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The State of Evidence in Geoscience Education Research

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Context

Discussions around learning and teaching and assessment of practice have long been a part of professional development in the Geosciences in K-12 and higher education, as evidenced through publications such as the *Journal of Geoscience Education* (http://nagt.org/nagt/jge/) and *Teaching Earth Sciences* (http://www.esta-uk.org/magazine.html) and national and international bodies including the National Association of Geoscience Teachers (http://www.nagt.org/), the National Earth Science Teachers Association (http://www.nestanet.org/) and, more recently, the *International Geoscience Education Organization* (http://www.geoscied.org/).

The profile of Geoscience education is increasing in the US as evidenced by the number of sessions on this theme at the Geological Society of America (GSA) and American Geophysical Union (AGU) meetings. Geoscience Education is currently the fifth largest division of GSA in terms of membership. In addition, the number of tenure-track positions in Geoscience education has been increasing steadily over the last decade as illustrated in Figure 1. This profile is not reflected internationally where typically only one or two higher education institutions will have faculty formally employed to undertake Geoscience education research and most national meetings do not include a focus on this theme.

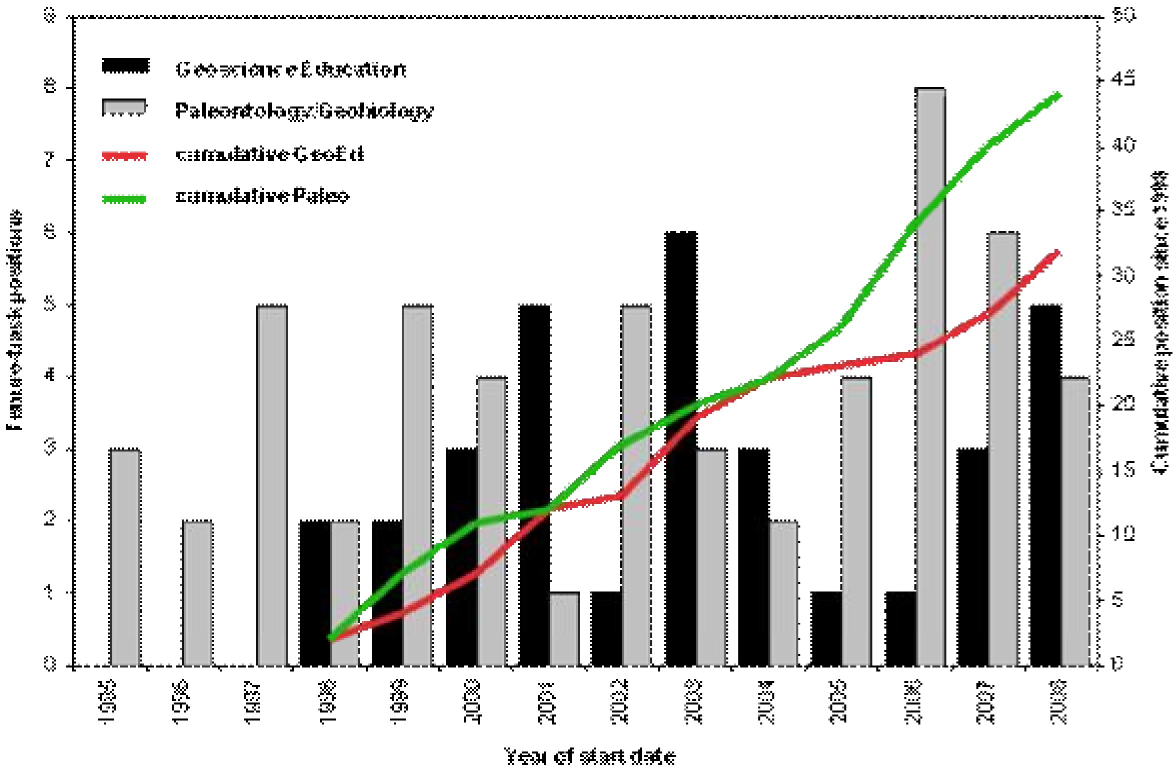

Figure 1: Job advertisements published in 'GSA Today' from January 1994 through December 2007. Tenure-track positions in geoscience education are compared to similar jobs in palaeontology and geobiology (produced by Julie Libarkin & Scott Clark, Michigan State University - 2008).

Most of the writing on geoscience education is around teaching practice. That is, taking ideas from education research (general, science or less frequently Geoscience) and adapting them for the Geosciences with some classroom assessment of the outcomes. Changes taking place in Geoscience teaching at undergraduate level include the introduction of active learning in the classroom, using an array of assessment strategies rather than simply written exams, introducing problem-solving in the field rather than (or in addition to) 'show and tell', and the use of visualizations to support student learning. Many innovative examples of classroom activities have been published in JGE. In their survey of 2207 Geoscience faculty across the US, Macdonald et al note that:

> *"There is no question that research on learning and resulting recommendations for best classroom practice that have emerged over the past decade have had an impact on geosciences classes. Our survey shows widespread use of interactive lecture techniques, problem-solving activities, and assessment strategies that challenge students to demonstrate higher order thinking. Extensive topical courses, interdisciplinary offerings, and use of problems of local and global interest, particularly at the introductory level, may reflect both a desire to make geoscience more relevant to students and an increasing awareness of the Earth as a system."* (Macdonald et al, JGE 2005 pg 251).

At K-12, teachers have more constraints on the topics they can teach in the classroom and anecdotal evidence suggests that not all elementary and middle school teachers are well-equipped to teach Earth / space science content. Evidence from the UK (King, 2007) suggests that school students are generally not aware of the impact of the Geosciences on their daily lives and do not see the discipline as particularly relevant to themselves or their future careers: Geologists *"study rocks"*. This perception may arise from how the subject is presented in the classroom / curriculum, from a narrow geology focus rather a broader Earth Systems Science approach (e.g. Ireton et al, 1997) and / or from their exposure to the Geosciences in the media. Further research into teaching, support for professional development and raising awareness of the Geosciences is important at K-12 in order to enthuse students to study the Geosciences and to develop environmentally aware citizens.

As suggested above, developments to teaching practice have mostly come about through adapting ideas and findings from general or science education research. Geoscience Education research is still relatively new and the implications for teaching are only just beginning to be explored. Therefore, the following outline of areas of research interest illustrates both the current state of research and possible future directions.

Geoscience Education Research

The following discussion provides a broad overview of research topics in Geoscience Education and does not constitute a formal literature review. The references provided are intended to be illustrative and by no means provides an exhaustive list of research activities. Further information can be found at the website "Bringing Research on Learning to the Geosciences" which has links to current activities, reports, recommended readings, projects and much more:
http://serc.carleton.edu/research_on_learning/index.html

The purpose of Geoscience Education research is to support an evidence-based / empirical approach to advancing learning of the discipline. Such learning might be within formal (e.g. schools and universities) or informal settings (e.g. public outreach). Stakeholders include:

- Learners: K-12, post-secondary students (undergraduate and graduate) and the public;
- Facilitators of learning: (teachers, classroom assistants, researchers, librarians, curators, faculty developers etc.);
- Policy Makers (administrators, politicians etc.).

Broadly speaking, Geoscience Education research endeavors to better understand expert and novice thinking and behavior so that strategies can be developed to move novices forward more effectively and efficiently. For the purpose of this report, topics in Geoscience education research have been roughly categorized into three main areas:

- Geoscience Knowledge
- Learning, Teaching and Assessment
- Ways of Thinking and Practicing Geoscience

Geoscience Knowledge

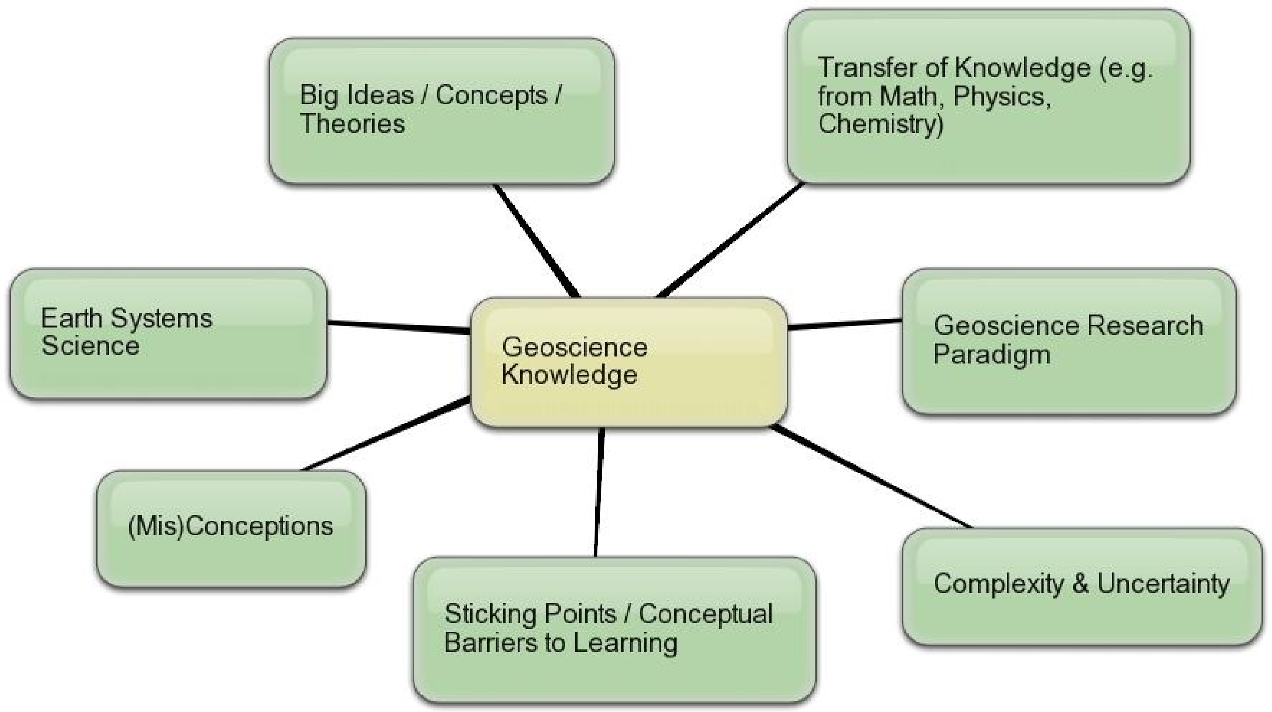

Figure 2: A schematic illustration of the issues / research topics associated with Geoscience knowledge. This illustration is not intended to be either definitive or exclusive: there are many inter-linkages with other areas of Geoscience education research.

Geoscience encompasses the study of the oceans, atmosphere, and solid earth, plus interactions between these physical systems and living systems. In order to inform the public and develop the next generation of Geoscientists it is necessary to identify the big ideas in the discipline. What should everybody know to be effective global citizens? What are the key concepts, theories and skills that students should master before becoming practicing Geoscientists?

Some policy initiatives (e.g. the Subject Benchmark Statement in the UK, QAA 2007) and community discussions (such as the SERC Building Strong Geoscience Departments project) have suggested key elements of the Geoscience curriculum. However, research is required to identify sticking points and conceptual barriers to student progression.

Students may have misconceptions about particular Geoscience ideas and theories. By exposing these misconceptions teaching strategies can be devised to help students reconstruct their knowledge and understanding. The Geoscience Concept Inventory (GCI) is a multiple-choice assessment instrument for use in the Earth sciences classroom. A customized 15-question GCI subtest can be selected by instructors from the pool of 73 questions. The test items cover topics related to general physical geology concepts, as well as underlying fundamental ideas in physics and chemistry, such as gravity and radioactivity, that are integral to understanding the conceptual Earth. Each question has gone through rigorous reliability and validation studies (e.g. Libarkin & Anderson, 2006). Over 45 institutions in the US have used the GCI. A larger, international dataset would help to identify commonalities and differences of misconceptions by students from various demographics.

As discussed in the Context section above, the conceptions that people hold of Geosciences in general will inform their interest in the subject and their perception of its relevance to their daily lives. An understanding of school students' and non-major freshmen's conceptions of the discipline will help to inform strategies for encouraging an interest in Geoscience.

General science literacy, the transfer of knowledge from other disciplines (particularly math, physics and chemistry) and the appreciation of (and comfort with) complexity / uncertainty and systems thinking are important for learning in the Geosciences, however students often struggle in these areas. A better conceptualization of the nature of Geoscience knowledge and a review of the impact of teaching strategies for the transfer of knowledge may be of benefit to undergraduate education.

Ways of Thinking and Practicing

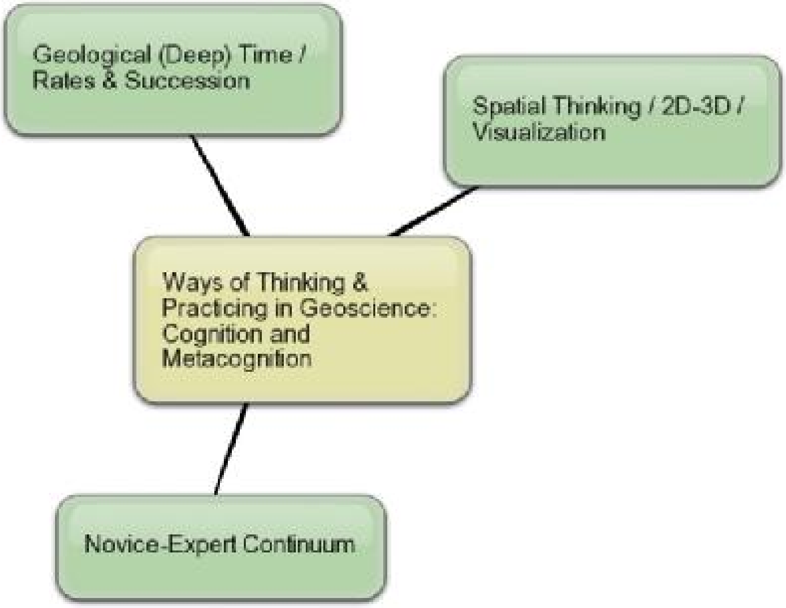

Figure 3: A schematic illustration of the issues / research topics associated with ways of thinking and practicing in the Geosciences. This illustration is not intended to be either definitive or exclusive: there are many inter-linkages with other areas of Geoscience education research.

It's not just the content of Geoscience that is required to understand the discipline but also the ways of thinking and practicing that expert Geoscientists employ. These cognitive and behavioral aspects of the discipline are often tacit – an expert will 'intuitively know or be able to see' something without necessarily being able to 'think aloud' their working. If these expert ways of thinking and practicing can be identified, described and made more explicit then learning, teaching and assessment strategies may be devised to help take novices forward more effectively and efficiently.

Topics in this area of research include the nature of practice in the Geosciences (including geologic reasoning and research e.g. Raab & Frodeman, 2002) and, most recently, the novice-expert continuum. The latter area involves a variety of approaches to illustrate the ways in which novices and experts think and behave particularly in the field (e.g. Manduca & Mogk, 2006; Petcovic & Libarkin, 2007). Of course, linkages can be made between this approach to Geoscience education research and many of the other topics suggested in this paper.

Particular aspects of thinking in the Geosciences include the concept of geological time (deep time, process rates and principles of succession) and spatial literacy (concepts of scale and visualization in various dimensions). As Kastens and Manduca note in the Synthesis of Research on Learning project *"Researchers have begun to develop instruments and methodologies to probe learner's knowledge of, interest in, and ability to reason about geological time."* The development of such knowledge and ability appears to be problematic and presents a conceptual barrier or sticking point for learning. Several examples of interesting practice have been presented in the literature to help learners develop a better understanding of geological time. The majority of formal research to date has been with K-12 students and teachers (e.g. Trend, 1998 & 2001; Dodick & Orion, 2003); more work needs to be undertaken to explore the issues for adult (post-secondary) learners.

"*Geoscience demands extensive spatial thinking from learners and practitioners [e.g. Kastens & Ishikawa, 2006]. Geoscientists describe, and classify, and look for causal meaning in the shape of myriad objects in nature, inferring strain history from the shape of a mineral, temperature of an ancient ocean from the shape of a marine microfossil, and atmospheric conditions from the shape of a cloud. … Students need to learn to combine data from 1- or 2-D information sources into a 3-D mental model of earth phenomena.*" This quote from Kastens & Manduca in their Synthesis project (http://serc.carleton.edu/research_on_learning/synthesis/spatial.html) neatly summarizes the importance of spatial literacy / awareness / ability to the Geosciences. Research has indicated that spatially-demanding tasks in Geoscience education are considered difficult by students and their performance in these is resistant to change. Recent studies have begun to identify the root of these difficulties, for example Kali & Orion (1996) found that students were often unable to envision the unviewed sides of a 3D block diagram and Dickerson et al (2005) discovered that students' misconceptions about groundwater were often a result of misunderstanding of scale or size. Again, as with the temporal aspects of the discipline, many research questions remain about cognitive processes, novice and expert abilities and behaviors and the implications of the development of spatial literacy for teaching strategies.

The investigation of these ways of thinking and practicing in Geoscience is wide open and ripe for further research. As with other aspects of education research, there is considerable scope for international and inter-disciplinary collaborations (such as with psychology, philosophy, cognitive and neuroscience).

Learning, Teaching and Assessment

The initial development of content knowledge and ways of thinking and practicing usually takes place within a formal education environment. Undergraduate and graduate education normally involves three main learning environments: the classroom (including lectures, seminars and tutorials), the laboratory and the field. In addition, some students may have the opportunity to undertake work placements as part of their Bachelor's, Master's or PhD training: to date this learning environment has elicited little research in the Geosciences.

Studies into learning in the classroom and laboratory has mostly been in the form of action research or assessment of practice; usually on the adaptation of ideas from general or science education research (e.g. active learning, problem-based learning, group work, teaching with large classes etc.). Of particular interest to Geoscience is the use of models (including visualizations) and analogies.

Research in this area is fairly new and includes activities such as eye-tracking students' use of visualizations. There is a strong link here with the development of spatial literacy. Further research is required into the different types of models and analogies and their effectiveness in enhancing student ability and learning.

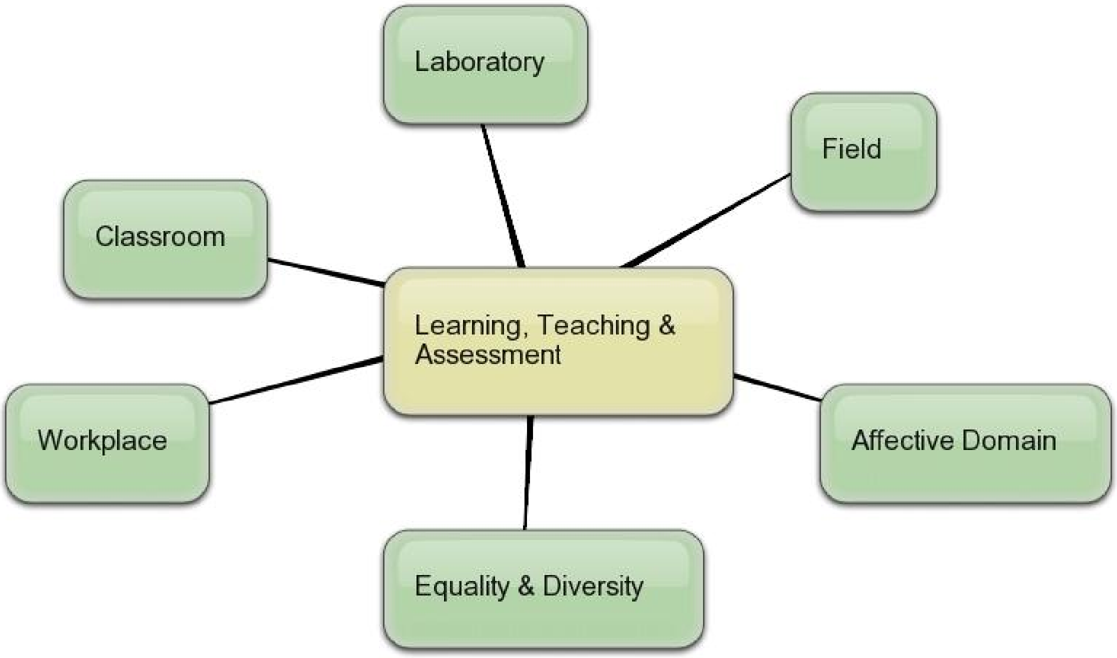

Figure 4: A schematic illustration of the issues / research topics associated with learning, teaching and assessment in the Geosciences. This illustration is not intended to be either definitive or exclusive: there are many inter-linkages with other areas of Geoscience education research.

Learning in the field might be considered a definitive feature of Geoscience and this experiential learning environment has been the focus of many education research activities. Though, as Kastens & Manduca note "*Much of the research to date on field-based learning has been in the form of educational evaluation of specific field programs in earth, ecological and environmental sciences*." Recent research has begun to focus around the student experience of working in the field and the impact of that environment on their learning. The social aspect of the residential field course offers a very different environment to that found in the classroom or laboratory and further research is required to investigate its role in enhancing student learning. There are links here with social learning theory, including communities of practice, that might be exploited for further research and to inform teaching practice (e.g. Stokes, 2008).

The novelty of the social environment may combine with other factors (geographic, psychological and cognitive) to impact on the students' learning. Research indicates that these dimensions of 'novelty space' change to varying degrees during a field experience and that the larger the novelty the greater the impact (usually negative) on student learning (e.g. Orion & Hofstein, 1994; Mogk, 1996; Elkins & Elkins, 2007). Further research is required to develop larger datasets, however, initial findings suggest that pre-field course activities to reduce novelty may help students to benefit more from the experience. Again, there are links here with many other areas of research including spatial and temporal understanding and the novice-expert continuum.

Studies on the role of the affective domain (motivations, interests, values, beliefs, attitudes, self-efficacy, emotions etc.) are also relatively recent but impact on the range of learning environments experienced in Geoscience. The role of the affective domain in fieldwork (e.g. Boyle et al, 2007) is closely linked to the concept of novelty space. In addition to the affective domain, research is required into broader issues that may impact on student learning such as equality and diversity. Much has been written on practices to support broadening participation (e.g. Journal of Geoscience Education special issue, December 2007 http://nagt.org/nagt/jge/abstracts/dec07.html). However, questions remain on aspects such as conceptual understanding and gender, the academic 'glass ceiling' and the interpretation and visualization of Earth processes and landscapes in different cultures.

For all of these learning environments it may be perhaps useful to explore those teaching strategies which may not be effective as well as those that are. For example, water is often used to explain the concept of density; this concept is then transferred to the Earth to understand why oceanic crust is lower in elevation than continental. The use of water for an analogy may partly explain why many students hold the misconception that the crust floats on a liquid mantle (Bair, 2008).

Summary and Conclusions

The major themes for geoscience education research, whilst categorized separately above, form an interactive, complex system around the notion of how and what people know, think and practice about the Earth (see Figure 5 below). Formal education provides a vehicle for supporting the transition from novice to expert using a variety of strategies to facilitate learning. That learning occurs in a variety of environments (classroom, laboratory, field and workplace) and is influenced by many factors (including cognitive, geographic, psychological and social). Geoscience education research is relatively young but has already identified discipline-specific themes and issues. Methodologies are beginning to be established but many traditional geologists do not recognize that geoscience education (or science education in general) is a rigorous field of scholarly research.

An invaluable synthesis of research on learning is being developed through an NSF-funded project at the Science Education Research Center. This synthesis draws together some of the central themes in Geoscience education research: Geological Time, Complex Systems of the Earth, Spatial Thinking in Geosciences and Field-based Learning:
http://serc.carleton.edu/research_on_learning/synthesis/index.html

Areas for further research relating to undergraduate education include (but are not restricted to):

- Important concepts and skills in the Geosciences;
- The nature of discovery in Geoscience (the Geoscience research paradigm);
- Public, K-12 and non-major / major undergraduate conceptions of Geoscience as a discipline;
- Undergraduate (mis)conceptions about Geoscience topics;
- Sticking points and barriers to developing correct conceptions including:
    - systems thinking,
    - complexity and uncertainty and
    - the transfer of knowledge from other disciplines such as math, physics and chemistry);
- Ways in which novices and experts think and practice including:
    - Spatial and temporal conceptualization and reasoning;
- Factors effecting learning in the classroom, laboratory, field and in work placements including:
    - the affective domain;
    - novelty space.

The community of Geoscience education researchers is relatively small but expanding. Progression in Geoscience education research would be usefully served through a variety of activities including:

- **Professional Development**: The provision of training in appropriate research methodologies (many geoscience education researchers are undertaking their work as a ‘second career’ after or as well as researching Earth-based geoscience phenomena and processes);
- A ‘think tank’ style residential event (as a follow-up to the 2002 Research on Learning workshop) to further develop the above listing of the research themes and to better ‘map the territory’ of geoscience education research;
- **Funding** for collaborative (inter-institutional, international and inter-disciplinary) research;
- **Dissemination**: Strategies to raise the profile of Geoscience education research as a valid sub-discipline of Geoscience.
- Strategies to disseminate the results of Geoscience education research in a context that is accessible to Geoscience faculty.

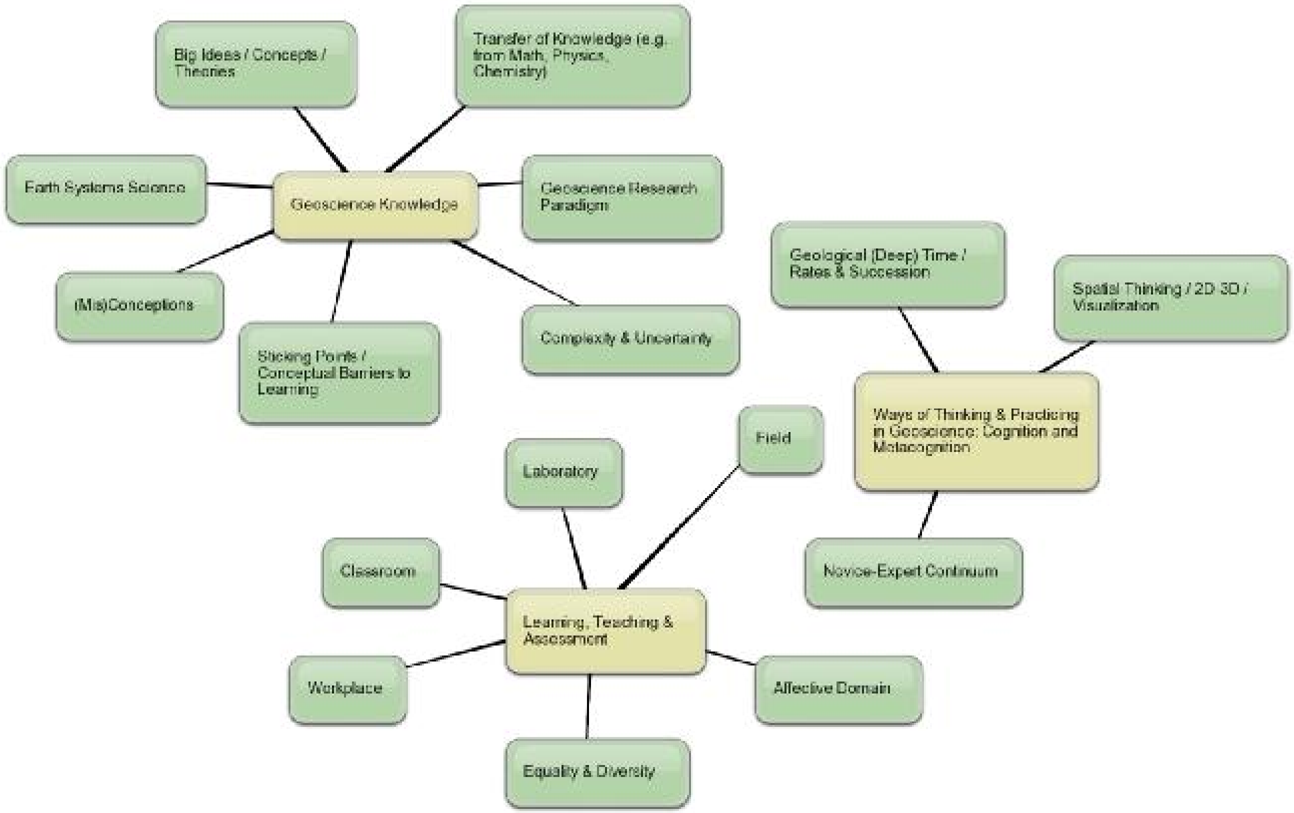

Figure 5: A schematic illustration of the issues / research topics of interest to Geoscience Education Research. This illustration is not intended to be either definitive or exclusive.

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References

Bair, A. (2008) “Threshold Concepts” in geology as key concepts integrated across disparate spatial and temporal scales: student learning difficulties with the concepts of density and erosion. *2nd International Threshold Concepts Conference, Kingston Canada.*

Boyle, A. P., Maguire, S., Martin, A., Milsom, C., Nash, R., Rawlinson, S., Turner, A., Wurthmann, S. & Conchie, S., 2007. Fieldwork is good: the student perception and the affective domain. Journal of Geography in Higher Education, 31, 299-317

Dickerson, D., Callahan, T. J., Van Sickle, M., & Hay, G. (2005). Students' Conceptions of Scale Regarding Groundwater. *Journal of Geoscience Education, 53*, 374-380

Dodick, J. and N. Orion (2003). Cognitive factors affecting student understand of geological time. *Journal of Research in Science Teaching, 40*, 415-442

Elkins, J.T. & N.M.L.Elkins (2007) Teaching Geology in the Field: Significant Geoscience Concept Gains in Entirely Field-based Introductory Geology Courses. *Journal of Geoscience Education* Vol.55 No.2 pp 126-132 http://www.nagt.org/files/nagt/jge/abstracts/elkins-v55p126.pdf

Ireton, M.F.W., C.A.Manduca & D.W.Mogk (1997) *Shaping the Future of Undergraduate Earth Science Education: Innovation and Change Using an Earth System Approach*. American Geophysical Union. http://www.agu.org/sci_soc/spheres/

Kali, Y. and Orion, N. (1996). Spatial abilities of high-school students in the perception of geologic structures. *Journal of Research in Science Teaching, 33*, 369-391

Kastens, K.A. and T. Ishikawa (2006). Spatial Thinking in Geosciences and Cognitive Sciences, in C. Manduca and D. Mogk (Eds.), *Earth & Mind: How Geoscientists Think and Learn about the Earth Earth*. Geological Society of America Special Publication 413

Kastens, K. & C. Manduca. Science Education Research Center (SERC) *Synthesis of Research on Learning.* http://serc.carleton.edu/research_on_learning/synthesis/index.html

King, H. (2007) School students’ perceptions of Geography, Earth and Environmental Science (GEES). http://www.gees.ac.uk/projtheme/stuperc/stuperc.htm

Libarkin, J.C., & S.W. Anderson (2006) Science concept inventory development in higher education: A mixed-methods approach in the geosciences; *Journal of Research in Science Teaching*, in prep. http://newton.bhsu.edu/eps/gci.html

Macdonald, R.H., C.A.Manduca, D.W.Mogk & B.J.Tewksbury (2005) Teaching Methods in Undergraduate Geoscience Courses: Results of the 2004 On the Cutting Edge Survey of U.S. Faculty. *Journal of Geoscience Education* Vol. 55, No.3 pp 237-252 http://nagt.org/files/nagt/jge/abstracts/Macdonald_v53n2p237.pdf

Manduca, C.A. & D.W.Mogk (Eds.)(2006) *Earth and Mind: How Geologists Think and Learn about the Earth.* GSA Special Paper 413

Mogk, D.W. (1996) Field Notes. http://serc.carleton.edu/files/NAGTWorkshops/mineralogy/activities/Mogk_Field_Revised_JBF.pdf

Orion, N. and Hofstein, A., (1994), Factors that influence learning during a scientific field trip in a natural environment, *Journal of Research in Science Teaching*, Vol. 31, pp 1097-1119

Petcovic, H.L. & J.C.Libarkin (2007) Research in Science Education: The Expert-Novice Continuum. *Journal of Geoscience Education* Vol.55 No.4 pp 333-339 http://nagt.org/files/nagt/jge/abstracts/column-v55p333.pdf

Quality Assurance Agency (2007) Honours Degree Benchmark Statement for Earth Science, Environmental Science and Environmental Studies. http://www.qaa.ac.uk/academicinfrastructure/benchmark/statements/EarthSciences.pdf

Raab, T. & R.Frodeman (2002) What is it like to be a geologist? A phenomenology of geology and its epistemological implications. *Philosophy and Geography* Vol.5 No.1 pp 69-81

Science Education Research Center (SERC) *Building Strong Geoscience Departments* http://serc.carleton.edu/departments/

Stokes, A. (2008) Abstract. What can social learning theory tell us about fieldwork? *Geological Society of America Annual Meeting.*

Trend, R. D. (1998). An investigation in into understanding of geological time among 10- and 11-year-old children. *International Journal of Science Education, 20*, 973-988

Trend, R. D. (2001). Deep time framework: A preliminary study of U.K. primary teachers' conceptions of geological time and perceptions of geoscience. *Journal of Research in Science Teaching, 38*, 191-221