that must go beyond mere teaching and learning the facts, laws and theories; it must involve understanding the nature of geoscience and its relationships with society'. (p. 696)

Broad statements like these, whilst giving a suitably large compass to geoscience, fail to provide detail. However, a recent synthesis of the attributes of geoscience study (Orion & Ault, 2007, p. 655) highlights the following:

- the *historical approach;*
- the concern for *complex systems* acting over the Earth;
- the conceptualisation of very *large-scale phenomena* through time and across space;
- the need for *visual representation* as well as high demand upon spatial reasoning;
- the *integration across scales* of solutions to problems; and
- the uniqueness of *retrospective scientific thinking*.

Effective methodologies for teaching these attributes are discussed by Dodick and Orion (2003a), who advocate a history of science approach, as also proposed by Duschl (1990). In support of these views, curriculum materials based on the development of geological thought in the context of plate tectonics provoked a very positive response from Portuguese teachers and learners (Thompson, Praia, & Marques, 2000).

This discussion illustrates that, whilst it is difficult to summarise the attributes of an effective geoscience education, more research is necessary to identify these attributes and to analyse the effectiveness of different curriculum approaches and materials in teaching them.

4. Geoscience education through a holistic systems perspective

In the 1970s the Gaia Hypothesis was proposed (Lovelock & Margulis, 1974) and developed (Lovelock, 1979), envisioning the whole Earth as an interconnected system with the biological components being crucial to its maintenance. Further work on the Earth system was brought together by NASA's Earth System Science Committee report of 1988 (NASA, 1988). At school level, this systems thinking underpinned a conference of US geoscientists and educators that culminated in the report proposing a number of goals and concepts about planet Earth that they felt every citizen should understand (Mayer & Armstrong, 1990). This took place against a background of concern that developments elsewhere in science education were being driven primarily by physics educators (Duschl, 1990).

A new initiative was formulated – the Program for Leadership in Earth Systems Education (Mayer, 1991) – where a 'framework for Earth systems education' was developed based on seven understandings (Figure 1). This was expanded into a proposal for a 'global science literacy' approach to the curriculum, based on the Earth system science (Mayer, 1995, 1997; Mayer & Kumano, 1999; Mayer & Tokuyama, 2002). Strong arguments in support of this approach, used by Mayer and Kumano (1999), include:

> 'current curriculum innovations still focus primarily on the reductionist concept of the nature of science which is implicit in the physical sciences. They do not sufficiently reflect … the "system science" approaches that will be important to the science endeavours of democratic nations.' (p. 73)

They argue that the environmental and social problems of the future will be addressed most effectively by the earth and biological sciences and that these should become the major topics of scientific inquiry in the future. They maintain that:

> 'the concept of the earth as a system, comprising many subsystems and itself a subsystem of a larger one … is a concept that can be the theme of science curricula worldwide … It can replace the current disciplinary approaches … with a conceptual approach that honours the important conceptual contributions of all sciences.' (p. 89)

A commentary on the development and implementation of the 'global science literacy' approach in a range of educational contexts worldwide is provided by Mayer (2002, 2003), with chapters on different strategies used in a number of countries.

Research into the implementation of Earth system science approaches at school level has focused primarily on developments in the USA, Israel and Germany. An exploratory study has shown that the knowledge of Earth system concepts and the perception of their importance were much higher for US students than for Korean students (Lee, Kim, & Mayer, 2003). Meanwhile Lee and Fortner (2003) showed that when a constructivist-based Earth systems curriculum was taught (using hands-on learning, authentic activity-based learning, cooperative learning, project-based learning and science field trips) the students gained in knowledge and understanding with respect to a comparison cohort of students.

An Israeli strategy for developing an Earth systems-based educational programme was outlined by Orion (2002). Kali, Orion and Eylon (2003) and Orion and Kali (2005) worked from the four-stage hierarchy of system thinking skills proposed by Gudovitch (1997) of:

(1) an acquaintance with the different Earth systems and an awareness of the material transformation between these systems;
(2) an understanding of specific processes causing this material transformation;
(3) an understanding of the reciprocal relationships between the systems; and
(4) a perception of the system as a whole.

They developed a methodology for gauging the progress of students in developing their thinking about systems. Their work showed that the Israeli students who undertook a system-based module on the rock cycle showed improvements in their system thinking skills, indicating that these could be learned through effective teaching. A similar study, involving the hydrological cycle (Ben-zvi-Assarf & Orion, 2005) showed that most of the students showed good development of their system thinking skills.

Orion (2007) recently reviewed progress in the development of a number of approaches to science education based on an Earth systems science approach, finding them to be

Framework for Earth systems education
Understanding 1: Earth is unique, a planet of rare beauty and great value. • The beauty and value of Earth are expressed by and for people through literature and the arts. • Human's appreciation of planet Earth is enhanced by a better understanding of its subsystems. • Humans manifest their appreciation through their responsible behaviour and stewardship of subsystems.
Understanding 2: Human activities, collective and individual, conscious and inadvertent, affect planet Earth. • Earth is vulnerable and its resources are limited and susceptible to overuse or misuse. • Continued population growth accelerates the depletion of natural resources and destruction of the environment, including other species. • When considering the use of natural resources, humans first need to rethink their lifestyles, then to reduce consumption, then to reuse and recycle. • By-products of industrialisation pollute the air, land and water and the effects may be global as well as near the source. • The better we understand Earth, the better we can manage our resources and reduce our impact on the environment worldwide.
Understanding 3: Development of scientific thinking and technology increases our ability to understand and utilise Earth and space. • Biologists, chemists and physicists, as well as scientists from the Earth and space science disciplines use a variety of methods in their study of Earth systems. • Direct observation, simple tools and modern technology are used to create, test and modify theories that represent, explain and predict changes in the Earth system. • Historical, descriptive and empirical studies are important methods of learning about Earth and space. • Scientific study may lead to technological advances. Regardless of sophistication, technology cannot be expected to solve all of our problems. • The use of technology may have benefits as well as unintended side-effects.
Understanding 4: The Earth system is composed of interacting subsystems of water, rock, ice, air and life. • The subsystems are continuously changing through natural processes and cycles. • Forces, motions and energy transformations drive the interactions within and between the subsystems. • The Sun is the major external source of energy that drives most system and subsystem interactions at or near the Earth's surface. • Each component of the Earth system has characteristic properties, structure and composition that may be changed by interactions of subsystems. • Plate tectonics is a theory that explains how internal forces and energy cause continual changes within Earth and on its surface. • Weathering, erosion and deposition continuously reshape the surface of the Earth. • The presence of life affects the characteristics of other systems.
Understanding 5: Planet Earth is more than four billion years old and its subsystems are continually evolving. • Earth's cycles and natural processes take place over time intervals ranging from fractions of seconds to billions of years. • Materials making up planet Earth have been recycled many times. • Fossils provide the evidence that life has evolved interactively with Earth through geologic time. • Evolution is a theory that explains how life has changed through time.
Understanding 6: Earth is a small subsystem of a solar system within the vast and ancient universe. • All material in the universe, including living organisms, appears to be composed of the same elements and to behave according to the same physical principles. • All bodies in space, including Earth, are influenced by forces acting throughout the Solar System and the universe. • Nine planets, including Earth, revolve around the sun in nearly circular orbits. • Earth is a small planet, third from the Sun in the only system of planets definitely known to exist. • The position and motions of Earth with respect to the Sun and Moon determine seasons, climates and tidal changes. • The rotation of Earth on its axis determines day and night.
Understanding 7: There are many people with careers that involve study of Earth's origin, processes and evolution. • Teachers, scientists and technicians who study Earth are employed by businesses, industries government agencies, public and private institutions and as independent contractors. Careers in the sciences that study Earth may include sample and data collection in the field and analyses and experiments in the laboratory. • Scientists from many cultures throughout the world co-operate and collaborate using oral, written and electronic means of communication. • Some scientists and technicians who study Earth use their specialised understanding to locate resources or predict changes in Earth systems. • Many people pursue vocations related to planet Earth processes and materials.

Figure 1. The framework for school-level earth systems education developed in the USA (Mayer & Tokuyama, 2002, pp. 7–8).

much more effective than the traditional 'science for all' approach for both high- and low-achieving science students. Orion (2007) encapsulates the Earth system science initiative instituted in Israel, with its constructivist approach involving: child-centred teaching; integration of skills within the course content; the teacher as a mediator for knowledge; inquiry-based teaching; multi-learning environments (classroom, lab, outdoors and computer); authentic based teaching that is derived from the real world; and innovative assessment. The 'science for all' approach discussed involved the teaching of broad and balanced science, including an Earth science component. Following a listing of previous Israeli studies indicating the effectiveness of the 'Earth systems science' approach, Orion (2007) presented evidence for significant improvement in the understanding of biology, chemistry and physics in 11–14-year-old Israeli students who had studied science in this way, compared with those who had not. However, this may be due to the range of other constructivist elements involved in the initiative, in addition to the Earth system science context.

The work of the 'System Erde' (System Earth) group in Germany was described by Hlawatsch et al. (2003) as a government-sponsored programme in Earth systems education for an educational system divided into separate biology, chemistry, physics and geography disciplines. The 'System Erde' approach involved three steps: (1) subject matter analysis (an analysis of the existing science/geography curriculum); (2) educational framework (the development of a system of basic concepts and teaching methods); and (3) empirical research (research into student conceptions, interests and also into the effectiveness of the implementation of the project) (Hlawatsch & Bayrhuber, 2006). This approach underpinned the development of a range of teaching units compiled on CDROMs for both secondary (high school) and primary (elementary) pupils. By 2006, Lüken, Hlawatsch and Raack were able to comment:

> 'The results of the study confirm the suitability of the "System Earth" instructional material for secondary high school classes. Students that were taught with these materials showed significantly more interest in (geo-)science topics and significantly more knowledge about these topics than students in the control condition. In addition the degree of system competency was also significantly higher …' (p. 81)

Meanwhile, Sommer (2006) noted:

> 'the evaluation of the newly developed teaching materials for elementary schools in the German "System Earth – primary school" project [showed that] even elementary students show the beginnings of system competency …' (p. 79)

A case study into the implementation of the 'System Earth' materials through professional development showed that the following factors were critical: that teachers should clarify their goals for using the materials; that strategies for the selection of suitable materials from the range provided should be implemented; and that the materials should be developed for use in local contexts (Hansen, Hlawatsch, & Lücken, 2007).

In parallel with the school-level developments described above, an Earth systems science approach was being considered at undergraduate level in the USA. Following the publication of three key documents in science education: *Shaping the Future, New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology* (National Science Foundation, 1966); *From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology* (NRC, 1996a); and the *National Science Education Standards* (NRC, 1996b), a workshop focused on Earth system science was convened by the American Geophysical Union. The report on the workshop (Ireton, Manduca, & Mogk, 1996) summarised the debate around seven fundamental questions: Why use an Earth system science approach to education? What should be taught in an Earth system science curriculum? How should we teach Earth system science? How should we integrate research and education? How can we change the academic culture to promote reform? How can we increase the diversity, recruitment and retention of students in the Earth and space sciences? How can we promote life-long learning in K–12 education, professional training and outreach to the public in the Earth and space sciences? The report identified the four major themes summarised in Figure 2.

The report provides a strong argument for the development of undergraduate courses based on the Earth systems approach, incorporating the development of systems thinking. The progress of US undergraduate students towards systems thinking through such courses was investigated by Raia (2005) who concluded:

> 'that students tend to conceptualise dynamic systems in static disjointed terms, considering the isolated behavior of the constituent components. Students also identify a single causal force, or linear chain of unique causal forces to explain complex natural phenomena.' (p. 297)

The findings of Libarkin and Kurdzeil (2006) were similar. Their study:

Themes of the American Geophysical Union report

1. Earth system science provides a unifying context to demonstrate the interrelationships between all components of the Earth system and humanity. We recommend that the Earth system science approach be adopted by all institutions in one or more of the following ways:
   - infuse the Earth system approach into existing courses in the Earth and space sciences;
   - develop new Earth system science courses at all levels of the curriculum;
   - set up new integrated degree programs in Earth system science;
   - reach consensus across sub-disciplines on an interdisciplinary Earth system science perspective.

2. New Earth system science courses and curricula must implement best teaching practices to educate all constituencies, including groups currently under-represented in science. We recommend that:
   - all educators become familiar with research on learning and implement effective teaching strategies at all levels; educators reaffirm the importance of classroom, laboratory and field activities that encourage active inquiry and discovery, critical-thinking, proficiency in written and oral communication, quantitative reasoning and life-long learning skills;
   - new instructional methods and materials be broadly disseminated through print and electronic media; training programs and ancillary support are essential for faculty to develop and implement new instructional materials and techniques;
   - educational technology be used to complement, supplement and extend, rather than replicate, activities that are available to students in field and laboratory exercises;
   - research and teaching not be viewed as separate endeavors; students at all levels be encouraged to get involved in research; faculty incorporate professorial research into courses, through lecturing and developing laboratories using research results, instrumentation and techniques;
   - the goals, strategies and outcomes of Earth science education be critically evaluated, with rigorous assessment of classroom materials, pedagogy and student learning.

3. The Earth and space science community must change its academic culture to actively support reform of science education and promote a recognition and reward structure that values excellence in the education of all students. We recommend that:
   - faculty, department chairs and administrators work together to create an environment of trust, support, and encouragement for faculty to promote excellence in the teaching of undergraduate students;
   - reward systems be established that explicitly recognize and value effective teaching;
   - the academic culture place equal value on education and research.

4. The conclusions presented respond to and affirm the recommendations of three important publications on science education published in the last year: *Shaping the Future, New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology* (NSF 96-139), *From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology* (National Research Council, 1996) and the *National Science Education Standards* (National Research Council, 1996). The entire Earth and space science community is encouraged to implement these recommendations as they apply to Earth system science education:
   - all students should have access to supportive, excellent programs in science, mathematics, engineering and technology and all students should acquire literacy in these subjects by direct experience with the methods and processes of inquiry (*Shaping the Future*, NSF 1996, *From Analysis to Action*, NRC, 1996)
   - we must recognize the unique opportunities provided to the Earth and space science community through the *National Science Education Standards* (NRC, 1996) and move quickly to implement the recommendations at all levels of instruction.

Figure 2. Major themes of the American Geophysical Union report (Ireton et al., 1996) recommending 'innovation and change using an Earth systems approach' at undergraduate level.

> 'suggests that students predominantly understand that changes occur on Earth without either (1) a concrete acceptance that these changes result from a cause or (2) an explanation for these causes beyond scientific terms such as "subduction".' (p. 408)

Nevertheless, recent work by Sibley et al. (2007) on the rock, water and carbon cycles, using a method asking students to link processes and products together (their 'box diagram approach') has shown that, after instruction, their US undergraduate students could: identify processes and products in a system; organise them within different frameworks; and understand the generally cyclic nature of the system. The students did, however, find it difficult to recognise parts of the system that were not readily apparent or visible, such as molecules or ions.

Together then, these research findings into the effectiveness of Earth systems education pose a conundrum. Why should all three groups of school level studies (in the USA, Israel and Germany) show improvements in the Earth systems understandings of the students, whilst no such improvements were revealed in the understanding of US undergraduate students (except for the use of the box diagram approach). Without much more information about the teaching methods employed and the research strategies utilised than is revealed within the published literature it is impossible to come to firm conclusions on this question. However, the following aspects of the school level work may have been critical:

- All three school-level programmes involved comprehensive in-service training programmes for teachers.
- All three programmes used a constructivist-based philosophy involving: child-centred teaching; integration of skills within the course content; the teacher as a mediator for knowledge; inquiry-based teaching; multi-learning environments (classroom, laboratory, outdoors and computer); authentic based teaching that is derived from the real world; and alternative assessment (Orion, 2007, p. 116).
- The Israeli research identified the following factors that were critical to the success of the initiative:
  - focusing on inquiry-based learning, using problem-solving approaches;
  - using the outdoor learning environment for the construction of a concrete model of a natural system;
  - using knowledge integration activities throughout the learning process (Orion & Ault, 2007).
- Orion's recent review (2007) has further stressed the importance of constructivist philosophies, including: siting learning in authentic and relevant contexts; moving learning gradually from the concrete to the abstract; adjusting the learning for different abilities; integrating the outdoor environment into the learning process; and focusing on both cognitive and emotional aspects of learning.

If some or all of these components were missing from the Earth systems science teaching approaches used for the US undergraduate students, this might explain the discrepancies in the outcomes. It is certainly likely that, as systems thinking involves the mental manipulation of difficult abstract concepts, increased levels of understanding in school level students are unlikely unless sophisticated packages of teaching and learning strategies are employed in teaching them.

Meanwhile, school-level research in Taiwan (Chang, Hua, & Barufaldi, 1999) has shown that, whilst students enjoyed learner-centred constructivist teaching in Earth science and found it valuable, they preferred teacher-centred didactic teaching, thinking it would help them to pass exams more effectively. Chang and Lee's recent survey work (Chang & Lee, 2006; Lee & Chang, 2006) involving Taiwanese Earth science teachers showed that preparing students for exams was an important practical goal for the teachers, despite it being one of their least preferred ones. However, their most important goal was that their students should acquire basic Earth science concepts. Further, the three Earth science themes judged by the teachers to be most significant in terms of Earth science literacy concerned environmental protection, whilst the most important skill for their students was that they should be able to apply their learning to everyday life.

Together these studies of the effectiveness of Earth systems education through different age ranges and curriculum systems show rather patchy progress. Nevertheless, it seems clear that the more comprehensive the curriculum innovation, the greater the chance of success, with the programmes involving focus on the learner, the development of well-planned curriculum materials and effective professional development for teachers being more successful than those of more limited scope. A good deal more research in a wider range of contexts will be necessary for this to be fully demonstrated, since each innovation has so far only been researched in one educational environment. A broader innovation/research base will be necessary for the most successful attributes of Earth systems curriculum innovation to be identified and highlighted.

It is critical that the attributes that systems thinking brings to the curriculum are studied, since it is not commonly taught in other curriculum areas, apart from in some parts of geography. A good deal of life involves interactions with complex feedback systems. Thus systems understanding can benefit not only ourselves, but also the social, economic and environmental systems we live in, from local to global scales.

5. Education in geoscientific spatial abilities

Spatial ability and three-dimensional thinking are involved in some school subject areas, for example in molecular structure in chemistry, the structure of organisms in biology and topographic studies in geography, and are crucial to art and design courses. However, the particular spatial abilities required to understand how three-dimensional rock structures interact with three-dimensional topographic surfaces is peculiar to geoscience. A further dimension to thinking is also required in examining how these complex three-dimensional interactions change over time.

The most effective ways of teaching the necessary spatial awareness for developing understanding of geological maps drawn on contoured surfaces were explored by Crossley and Whitehead (1979) and further developed through the making of three-dimensional paper models and annotating these with lines and shading (Crossley & Whitehead, 1980). The three-dimensional paper model approach was developed from an illustrative method used previously by the Open University (Gass et al., 1972), although the effectiveness of these approaches was not researched.

The 'Geological Spatial Ability Test' (GeoSAT) for assessing the spatial skills of students developed by Kali and Orion (1996), showed that students had different levels of ability to mentally penetrate the image of a geological structure. They concluded that:

> 'Earth science students should be provided with appropriate assistance for enhancing their abilities to perceive and mentally bisect geologic structures … Such assistance could be given by providing students with opportunities to disassemble models of geologic structures and investigate the spatial configuration of each layer …' (p. 388)

Kali, Orion and Mazor (1997) reviewed the literature discussing whether concrete models or computer graphics were more effective in developing 3D visualisation skills. They concluded that whilst there was a general opinion that concrete models could be more easily comprehended, sometimes this was not true, as at other times the concrete models led to confusion. They went on to design computer software to assist secondary (high school) earth science students to perceive geological structures and to visualise cross sections through these structures using computer animations. Research showed that the software was effective in developing 3D visualisation skills and a powerful demonstration tool for teaching structural geology, whilst developing a positive attitude in their students.

Orion, Ben-Chaim and Kali (1997) then researched students undertaking an introductory geology course to establish whether links existed between the study of geoscience and the development of spatial visualisation ability. Their results showed that the spatial skills of the students did develop, whilst student interviews indicated that the earth science course was the only one of their introductory courses that taught spatial skills. They concluded: 'It is suggested that there is a two-way relationship between studying earth science and spatial-visualisation skills' (p. 129). Black (2005), investigating non-science US undergraduate students enrolled on minor science courses, found a positive correlation between their results from an Earth science conceptual understanding assessment and their scores on three types of spatial tests. She concluded: 'Results suggest that an opportunity may exist to improve Earth science conceptual understanding by focusing on spatial abilities …' (p. 402) – a conclusion very similar to that of Orion et al., above.

As part of the Hidden Earth Curriculum Project aimed at developing spatial visualisation abilities in US undergraduate geoscience courses, Reynolds et al. (2002, 2005) have developed software to teach a range of spatial skills through animation. Their research into student use of this software has shown that whilst the experimental group had significantly lower spatial awareness than the control group in the pre-test results, the post-test results were equal, showing that the experimental group had significantly increased their skills through the module.

The topic of gender differences in spatial ability has been reviewed by Kali and Orion (1996), who concluded that:

> '… many researchers agree that the spatial abilities of males are more highly developed than those of females [but that] … evidence exists that instructional programs produce similar improvement rates for males and females (Ben-Chaim, Lappan, & Houang, 1988).' (p. 370)

Kali and Orion (1996) and Reynolds et al. (2002, 2005) both found that males outperformed females in pre-instructional tests, supporting the findings of the Kali and Orion (1996) review. However, whilst Ben-Chaim et al. (1988), quoted by Kali and Orion, found similar improvement in males and females, Reynolds et al. (2002, 2005) showed that females increased their spatial abilities through instruction to a greater degree than males, gaining equal scores with males in the post-test results.

In view of the correlations shown by research between conceptual ability in geoscience and spatial ability, it seems clear that an important part of geoscience teaching should focus on spatial ability, using either concrete modelling or computer animation. Computer animation provides a valuable new tool for the development of spatial ability in geoscience.

6. Education in the understanding of geological time

Oldroyd (1996), in reviewing the development of ideas about geological time, introduced the main players by beginning:

'In his biography of James Hutton, Playfair described the emotions felt when … they looked at the rocks of Siccar Point … and realised what the unconformity there implied for the age of the Earth. As Playfair … put it: "The mind seemed to grow giddy by looking so far into the abyss of time" … Yet by the mid-nineteenth century, most geologists had looked into the abyss and overcome their vertigo. The men who wrought this change included great theorists such as Georges Cuvier and Charles Lyell …' (p. 131)

It was Lyell's perspective on geological time that so influenced Charles Darwin as he developed his theory of evolution.

An understanding of the vast amount of time available for geological events to take place is central to the teaching of geoscience, as discussed by Hume (1978) and Ault (1982). Two aspects of understanding about geological time are crucial, the amount of time, as measured in years, millions of years or billions of years (known as *absolute time* – the 'deep time' of McPhee, 1981) and the sequencing of events (or *relative time*).

In researching understanding about absolute time in US college students, Libarkin and Anderson (2005) noted, 'in particular, students have a poor idea of the scale of geologic time … and the specifics of absolute age dating' (p. 400) and Libarkin, Dahl, Beilfuss and Boone (2005) found that fewer than 50% of US college students in their study and, at some institutions, less than 10%, believed that the Earth was 4.5 billion years old. Meanwhile Dahl, Anderson and Libarkin (2005), for pre-service and practising teachers, found widespread misunderstanding of how the age of the Earth is calculated.

The understanding of relative time methods involves appreciating the methodologies of geoscientists in sequencing rocks and geological events and in correlating rocks and events from different areas. It also involves a basic knowledge of the sequence of major geological events from the beginning of the Earth to today. Following early studies by Ault (1982), Schoon (1992, 1995) showed that nearly a third of the US primary (10–11-year-old) pupils and a fifth of the pre-service primary teachers he surveyed, thought that dinosaurs lived at the same time as cavemen.

Trend (1998) investigated the understanding of geological events and their sequence amongst UK pupils aged 10–11 years and found that, whilst they had a general awareness of major geological events, 'a clear chronology is almost entirely lacking' (p. 973). The children generally placed events into two distinct time zones, the 'extremely ancient' and the 'less ancient'. Trend followed this with a similar survey of trainee (pre-service) primary teachers (2000, 2001a), indicating 'an all-pervasive confusion with deep time, both relative and absolute' (2001a, p. 196), arguing that the trainee teachers needed to develop a deep time framework themselves if they were to enable their pupils to place geological events into deep time contexts effectively. Trend's further work (2001b) into the understanding of UK 17-year-olds of major geo-events in a geological time framework, showed misunderstanding of both the nature and timing of major events. On the basis of this he devised a deep time framework for use in education focused on: planetary and lithospheric geo-events; biospheric geo-events; and atmospheric and hydrospheric geo-events (pp. 317–318). Meanwhile Marques and Thompson (1997a) also found common misconceptions in the ordering of evolutionary events by 10–15-year-old Portuguese students and Hidalgo and Otero (2004) showed that Spanish students found it difficult to remember timed events in isolation and to conceptualise long periods of time.

In addition to investigating the ordering of geological events by Israeli students, Dodick and Orion (2003c) developed a 'Geological Time Aptitude Test' (GeoTAT) to discover how students solved geological time-based problems (Dodick & Orion, 2003b). This revealed that 14–15-year-olds could think significantly better in time terms than 12–13-year-olds and that geology students could solve time-based problems better than non-geology students.

After a second year of geological study, the geology students had significantly improved their time aptitude, with fieldwork studies being critical to this development. They also found a correlation between the understanding of geological time and spatial ability, implying that well-designed geological fieldwork would enhance both.

Libarkin et al. (2005) found that US college students held misconceptions about the dating of the formation of the Earth and the formation of life and Libarkin and Anderson (2005), through use of their Geoscience Concept Inventory (GCI), found that US undergraduate students had poor ideas of the scale of geologic time, the occurrence of events in geologic history and absolute age dating. Meanwhile, Dahl et al. (2005), using the GCI with teachers, found that whilst US practising teachers were fairly comfortable with relative dating, they were uncomfortable with dating geological events.

These geological time-based studies show that new curriculum materials should be developed for three aspects of time-study:

- a knowledge of the length of geological time (absolute or deep time);
- the development of a time framework into which major geological events fit; and
- the enhancement of time-based thinking skills, enabling students to solve relative time-based problems.

Implementation of such new materials should be surrounded by research into the effectiveness of the materials in different educational contexts and systems.

7. Geoscience educational fieldwork

Frodeman (1996), in discussing how geoscientists perceive rock exposures, states that: 'geologic seeing requires a type of poetic envisioning tempered and disciplined by the rigor of science' (p. 417). This perspective underpins the discussions below.

Although fieldwork can form important parts of biology, geography and some history and social science courses, the particular attributes of geoscience fieldwork are very distinctive and require the development of particular kinds of skills and techniques, as detailed below.

Hawley (1998) provided a useful summary of the rationale for geoscience fieldwork, citing the work of Lonergan and Andresen (1988), who listed four educational opportunities provided by 'the uniqueness of field experiences' together with three perspectives on learning. Hawley's summary also included the work of Compiani and Carneiro (1996), who listed six key objectives for geoscience fieldwork, and his own list of five particular cognitive benefits of learning in the field.

Previously, Thompson (1982) had noted forty possible objectives of geoscience fieldwork under four headings:

- to develop intellectual skills and abilities (13 objectives);
- to develop practical skills and abilities (12 objectives);
- to master practical techniques (4 objectives);
- to develop interests and attitudes (11 objectives).

This built on his previous work (Thompson, 1974, cited in Hawley, 1998).

Different sorts of field excursions with different objectives have been recognised, with Compiani and Carneiro (1996, cited in Hawley, 1998) listing six different types (to widen previous geological knowledge; to recognise geological features and phenomena; to suggest problems and work on doubts and questions; to structure hypotheses, solve problems and produce synthesis; to develop practical abilities; and to develop new attitudes and values). Bland, Chambers, Donert and Thomas (1996, cited in Hawley, 1998), recognised only three field excursion types (a 'look and see' approach, with the emphasis on dissemination of knowledge; an investigative approach, with the emphasis on process; and an enquiry approach, with the emphasis on decision-making and interpretation). Meanwhile, Buck (2006) recognised a spectrum of different teacher approaches in the field, from teacher as expert to teacher as guide.

This analysis of geoscience fieldwork clearly shows that the wide range of teaching and learning objectives possible in the laboratory/classroom through a great variety of teaching strategies and approaches are equally applicable in the 'outdoor classroom'. However, these reviews indicate that geoscience fieldwork offers additional important educational opportunities, including:

- the study of processes and their products not available in the classroom, with their variety of scales, dimensions and complexity;
- the application of outdoor investigational skills and techniques that cannot be used in the classroom;
- a wide range of new problem-solving and investigational possibilities; these include: the evaluation of varieties of evidence; the interpretation of changes through space and time; the detective work involved in retrodiction ('predicting' the past); the evaluation of resources; and the assessment of environments; and
- the potential development of new interests, attitudes and values relating to the outdoor world.

These are in addition to the variety of opportunities for developing social skills, such as leadership potential, team-working skills and opportunities for seeing teachers and peers from new perspectives offered by fieldwork, that are not so readily available in the classroom.

Although a wide range of different approaches to geoscience fieldwork was recognised, little research appears to have taken place before the 1990s on the educational effectiveness of different approaches. In 1993, Orion devised a model for the development and implementation of field excursions and tested it on 14–17-year-olds (Orion & Hofstein, 1991). The evaluation showed that younger students regarded the excursion more as a social event whilst older students valued it as a learning event, particularly the individualised learning aspects. The attitudes to learning of the older students also improved and they particularly valued the potential for individualised learning provided by excursions.

Orion and Hofstein (1994) went on to show that the educational effectiveness of field trips for students is enhanced if they are run early in the course and are preceded by a short preparatory unit focused on familiarising the students to the learning setting of the field trip. They found in particular that the attributes they termed the 'novelty space' should be minimised by the preparatory work. They subdivided 'novelty space' into three areas, the cognitive (requiring student acquaintance with concepts and skills), the psychological (reducing the gap between student expectations and reality) and the geographical (acquainting students with the area) (see Orion & Ault, 2007, p. 672). This is rather similar to the 'concrete preparation' phase recommended for scientific practical work devised to develop thinking skills, by Adey, Shayer and Yates (2001). In further work with Israeli students, Kempa and Orion (1996) found that although the students completed field tasks successfully, they often had a low sense of individual learning benefit, despite their positive teamwork experiences.

Fisher (1995) reviewed the changes in geoscience fieldwork perspectives required by the UK National Curriculum for Science, which had recently been introduced. This required pupils to 'identify problems for themselves and solve them using a range of scientific concepts and skills' (p. 385) – a movement towards the investigative geoscience fieldwork described above. This perspective on fieldwork has since been carried over into all geology syllabuses in the UK, offered as optional courses to 14–18-year-olds.

The research of Orion and Thompson (1996) into changes in perception and attitude to out-of-school activities of UK trainee (pre-service) teachers on a one-year training course are relevant – that:

> 'At the end of the programme, the earth science teachers showed higher confidence in teaching science in non-school settings (museums, industrial sites, the natural environment). Their confidence was significantly higher than that of chemistry and physics students.' (p. 596)

When Marques, Praia and Kempa (2003) explored the impact of Orion's (1993) fieldwork model on Portuguese students, their study supported the importance of pre-fieldwork preparation and found a positive influence on student learning but also highlighted the difficulties teachers faced in adapting to the novel, outdoor learning environment. Research on the impact of geoscience fieldwork on Portuguese students by Vasconcelos and Salvador (2003) using a 36-item scale focussed on: 'teacher/student relationship'; 'construction of knowledge'; 'development of attitudes and values'; and 'scientific literacy', showed student improvement in all these areas as a result of three field-based activities. Rebelo at al. (2003a, 2003b) found that Portuguese students valued fieldwork and gave positive feedback, although teachers lacked confidence in leading fieldwork. Meanwhile, Midyan and Orion (2003) noted a wide gap between Israeli teachers' positive attitudes to the educational goals of fieldwork and their actual practice.

Recently Elkins and Elkins (2007) have applied the 'Geoscience Concept Inventory' of Libarkin and Anderson (2005) to US college students and demonstrated greater improvements in geoscience content knowledge as a result of geoscience field experiences than in non-field based courses. Hawley concluded his 1998 review by stressing:

> 'the key thinking that … [had] emerged on teaching and learning approaches to field-based learning in geoscience, … [which emphasised] that there should be a balance of different teaching approaches, matched closely to learning objectives.'

This is given a wider perspective in the review of fieldwork by Orion and Ault (2007) who stressed the importance of:

> 'a holistic model that connects the outdoor and the indoor learning environments. The guiding principle of this model is a gradual progression from the concrete levels of the curriculum toward its more abstract components.' (p. 761)

They emphasised the key points that:

> 'the outdoor learning environment addresses phenomena and processes that *cannot be cultivated indoors*. The outdoors, however, is a very complicated learning environment and includes a large number of stimuli that can easily distract students from meaningful learning.' (p. 761)

Thus there is clearly much more research to be done on the effectiveness and impact of different fieldwork approaches. The important research questions that Hawley (1998) identifies are:

'"Why is the field experience so important for learning geoscience?", "What are the learning processes students go through in field-based learning?", "Do all students learn from fieldwork in the same way?", "Do different students learn different things from different types of fieldwork?", "What is progression in fieldwork?". In short, how does fieldwork add to conceptualisation in geoscience? We should seek the answers to these questions out of our duty to make the most of "being there".'

The following research questions for school-based fieldwork could be added. Which fieldwork strategies:

- make students more enthusiastic for geoscience?
- are more effective in developing geoscience understanding?
- promote environmental understanding more successfully?
- develop cognitive skills more effectively?
- are more effective in developing understanding of space and time?
- develop transferable skills that are valuable in any walk of life?

Since field education and geoscience education are so inextricably linked, we should make the most of each in promoting the other.

The preceding sections have examined the progress of global geoscience education through the key strands of the distinctive methodologies of geoscience; the holistic systems perspective; geoscientific spatial abilities; the understanding of geological time; and the methodologies and attributes of geoscientific fieldwork. In addition, important bodies of published work encompass misconceptions in geoscience and the professional development of geoscience teachers. These are discussed below.

8. Misconceptions or alternative frameworks in geoscience education

8.1. Misconceptions identified

There has been much discussion in the literature about the best way of describing the ideas that students hold that are contrary to the consensus of scientific views. These alternative ideas have most frequently been called 'misconceptions' or 'alternative frameworks'. Both these terms imply that students hold deep-seated views about the ideas that go well beyond simple 'errors' and can greatly affect their future understanding of a topic unless they are suitably addressed. The term 'misconceptions' is probably the most widely used of these terms and is adopted for the discussions below. For each area, a modern scientific consensus definition is given in italics.

Rocks

Rocks are *naturally occurring aggregates of minerals, organic materials or other rock fragments*. Misconceptions about rocks and how they are formed have been studied since the early work of Piaget (1929) on *The Child's Conception of the World*. Dove (1998, p. 185) has summarised work since then as showing that pupils of all ages regarded rocks as, 'dull, heavy, large, dark material … [whilst] colour was also an important criterion'. Happs (1982) found non-scientific usage of the term 'rock' and Dove (1996) noted wide misunderstanding of the term, whilst Ford (2003) found that most children naturally look for properties that provide no evidence of the mode of rock formation. Blake (2004) also found that children focused, 'on simple physical properties such as colour or shape and reveal only limited ideas about the origins of rocks' (p. 1857). Meanwhile Happs (1985a) showed that even when children do make the observations that would allow them to interpret how rocks were formed, they often misinterpret these clues and come to incorrect conclusions. Given these misconceptions it is not surprising that when trainee (pre-service) teachers were asked to teach rock identification, they showed relatively high anxiety levels (Westerback, Gonzalez, & Primavera, 1985).

These studies reveal that many students see rocks as items to be sorted on a table rather than specimens to be examined for common characteristics that can be used in setting up identification systems or in interpreting the evidence for the mode of formation that each rock contains. Clearly, rock characteristics and classification should be taught using the intrinsic features of rocks that provide evidence of the processes that formed them, such as the strategy described by Hawley (2002).

Minerals

Minerals are *naturally occurring elements or chemical compounds, with chemical composition, atomic structure, and physical properties that are fixed or vary between known limits*. Blake (2004) noted that the term 'mineral' was a problematic concept for 9–11-year-old children whilst Happs (1982) found no 11–18-year-old students that were able to use the term 'mineral' scientifically. Confusion between 'rock' and 'mineral' was also noted (Happs, 1985b; Oversby, 1996). The distinction between mixtures (e.g. rocks) and compounds (e.g. most minerals) is usually taught at lower secondary level (to 11–12-year-olds) and it would clearly be helpful to later understanding of mineral- and rock-forming processes if the mixture/compound distinctions made in teaching at that stage included minerals and rocks.

Fossils

Fossils are *the preserved remnants of life (more than 10,000 years old)*. Ault (1984) discovered misunderstandings about fossilisation, such as, 'Water makes stone turn to mud. Mud traps animal. It must have been behind a waterfall. The water dried up and the mud turned to stone'. Oversby (1996) showed that many pupils and pre-service teachers could not distinguish fossils from a range of descriptions. Unless fossils are understood as evidence of past life, they cannot be used in interpreting past environments or in developing evolutionary concepts.

Sedimentary processes

Sedimentary processes are those that *form and accumulate sediment and can consolidate them into sedimentary rock*. Driver, Squires, Rushworth and Wood-Robinson, (1994) summarised the work of Happs (1982) on misconceptions about sedimentary processes: 'Very few children … appreciated the relationship between sedimentary rocks and the sedimentary processes by which they are formed' (p. 113). Dove (1997, 1998) found widespread misunderstanding and confusion between the sedimentary processes of 'weathering' (*the break up/break down of rock in place, without the removal of solid material*) and 'erosion' (*the removal of solid material*) and attributed this to change in the meanings of these terms over time. Nevertheless, their scientific definitions are clear in current authoritative textbooks.

Leather (1987) researched the understanding of oil-formation and accumulation in 11–17-year-old students, finding that most thought oil derived from dead sea creatures (or animals), when the consensus view is that most oil derives from microscopic plant material and bacteria. Many students also thought that oil became trapped in caves or cavities underground (rather than in permeable rocks) whilst some younger pupils thought it collected on the seabed. This work reveals not only misunderstanding of terminology, but important conceptual disconnects between sedimentary processes and rocks.

Metamorphic processes

Metamorphic processes *transform pre-existing rocks by increased heat and/or pressure into metamorphic rocks* but a common confusion between metamorphic processes and the biological processes of metamorphosis was noted by Happs (1982), quoted in Driver et al. (1994).

Igneous processes

Igneous processes *involve the melting and subsequent solidification of rock.* Work on igneous process misconceptions was reviewed by Dove (1998), who found confusion between volcanic eruptions and earthquakes. Libarkin et al. (2005) showed that US college students ‘believed that volcanoes only occur on islands, that they are associated with warm climates and that volcanoes only occur along the equator’ (p. 24) and Marques (1988) reported similar findings for Portuguese students of ages 10–15. Lillo (1994) and Dahl et al. (2005) identified the misunderstanding that the magma that erupts through volcanoes originates in the Earth’s core, when virtually all magma is thought to originate in the upper portion of the mantle or the crust. This work shows that many pupils do not connect volcanoes with the processes that form them.

The rock cycle

The rock cycle – *sedimentary, metamorphic and igneous processes linked into a cyclic model.* Ford (2005), in researching understanding about the rock cycle in 11–12-year-old US pupils who had previously been taught about it, found that:

> ‘students did not grasp the purpose of instruction about the rock cycle. Instead their responses indicate they perceive the rock cycle as the *cause* of rock formation, rather than a model representing relationships between rock categories and their formation. For example … one student responded, “It went through the rock cycle” much as laundry goes through a wash cycle …’ (p. 375)

Meanwhile, Stofflett (1993), working with pre-service primary (elementary) teachers, commented that ‘the misconceptions exhibited in this study [about rocks and their formation] were, quite frankly, appalling’ (p. 230) and also showed (Stofflett, 1994) that the ‘average teacher candidate understood only 18% of the concepts [relating to rock-forming processes] presented’ (p. 495). Kusnick (2002), in another survey of pre-service primary teachers, showed that ‘students hold a surprising number of misconceptions about how rocks form’ (p. 31), commenting that ‘a startling number of students described rocks as forming by processes that no geologist would recognise’ (p. 37) and concluding that ‘students need schooling experiences which build a basis for conceptual understanding’

(p. 38). Given the widely held misconceptions about the rock cycle, it is reassuring that Kali et al. (2003) have shown that the high-order thinking skills required for understanding the rock cycle can be developed through appropriate teaching strategies, whilst Sibley et al. (2007) have shown that the development of interconnected diagrams can be effective in teaching thinking systems of this type.

This work clearly shows that an understanding of the elements of the rock cycle need to be developed progressively through study of the processes and their products through curriculum materials specifically developed for this purpose.

The evolution of life

The evolution of life – *from single-celled organisms through invertebrates to vertebrates*. Marques and Thompson (1997a) showed that many of the 10–15-year-old Portuguese students that they surveyed believed that the origin of life and the Earth occurred simultaneously. Many also had a mistaken view of the sequence of appearance of certain familiar animals, some thinking that fish were the earliest forms of life to appear whilst others thought that birds were the latest forms, from the choices given. Jenson and Findlay (1996) used four different strategies for teaching evolution to US college students and found, through pre- and post-test assessment, 'gains in correct conceptions but few reductions in alternative conceptions' (p. 879).

Libarkin et al. (2005) also found a variety of misconceptions about life on Earth amongst US college students, including some 30% of students at one college who thought that life existed when the Earth formed, giving a range of examples of organisms that were there at the time, including dinosaurs, 'insects and fish in the ocean …' (p. 22), trilobites, plants and humans. Catley (2006), in arguing that macroevolution should be taught in schools, has commented, 'students and teachers still have poor understanding of the [evolutionary] processes which operate at the macro level, and virtually no understanding at all of the history of life on our planet …' (p. 767). However Dodick and Orion (2002) have demonstrated how a curriculum module linking natural selection to geological time using fossil material can be effective in developing understanding of macroevolution.

These studies indicate the importance of developing a time framework in students, into which the evolution of life can be fitted, as discussed in the 'Education in the understanding of geological time' section, above, and stressed particularly by Trend (2001b).

Earthquakes

Earthquakes – *caused by seismic shock waves triggered primarily by underground rock fracture; most large earthquakes are linked with plate margins, but minor earthquakes occur in most regions*. Leather (1987) found that most of the UK 11-year-old pupils he surveyed thought that earthquakes were linked with hot climates or volcanic eruptions. These findings for primary-age (elementary) pupils were similar to those reported by Sharp, Mackintosh and Seedhouse (1995) in the UK and Ross and Shuell (1993) in the USA. Leather (1987) went on to show that these misconceptions faded with age, being replaced with more scientific ideas, however, Libarkin et al. (2005) found that such ideas were still retained by a few US college students. Leather (1987) also found that many 11–14-year-old children thought that earthquakes did not occur in the UK. This corresponds with the findings of Schoon (1992, 1995) in the USA that nearly a third of both primary pupils (10–11-year-olds) and pre-service primary teachers thought incorrectly that an earthquake could not damage Chicago. Even in Israel, a country prone to earthquakes, 77% of the 12–16-year-old students surveyed were unaware that their school was situated in a high-risk area (Rutin & Sofer, 2007) and many had little idea of the correct response to a future earthquake. Meanwhile Tsai (2001) found that some 10–12-year-old Taiwanese students believed that earthquakes are caused by supernatural or mythological forces, giving ghosts, the devil and an angry God as examples.

The structure of the Earth

The structure of the Earth – *composed of the crust, mantle and core, each of these differing chemically from the others*. When Lillo (1994) asked 10–15-year-old Spanish pupils to draw pictures of the Earth to show its structure, he found that most students considered it to be formed of concentric layers, but that some thought there was fire, lava or a magnet in the centre. Marques and Thompson (1997a) showed that many Portuguese 10–15-year-olds thought that the densest material in the Earth would be found near the South Pole, but more of the older pupils correctly thought that the densest materials would be at the Earth's centre. King (2000) also found a poor understanding of the variation of density with depth in UK science teachers. Libarkin et al. (2005) found that almost all the US college students they surveyed:

> 'mixed physical state (lithosphere, asthenosphere, mesosphere, inner core, outer core) and chemical boundary (crust, mantle core) terms, indicating a lack of understanding of the basis for subdividing Earth's interior.' (p. 24)

King (2000) uncovered similar misunderstandings among practising UK science teachers.

A persistent misunderstanding noted by Lillo (1994) was that the molten core of the Earth was the source of volcanic lava. Meanwhile, King (2000), King et al. (2003, 2005) and Sellés-Martinez (2007) found the widespread misconception that the mantle is liquid (when it is almost entirely solid), with many textbooks suggesting that the 'liquid mantle' is the source of magma and volcanic lava.

Most students in Lillo's (1994) survey drew the crust much thicker than it should be shown, paralleling a similar misconception of UK practising science teachers (King, 2000) and US college students (Steer, Knight, Owens, & Mcconnell, 2005). Steer et al. (2005), having identified this misconception, used practical model making and peer group discussion to teach the correct dimensions of the Earth's core, mantle and crust, with a high level of success, as shown by post-course assessment several weeks after completion of the course.

Plate tectonics

Plate tectonics – *the causes and effects of the movement of the Earth's plates*. Marques and Thompson (1997b) researched the understandings of Portuguese 16–17-year-old students after being taught about plate tectonics. They found that a broad range of misconceptions had been retained concerning the continents, ocean basins and continental drift; the Earth's magnetic field; and plates and their motions. This research underpinned the design of a teaching module based on a constructivist approach, which was trialled with a group of students. However, even after receiving this teaching, 'some of the students still had difficulty in tackling novel problem-solving tasks related to the topics' (p. 219).

Libarkin et al. (2005) found that some US college students were unsure of the position of the tectonic plates, 'believing them to be somewhere below the surface', whilst a few, 'place tectonic plates at the Earth's core or in the atmosphere' (p. 23). Meanwhile Libarkin and Anderson (2005) found that most US college students, 'are exiting courses with a poor understanding of the location of tectonic plates' (p. 394) and King (2000) showed that the UK science teachers surveyed had little understanding of how earthquake and heat flow distributions on Earth were linked to plate tectonics. Libarkin (2006) commented on 'the fact that most [US] college students would claim that they have learned about gravity or plate tectonics in prior coursework does not mean that they fully understand these phenomena' (p. 9).

Since the theory of plate tectonics underpins most of our current understanding of geoscientific processes, clarity of teaching is vital to a broader understanding of Earth processes. If plate tectonic theory is taught through scientific evidence and explanation, seeking the evidence for each part of the theory and then providing scientific explanations for the evidence, then it is less likely that many of the misconceptions described above would survive.

8.2. Misconceptions reviewed

The literature shows that misconceptions about the Earth are widespread amongst people of all ages and that whilst many of these misconceptions are lost with time, others can be very long-lasting. This is particularly so with abstract concepts and 'unseen' elements of processes, such as atoms and tectonic plates.

Whilst some of the instances cited above are simple errors (such as confusion between 'weathering' and 'erosion') others reveal more deep-seated misunderstandings that can have impact on large areas of geoscience understanding. For example, if students are unable to link rocks with the processes that formed them, they cannot understand the evidence provided by rocks for ancient Earth processes. Likewise, if models like the rock cycle and plate tectonic theory are not understood as such, then the scientific evidence and explanation for them are not seen as critical elements of their study. Such deep-seated misconceptions can greatly inhibit geoscience understanding.

The widespread misconceptions found amongst pre-service and practising primary (elementary) and secondary (high school) teachers is particularly disconcerting. Furthermore, many of the misconceptions identified are also widespread in science textbooks (AAAS Project 2061 website; King et al., 2005). However, it is reassuring to note that effective teaching can greatly reduce the prevalence of such misconceptions (Dodick & Orion, 2002; Kali et al., 2003; Marques & Thompson, 1997b; Sibley et al., 2007; Steer et al., 2005).

9. Professional development in geoscience education

9.1. The development of practicing teachers

In their comparison of the success of novice and expert Earth science teachers in solving simple Earth science problems, Barba and Rubba (1993) found:

> 'The expert earth and space science teachers in this study obtained the correct answers when solving problems more frequently than did the novice earth and space science teachers, even though those problems were "typical" of the secondary school science curriculum and should have been readily solved by both.' (p. 280)

They concluded:

> 'Educating teachers in procedural knowledge [knowledge of "how to do things"] is vital to a balanced earth and space science curriculum. Existing earth science and earth science education courses need to incorporate more elements of procedural knowledge or laboratory methods as part of teacher training.' (pp. 280–281)

Whilst it is reassuring that expert geoscience educators can solve school-level geoscience problems more effectively than novices, the key question remains of how to bring that expertise to the wide range of teachers from diverse backgrounds who are currently teaching geoscience. The strategies used to tackle this issue have depended upon the context of geoscience education in different countries. Where geoscience forms a small part of a national curriculum and is being taught by a wide variety of science and/or geography teachers, short courses have generally been most appropriate. One exception is Israel, where it has been possible to present longer courses to national curriculum teachers. In the USA, where much longer geoscience modules are taught, longer courses have generally been used.

9.2. Professional development courses in the geoscience components of national curricula

As part of their research underpinning the presentation of short courses to secondary (high school) science teachers in the UK, King and Lydon (King, 2001; Lydon & King, 2003) found a pre-course low level of confidence in teachers of Earth science together with a low perception of the value of Earth science. However, research into the impact of the short (90 minutes) workshops involving interactive practical curriculum materials, undertaken a year after the workshop had taken place, showed that all the schools that responded had made long-term changes to their geoscience teaching (King & Lydon, 2007; Lydon & King, in press).

The Portuguese experience of using short courses to develop curriculum materials for teaching geoscience fieldwork with teachers generated positive student feedback (Rebelo, 2003b). Nevertheless, the study also found that many teachers lacked confidence in planning fieldwork and that both teachers and pupils had negative feelings about the experience (Rebelo, 2003a) although both teachers and many students realised the importance of the fieldwork. This corresponds with the gap between Israeli teachers' attitudes to fieldwork and their actual practice found by Midyan and Orion (2003).

As part of their initiative to develop earth systems education in Germany, Hansen and Hlawatsch (2006) found that in-service professional development workshops were crucial to the effective implementation of their new curriculum materials and that implementation was most effective when the materials were customised for the local situation.

These initiatives indicate that the integration of innovative and accessible curriculum materials with the short courses is critical to the successful implementation of this approach to professional development.

These positive results from short development courses for national curriculum teachers need to be set alongside the well-researched Israeli experience (Orion & Ault, 2007) of using long professional development courses for teachers of the Earth science content of the Israeli national curriculum:

> 'From each of these studies came the conclusion that despite their participation in long-term, in-service training programs, the vast majority of the teachers did not undergo genuine professional development. Professional inertia was the rule. Results indicated a clear gap between teachers' perceptions of their development as expressed through questionnaires and interviews

> and their actual teaching practice. In addition to teachers' reluctance to implement new teaching methods and incorporate new scientific topics, the interviews uncovered four additional factors preventing them from genuinely implementing reform. They felt, in general, apprehension toward change and that professional training institutes did not provide them with the practical tools needed to overcome their apprehension. Teachers believed that school administrators failed to provide them with the resources necessary for reform, such as laboratory equipment, smaller class sizes in the laboratory, computers and access to outdoor learning environments. Reform placed, in their judgement, inordinate demands upon their time. Finally, teachers faulted the Ministry of Education and its science education inspectors for a double standard. On the one hand, the Ministry initiated reform and inspectors encouraged participation. On the other hand, resources were not forthcoming and the Ministry called upon the inspectors to implement a national testing regime. The focus of testing tended to institutionalise objectives antithetical to the Science for All paradigm and the earth systems approach.' (p. 679)

Although the research into professional development for teachers of the geoscience components of national curricula has been limited, it has been demonstrated that short courses can be effective in changing the day-to-day teaching of teachers. However, the ambitious goals of the longer Israeli courses, to change the perspectives of teachers through geoscience professional development, have not generally been met. Clearly a more comprehensive programme of professional development across science education, well supported by both schools and the government, would be necessary to institute wider changes in daily teaching and learning experiences.

9.3. Professional development courses for teachers of more extended geoscience modules

Research into the effects of professional development on the teaching of more extended geoscience modules that are not part of national curricula comes largely from the USA. Birnbaum, Morris and McDavid, (1990), using pre- and post-course exams, found a 20% improvement following their professional development courses in the USA. They concluded that: a lecture/laboratory/field approach was most beneficial; laboratory sharing and curriculum development was important; and that participants should be involved in more than one course for continuity and support.

Marlow, Wright and Hand (2003) examined the effectiveness of teaching US teachers about enquiry skills in a geological context. They found that most teachers developed a greater understanding of the process. Schwerin et al. (2006), following the implementation of an on-line Earth systems course, found, through pre- and post-course surveys, follow-up surveys and case studies with course participants, 'that the courses have had a significant impact on teachers' content knowledge, attitudes and practices' (p. 215). Dawkins and Dickerson (2007), through their study of the impact of a professional development Earth/environmental science course to middle and high school teachers, identified key aspects of the course as being:

> '(a) interactions with faculty [staff] beyond the formal instructional settings; (b) extensive year-round communications with other participants, especially the small groups with which they identified during the summer sessions; and (c) a strong content focus aimed at the instructional responsibilities that the teachers have in common.' (p. 67)

These findings indicate that a crucial element of long-term professional development is the long-term support of the teachers involved, as shown in particular by the work of Dawkins and Dickerson (2007) and echoed by the professional development work in Israel (Orion & Ault, 2007).

10. Discussion and conclusion

This review has shown that there are important pockets of geoscientific educational research from different parts of the world, particularly Germany, Israel, Portugal, Taiwan, the UK and the USA. This research is often driven by one individual, but supported by a group. Much of the research is associated with curriculum development. However, one of the major issues has been that geoscience educators often have had little opportunity either to influence the curriculum or to find space in the curriculum for evaluating new strategies and curriculum materials. Nevertheless, there is still much to be done and many windows of opportunity to be exploited.

A clear imperative is for the *evaluation tools* devised in some countries to be tested in other regions and curriculum situations, including: the 'Geological Spatial Ability Test' (GeoSAT) of Kali and Orion (1996); the 'Geological Time Aptitude Test' (GeoTAT) of Dodick and Orion (2003b); the Earth systems thinking tests of Ben-zvi-Assarf and Orion (2005); the outdoor activity evaluation scale of Vasconcelos and Salvador (2003); and the 'Geoscience Concept Inventory' of Libarkin and Anderson (2005).

Furthermore, each of the seven areas of geoscience education identified at the outset of this review requires more development and research.

The broad sweep of *geoscientific methodology,* involving a wide assemblage of strategies and skills, appears to have been little researched pedagogically. There is little holistic research around how these broad skills should be taught and learned most effectively, apart from the specific instances below. This large research area could be tackled through a range of qualitative and quantitative approaches, from case studies of teaching or learning, to reviews of questions set in examinations and project work.

Understanding aspects of the *Earth as a system* involves the abstract concepts of a range of models and cycles and how these interact, so it is not surprising that students find them difficult to assimilate, as shown by the US college experience. Nevertheless, effective ways forward have been demonstrated by research around particular school-level projects. These involved the integration of well-designed curriculum materials involving constructivist elements with professional development and support for teachers. There is scope not only for testing these approaches in other educational systems, but also for their development, linked with associated research. This is critical for the future, since not only does environmental thinking involve the understanding of complex systems and their interactions, but social and economic thinking requires similar understandings, from local to global scales. Nowhere is this better illustrated than in the present concern about global climate change and the factors that control it, both long- and short-term; naturally and humanly induced (Schreiner, Henriksen, & Kirkeby Hansen, 2005).

The approaches to teaching *geoscientific spatial abilities* by computer animation devised in Israel (Kali et al., 1997), the USA (Reynolds et al., 2002, 2005) and in the UK (UK Earth Science Courseware Consortium website) should be tested and evaluated in other educational systems. The specific skills that underpin three-dimensional spatial understanding could be teased out by methods like the GeoSAT test of Kali and Orion (1996) and used for the development and testing of non-computer-based curriculum materials as well – for use where computers are not commonly available.

Now that research concerning the *geological time* framework, its length and sequence has provided insight into the lack of understanding of major groups of the population, curriculum approaches such as those described by Trend (2001a) should be developed and tested. Whilst the understanding of time is an abstract concept, difficult for many, Dodick and Orion (2003b), through their aptitude test, GeoTAT, have shown that studying geoscience is effective in developing this understanding. This is necessary if the complex changing systems of our planet are to be understood.

Hawley's (1998) review of *geoscientific fieldwork* identified a range of key educational questions requiring research. Important additional questions are focused on the development of school-level geoscience fieldwork. These concern the most effective approaches for developing student enthusiasm and the geoscientific understanding, environmental understanding, cognitive skills (including understanding of space and time) and transferable skills of the students involved.

A wide range of deeply held *geoscience misconceptions* has been identified and, in some cases, the reasons for these misconceptions have been probed. There is scope for further identification and probing of misconceptions. However, a more pressing need is for constructivist curriculum materials involving correcting misconceptions, such as the work of Marques and Thompson (1997b), to be developed and widely tested.

Effective *professional development for teachers of geoscience* is crucial since it has been widely shown that teachers rarely use new curriculum materials (Council for Science and Technology, 2000; King, 2001) unless they are accompanied by effective professional development. Thus, all the curriculum initiatives and associated research proposed above are unlikely to be effective unless accompanied by, and integrated with, well-prepared and tested professional development courses.

Until recently, the overwhelming view of researchers has been that only extended courses with long-term support provide professional development that results in improved classroom learning (Guskey, 2000; Joyce & Showers, 1988). As Adey (2004) summarised:

> 'There is universal condemnation in the research literature on professional development for the one-shot "INSET day" as a method of bringing about any real change in teaching practice.' (p. 161)

However, he went on to say, 'Perhaps the only exception to this rule is the introduction of a very specific technical skill, such as the use of new piece of software' (p. 161). King and Lydon (2007) and Lydon and King (in press) have shown that short interactive courses, if based on effective new curriculum materials, can have a major impact on teaching if participants are involved in carrying out activities themselves and in reporting back to the overall group. The reporting back session encourages them to demonstrate what they have done and to evaluate its usefulness and the scientific thinking behind it. This is a key finding, since in most parts of the world there are no opportunities for long-course professional development of the teachers who teach geoscience through their national curricula.

It would be interesting and important to research the International Year of Planet Earth Earthlearningidea initiative (Earthlearningidea website) from this perspective to discover the impact of well-designed interactive activities requiring few resources in classrooms across the world, where teaching without the use of such activities is the norm and where professional development cannot be provided.

In summary, this review of geoscience educational research publications shows that the most effective way of progressing geoscience education worldwide involves a two-stage process. First there must be opportunities for teaching geoscience, either through geoscience as part of a national curriculum or through optional geoscience courses. Secondly, when these opportunities are available, if the curriculum is to develop and its teaching is to be effective, well-designed curriculum materials must be integrated with professional development, with well-constructed research programmes built around them. Curriculum development initiatives on their own are not enough since, unless their impact in the classroom can be demonstrated, there is no evidence, either for their long-term effectiveness or for ways in which they should be developed in the future. Baker (1996) made a strong plea for support of the study of geoscience:

> 'The natural record of geologic change is the greatest repository of available information on change in Earth real-world environments. The knowledge of this record derives from the reading of the Earth's indices or signs, the scientific interpretation of which defines the geologist … this "conversation with Earth" has at least as much to provide in understanding the environment as does the detached analytical science that has heretofore been overcommunicated to the public. It is time for geologists to make known their pragmatic approach to sustaining a habitable planet by sharing their naturalist reasoning processes with the public.' (p. 43)

He went on to write:

> 'It is the responsibility of geologists, confident in the status of their science, to bring this experience into the modern scientific discourse. Moreover there is need to go beyond the providing of scientific information alone. Its limitations and strengths need to be made clear to the decision makers. Only by participation in the whole process, from initial problem recognition, through scientific study, then through societal action, will the geological approach reveal its full potential. In this time of environmental change, it is time that geologists emerge as leaders of the science best able to help society cope with that change.' (p. 43)

Things have changed very little since this was written more than ten years ago and there is still an imperative for geoscientists to be at the heart of scientific debate about the future of our planet. Geoscience educators play a key role in this imperative, in enthusing students to want to study the Earth through becoming geoscientists and in educating the population at large in the understanding of geoscientific ideas.

Geoscience educational researchers have their own imperative to ensure that geoscience educational initiatives have maximum impact. As demonstrated above, there is great scope and need for such research, into education in geoscience methodologies and Earth system approaches, into geoscientific spatial, time and fieldwork understanding, into misconceptions prevalent in geoscience students and into the effectiveness of professional development initiatives intended to address many of these issues.

This review indicates that geoscience education will only progress through:

- ensuring geoscience education becomes part of the curriculum of every child;
- providing effective geoscience learning, through innovative, engaging and motivating curriculum developments;
- educating teachers in effective implementation of new curriculum initiatives through well-designed professional development;
- evaluating the progress of the initiatives and using the results to refine them; and
- researching the whole process, to demonstrate its effectiveness and to ensure wide dissemination on the basis of solid research findings.

This review, based on published materials, has thus identified the priorities and provided recommendations for where future development and research into geoscience education should be focused.

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