From agricultural geology to hydropedology: forging links within the twenty-first-century geoscience community

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Abstract: Despite historical linkages, the fields of geology and soil science have developed along largely divergent paths in the United States during much of the mid- to late-twentieth century. The shift in recent decades within both disciplines, towards greater emphasis on environmental-quality issues and a systems approach, has created new opportunities for collaboration and cross-training. Because of the importance of the soil as a dynamic interface between the hydrosphere, biosphere, atmosphere and lithosphere, introductory and advanced soil-science classes are now taught in a number of Earth and environmental science departments. The National Research Council's recent report, *Basic Research Opportunities in Earth Science*, highlights the soil zone as part of the land surface to groundwater 'critical zone' requiring additional investigation. To better prepare geology undergraduates to deal with complex environmental problems, their training should include a fundamental understanding of the nature and properties of soils. Those undergraduate geology students with an interest in this area should be encouraged to view soil science as a viable Earth-science specialty area for graduate study.

Geology's traditional subspecialties have looked at the Earth divided by major rock types (e.g. igneous, sedimentary and metamorphic petrology); by links to engineering, chemistry, physics, and biology (i.e. engineering geology, geochemistry, geophysics and palaeontology/geobiology); by a focus on a specific environment or resources (i.e. oceanography, hydrogeology and economic geology); or by a focus on the static and dynamic properties of Earth materials (i.e. mineralogy, geomorphology and structural geology). Soil science looks at the outer skin of the Earth. By definition, its place as a geology subspecialty is clear. But the reality is that soil science in the United States has developed in a remarkably separate and distinct way from geology, and it is typically regarded as an agricultural science rather than an Earth science. In the past two decades, however, both fields have shown major shifts towards a focus on environmental-quality issues. Soils play an essential role in supporting life on Earth; are a scarce resource of great economic value; are easily disturbed and respond quickly to environmental changes; and indeed, as Haff (2002) has noted, bear the brunt of human impact on the land surface. These realities have no national boundaries. While the examples in this paper are, based on the author's experience, largely from the United States, it is hoped that the discussion will encourage others to compare and contrast the status of soil science within the larger Earth-science community in their nations.

The need for interdisciplinary approaches to address complex issues of resource- and waste-management in the surficial environment has created greater opportunities for geologists and soil scientists to work together. With this shift has come the need for greater cross-training of students in each field. To encourage such interaction, it is of value to look at areas of connection in the past and present, and to examine ways to bridge the gaps that divide the disciplines.

Historical setting

Soil science emerged as an integrated discipline from work in geology on soil formation, and work in agricultural chemistry on plant nutrition. Agricultural geology was a recognized specialty for geologists in the nineteenth and early twentieth centuries (Tandarich 1998). At the beginning of the twentieth century, there were geological institutes in Hungary and elsewhere in Europe with departments of agrogeology (Szabolcs 1997). In the United States, many early reports from state geological surveys contained sections on the distribution of soils and crop production (e.g. Jackson 1840).

While geology departments exist in the colleges of arts and sciences at many institutions of higher learning in the United States, soil-science departments typically have been confined to the land-grant universities in each state. The Morrill Acts of 1862 and 1890

FROM: FROSSARD, E., BLUM, W. E. H. & WARKENTIN, B. P. (eds) 2006. *Function of Soils for Human Societies and the Environment.* Geological Society, London, Special Publications, **266**, 133–140.
0305–8719/06/$15

established the land-grant institutions to promote education in agriculture, and it was within this academic setting and its associated system of agricultural experiment stations that the field of soil science traditionally has been taught and practised. In some universities outside of the United States (e.g. Massey University in New Zealand, the Czech University of Agriculture in the Czech Republic, Ghent University in Belgium and Wageningen University in the Netherlands), there currently are joint soil-science and geology departments. Indeed, this was the case at some American land-grant colleges at the turn of the twentieth century.

> Soils occupy a niche that gives them a dynamic character and a subtle memory. The organic content of surface soil can change rapidly (in as little as 10 to 100 years) in response to climatic and ecological changes or land management practices. In contrast, extensive weathering of a soil's mineral content requires much more time. Soils thus acquire their basic attributes at very different rates. They reflect both the present and the past, recording how they have changed in response to recent events while they document changes (like weathering) that have occurred over tens of thousands of years.

This elegant quote from University of Wisconsin soil scientists Kevin McSweeney and John Norman (1996) sums up the central role of soils in biogeochemistry. Indeed, the field has its roots in the 1926 treatise *The Biosphere* by Russian soil scientist Vladimir I. Vernadsky. Research on cycling of nutrients such as carbon, nitrogen, sulphur and phosphorus, and of contaminant elements such as arsenic, is under way in many soil science departments today.

Soil scientists have made major contributions in the fields of geology and hydrology. For example, over the past five decades, soil scientists at the US Geological Survey (USGS: the largest geoscience research agency in the United States government) have been leaders in studies on:

(1) the isolation and characterization of the nature and properties of soil and aquatic humic substances;
(2) the retention of trace elements by iron and manganese oxides, and development of selective extraction techniques for use in geochemical prospecting;
(3) the effects of industrial activities on the distribution of trace elements in soils and plants;
(4) carbon cycling and sequestration in watersheds;
(5) the movement of water, soil gases and contaminants in the unsaturated zone at nuclear-waste burial and other sites;
(6) the geochemical forms of radionuclides in uranium mill-tailings, and their mobilization by microbial processes;
(7) the relation of groundwater quality to land use; and
(8) the modelling of the transport of reactive solutes in porous media.

At present, the most requested dataset in the USGS National Geochemical Database consists of analyses of 1300 surface soils collected from non-cultivated fields with native vegetation in the conterminous United States during the 1960s and 1970s; these data are widely used to establish baseline concentrations of metals and other elements (Smith *et al.* 2003). With the goal of expanding the database and extending its coverage to all of North America, the USGS, and partners in Canada (Geological Survey of Canada; Agriculture and Agri-Food Canada) and Mexico (Consejo de Recursos Minerales; Instituto Nacional de Estadistica Geografia e Informatica) have recently established a Geochemical Landscapes Project to sample about 10 000 sites over the span of about a decade. Total elemental analyses, as well as partial extractions (deionized water extraction; simulated human gastric-fluid extraction) to assess bioaccessibility, will be performed on O-, A-, B- and C-horizon materials. The microbial communities in the A-horizon will be documented by techniques such as phospholipid fatty-acid analysis (PLFA), enzyme assays, and BIOLOG carbon source metabolic profiling. Selected samples will be analysed for organic contaminants.

Other soils-related research uses artificial intelligence systems to describe habitat suitability of soils for hosting the fungus *Coccidiodes*. Airborne spores of this organism can cause coccidioidomycosis ('valley fever') in humans (Bultman *et al.* 2004). Living up to its new motto science for a changing world', the USGS is now different from what many in the geological and soil science communities may remember or recognize. In the USGS and other geosciences agencies today, where topics such as pesticide-, nutrient- and pathogen-transport, carbon storage, medical geology and rangeland quality are now commonplace subjects for investigations, research opportunities for soil scientists and geologists with training in soil science are growing rapidly on multiple fronts.

'The Critical Zone'

In its most recent assessment of Earth science research in the United States, the National

Academy of Sciences/National Research Council (2001) noted the need for more multidisciplinary, integrative studies of the Earth's heterogeneous surface and near-surface environment 'where complex interactions involving rock, soil, water, air, and living organisms regulate natural habitats and determine the availability of life-sustaining resources.' The focus in the NAS National Research Council (2001) report on the 'Critical Zone' [defined as including the soil zone (pedosphere), unsaturated vadose zone, and the saturated groundwater zone] is striking, and far more emphatic than in the previous major assessment by the group (National Research Council 1993). In order to better understand biogeochemical processes active in the Critical Zone, to assess human impacts there, and to help society adapt to the consequences of these impacts, soil science and the study of coastal zone processes were singled out as disciplines requiring greater attention and funding by the National Science Foundation's (NSF) Earth Science Division. The research direction and training priorities established in the 2001 report can be expected to guide funding decisions in the US Earth-science community during the coming decade.

Following up on the NAS National Research Council (2001) report, an NSF-sponsored workshop 'Frontiers in Exploration of the Critical Zone' (October 24–26 2005, University of Delaware) addressed four major questions (Brantley *et al.* 2006):

(1) How are the rates of physical and chemical weathering perturbed by environmental forcing?
(2) How do important biogeochemical processes occurring at Critical Zone interfaces govern long-term sustainability of soil and water resources?
(3) How do processes in the Critical Zone nourish ecosystems and how do they respond to changes in external forcing?
(4) What processes in the Critical Zone control biosphere atmosphere exchanges of atmospherically important gases and particulates?

A proposal from a team of soil scientists and geologists (the Weathering System Science Consortium; http://www.wssc.psu.edu/) is already in place to study the Earth's weathering engine (Anderson *et al.* 2004). The plan calls for establishment of three highly instrumented 'node' field sites to study weathering at the soil profile- and catchment-scales, and a broader network of 'backbone' soil sites across a range of lithologies, ecosystems and topographies; data from these sites will be used in development of models to interpret weathering systems.

A recognition of the importance of soils is not limited to the basic science community. Geologists and engineers are increasingly dealing with soil-contamination clean-ups and wetland delineation. Demand for housing and commercial space in the United States has led to the rapid expansion of suburban communities in areas beyond the reach of existing sewer systems. More than 37% of new development in the United States uses on-site wastewater disposal systems (Dix 2001). This has created an increasing need for expertise in soil suitability for the safe disposal of wastewater using septic fields and alternative technologies. Environmental health specialists, engineers and geologists who are called upon to make these siting decisions look to soil scientists for guidance on issues such as soil structure and redox status as indicators of suitable soils. In assessing the long-term fate of contaminants in mine and mill tailings, soil-forming processes provide a scientific framework. For example, a knowledge of the similarities between acid sulphate soils and pyritic tailings can aid in the management of each. As the mission of geoscience agencies shifts from classical geological projects (mineral resource assessments, bedrock mapping, palaeontology) to environmental issues focused on the surficial environment (water quality, land-use planning, remedial action at contaminated sites), hiring of soil scientists and providing mid-career training in soil science to the existing workforce can add a necessary component of expertise in multidisciplinary environmental investigations.

K-12 education

Although the thrust of this paper is on the need for integrated soil science and geology education in colleges and universities, the underpinning of these undergraduate and graduate programmes is Earth-science education at the kindergarten to high-school level (grades K-12). At present (2001 statistics), less than 7% of the high-school students (grades 9–12; ages 14–17 yr) in the United States will take a class in Earth and space science (Ridky 2002). This is a steep decline from the 26% figure in 1968 (Earth Science Curriculum Project 1969). The decline mirrors a general drop in science literacy in American society, and presents a challenge for recruiting the next generation of Earth scientists. New national education standards for K-12 do, however, call for training in Earth and space science. In Virginia, for example, fourth-grade students are now taught soil formation, soil horizons and soil properties (colour, texture, structure and moisture-holding capacity). Geochemical cycles are taught in grades 9–12 (National Research Council 1996).

There are other bright spots in the K-12 picture. Recent efforts to improve the teaching of soils at the middle-school level (grades 6–8; ages 11–13 yr) have been undertaken by the American Geological Institute as part of its enquiry-based Investigating Earth Systems curriculum (http://www.agiweb.org/education/ies/soils/index.html. NASA soil scientist Elissa Levine hosts a comprehensive K-12 soil-science education home page (part of NASA's GLOBE Program) at http://www.globe.gov/fsl/welcome.html. Among the topics included are ion exchange, thin sections, soil monoliths and soil characterization. Interest in stimulating K-12 interest in soils is also apparent in other nations. For example, G. V. Dobrovol'skii and colleagues at Moscow State University have chronicled the teaching of soil science in Russian primary and secondary schools, and the availability of texts from the early twentieth century to the present (Dobrovol'skii *et al.* 2002).

With the support of the Soil Science Society of America, a major exhibit on soils at the Smithsonian Institution's National Museum of Natural History in Washington, DC is in preparation (http://www.soils.org/smithsonian). This is the most-visited museum in the world, with six to nine million visitors annually. The soils exhibit will complement existing Earth-science halls devoted to fossils and minerals (including the very popular display of the Hope Diamond), and an insect zoo with termite and ant mounds. Tentative topics for the soils exhibit include the role of soil in the environment; food and medicine from soils; soils in cultural history; and careers in soil science. This exhibit and its potentially huge audience represent an unprecedented opportunity to reach a large number of students with the message: Soils Sustain Life. Smaller outreach and educational efforts, prepared by individuals and teams of soil scientists in various states, include a 'living soil tunnel' – a trailer unit taken to schools, and soil-pit demonstrations for grade-school students (grades K-5; age 5–10 yr).

College and university level

Introductory geology classes and textbooks must cover a wide range of topics. Soils and weathering generally receive one-chapter treatment. The focus in most introductory texts is on the soil profile. The modern system of soil classification used in the United States is often ignored in favor of the old 'podsol–pedalfer–pedocal–laterite' system. The new system, with its 11 soil orders, is an elegant scheme, developed over several decades, based on observable and measurable soil features, and using nomenclature with information-filled prefixes and suffixes. Its inclusion in introductory geology classes will fill an obvious gap. For supplementary topics in upper division courses (years 3 and 4 of 4 yr undergraduate curriculum), instructors should consider including material on the dynamic properties of soils – e.g. discussions in geochemistry classes of ion exchange and nutrient cycling, and discussions in hydrogeology classes of shrink–swell behaviour and water movement. Suggested topics for inclusion in undergraduate geology courses are given in Table 1.

Introductory and, in some cases, advanced soil-science classes are presently taught in a rapidly expanding number of geography and Earth- and environmental-science departments in the United States. Cross-training across traditional academic boundaries is growing. Among the geology faculty at a variety of institutions, one now sees soil scientists, or geologists with graduate or post-doctoral training in soil science, in a variety of new faculty positions targeting surficial processes. These trends are also apparent in graduate student-, post-doctoral- and research-support staff recruitment and hiring.

Cross-disciplinary training and hiring is a reality for soil scientists, as well as for geologists. For example, the undergraduate soil-science programme at Pennsylvania State University now requires a course in hydrogeology. Students from soil science with interests in palaeosols and saturated zone hydrology may opt for graduate training in geology departments. Tackling groundwater vulnerability, soil contamination, land-use and other issues dealt with by regulatory agencies and environmental consulting companies requires a breadth of Earth-science expertise. As a result, employment opportunities for students with cross-disciplinary training in soils and geology can be expected to grow in coming years.

In the United States, advanced undergraduates in geology and other fields wishing to explore career options in soil science can get research experience as summer interns at Washington State University, Pennsylvania State University and the University of California at

Table 1. *Possible soils topics for inclusion in undergraduate geology courses*

Ion exchange, and origin of permanent and pH-dependent charges on minerals
Concept of bioavailable nutrients. Use of plant-available soil-testing procedures and other selective extraction procedures (in contrast to total-element measurements)
Bulk density, soil structure and their effects on water flow
Soil (and rock) colour description using the Munsell charts. Use of soil colour to identify redox conditions in soil profiles, and implications for land-use management
Concepts of plant-available water, water-holding capacity and use of the soil-moisture retention curve to calculate available water
Five factors of soil formation
Soil taxonomy; its nomenclature and diagnostic criteria
Soil micromorphology, and use of soil thin-sections (Stoops 2003; accompanying CD contains hundreds of thin-section images)
Indices of soil quality
Role of micro-organisms in cycling of carbon, nitrogen, sulphur and iron
Examination of soil and rock materials in criminal investigations (Murray & Tedrow 1975; Murray 2004)

Davis under the NSF-funded Integrative Graduate Education, Research, and Training (IGERT) programme. The IGERT centres are also bringing geology and soil-science faculty, post-docs, and graduate students together on research projects dealing with biogeochemistry, surface and colloid chemistry, biodegradation of soil contaminants, and soil-water movement. The IGERT programme is expanding to other campuses.

In Europe, similar interactions across Earth- and environmental-science disciplines are made available for doctoral students by the EU Marie Curie Training Sites Programme (MCTS). Among those programmes with research opportunities in soil science are the MCTS Postgraduate Centre for Biogeochemistry at the University of Newcastle upon Tyne (http://www.ceg.ncl.ac.uk/mariecurie/mariecurie1.htm), and the Chemical Speciation, Biological Availability and Ecotoxicological Effects of Contaminants in Soil and Water MCTS of the Netherlands Research School for the Socio Economic and Natural Sciences of the Environment (SENSE), a consortium of environmental research groups at seven Dutch universities (including the soil-quality group at Wageningen University and Research Centre) (http://www.sense.nl/MCTS).

Maintaining enrolment of students majoring in soil science and geology is a challenge at many American colleges and universities. With declining student numbers and shrinking budgets, as well as proactive steps toward intellectual integration, have come moves to consolidate departments and to change their focus. These transformations within academic institutions are not unique to our science, or to our era. To use the language of the business world, one sees 'morphing and reinvention' (e.g. in 2004, the Department of Wood and Paper Science at the University of Minnesota became the Department of Bio-based Products) to meet perceived changes in the scope of the field. Mergers and acquisitions represent another restructuring strategy; e.g. in 1975, the Department of Soils and Plant Nutrition at the University of California at Davis merged with the Department of Water Science and Engineering, and with the Atmospheric Science programme of the Department of Agricultural Engineering, to become the Department of Land, Air and Water Resources. At the University of Maryland, soil science, plant sciences, and landscape architecture are now all housed under the umbrella of the Department of Natural Resource Sciences and Landscape Architecture. These examples, far from being isolated anecdotes, represent the main trend. Nevertheless, counter-examples exist. For example, at the University of Maryland, the geology and agronomy faculties (now in separate departments and colleges) were in the same department until 1973 (Robert Ridky, pers. comm. 2002).

Although transformations of organizational boundaries are traumatic, one side-benefit of mergers may be enhanced interdisciplinary teaching and research – including those across the soil-science–geology interface. Likewise, it should be noted that the evolution or restructuring of classical geology departments into departments with a broader environmental geoscience orientation is not without peril. The preservation of the core geology base should be a guiding principle in such actions, in order to yield graduates able to pursue more traditional geoscience career paths (e.g. within the petroleum and mining industries), as well as those seeking employment in government agencies, non-profit organizations, and commercial enterprises with a more integrated geoscience approach. The same can be said of classical soil-science departments and their need to preserve core strengths in soil fertility and plant nutrition, and other areas not closely allied with the environmental geoscience interface.

Recruitment of new soil scientists is a continuing concern, especially now with a large wave of retirements anticipated in the next decade. While the 'big three' sciences (biology, chemistry, physics) have prominence in the high-school curriculum, subspecialty sciences such as soil science do not have such exposure. What mechanisms are most effective in providing career information to high-school and undergraduate students? Little research seems to have been done in this area. Older approaches, such as career brochures and limited outreach programmes, may not be the most effective route in the present, web-dominated information age. The same holds true for other subspecialty sciences such as entomology and plant pathology. Recruitment of new talent is critical to the future problem-solving needs of society.

Professional society activities

The Soil Science Society of America (SSSA) is the major soil-science professional society in the United States, with some 5700 members. In 1993, SSSA became a member of the American Geological Institute, which is a federation of 43 geoscience societies. The place of soil science in the greater Earth-science community has been greatly enhanced by this affiliation. The SSSA has an outreach programme whose goals are to spread soil-science knowledge to other fields of science, and to heighten the awareness of soil science as an Earth-science discipline. Its sponsorship of a 2001 workshop aimed at promotion of soil-science training in the undergraduate geology curriculum at non-land-grant colleges and universities was a recent step in that direction. A landmark event will occur in 2008, when SSSA and the Geological Society of America (GSA) will hold a joint annual meeting. Among the existing co-operative efforts of SSSA and GSA is publication of the *Vadose Zone Journal*, and co-sponsorship of the new biogeosciences website (http://www.biogeosciences.org/). Other Earth-science professional societies in which a good mix of soil scientists and geologists exists include the Friends of the Pleistocene, the Hydrology Section of the American Geophysical Union, and the Clay Minerals Society. Informal, one-on-one interactions within these societies have had a major role in helping to integrate the disciplines.

As exemplified by this book, the 32nd International Geological Congress in Florence in 2004 had a strong soil-science presence. Integration at the international level has continued at the International Union of Soil Sciences-sponsored 18th World Congress of Soil Science in Philadelphia in 2006 (http://www.18wcss.org/). Symposia included:

(1) soil geochemical patterns at the regional, national, and international scales;
(2) arid soils: genesis, geomorphology and geoarchaeology;
(3) soils on limestones: their properties genesis and role in human societies;
(4) imprint of environmental change on palaeosols;
(5) soil mineralogy and geophysics: environmental and soils management and mineral exploration; and
(6) soils and natural hazards.

The path forward

In the late 1880s and early 1890s, John Wesley Powell, the second director of the USGS and a strong supporter of soil surveys, pressed to have the agency moved from the Department of the Interior to the newly formed Department of Agriculture (Amundson & Yaalon 1995). Such were the ties between geology and soil science a century ago. We are now at another interesting crossroads. The modern societal and scientific perception of soils has been extended beyond soil as solely a medium for plant growth. Soil is now also viewed as a natural body, a structural mantle, a water-transmitting mantle and an ecosystem component (Smith & Hudson 2002). Clear links exist from these perspectives of soils to geography, geomorphology, engineering geology, hydrology and hydrogeology, and biogeochemistry. This is an exciting time to be working at the soil science/geology interface. Hydrogeologists are investigating macropore flow, a phenomenon first studied by soil physicists, as a possible aquifer-recharge mechanism in semi-arid regions (Wood *et al.* 1997). At the same time, we have soil scientists using acoustic bathymetry data collected by the National Oceanic and Atmospheric Administration to help map subaqueous soils (Bradley & Stolt 2002).

Within the geological and geographical sciences, there has been a recent emergence of many subspecialty and hybrid fields, in which a knowledge of the properties and behaviour of soils, and an appreciation of their spatial heterogeneity and temporal dynamics is critical. These include:

Ecohydrology – the study of plant–water interactions; of the effects of hydrological processes on the distribution, structure, and function of ecosystems; and of the effect of biological processes on components of the hydrological cycle (Eagleson 2002; Newman *et al.* 2003).

Ethnopedology – the study of the perception, classification, appraisal, use and management of soils by indigenous people (WinklerPrins & Sandor 2003).

Hydrogeophysics – the application of geophysical techniques for hydrogeological characterization of the shallow subsurface (Hubbard & Rubin 2002; Müller 2003).

Hydropedology – the bridging of traditional pedology with hydrology, geostatistics and soil physics for application in soil-landscape modelling (Lin 2003).

Nanogeoscience – the study of geological processes (typically near-surface) involving particles smaller than 100 nanometres (National Science Foundation 2002).

Neogeomorphology – the study of the change of the Earth's surface as a result of human activity (Haff 2002).

While today there are many cross-cutting issues in geology and soil science – such as carbon sequestration, water quality and vadose-zone hydrology and contamination – there are also differences in perception, training and institutional affiliations that tend to keep the disciplines and individual geologists and soil scientists apart. The realities of dealing with complex environmental problems, and the actions of scientific advisory groups and professional societies, are helping to bridge these gaps. Exposure of geology undergraduate students to an in-depth examination of the nature and properties of soils will be of benefit to their professional development and later work experience. Graduate training in a soil-science department should be viewed as a viable option for undergraduate geology students with interests in the surficial environment, and as a continuum of their development as geoscientists. Soil-science departments offer unique opportunities for training, with a disciplinary depth not generally available elsewhere, in pedology, soil physics, soil chemistry and mineralogy, and soil microbiology.

The views expressed here are those of the author, and do not reflect official policy of the US Geological Survey. This paper is updated and adapted from an earlier journal article: Landa, E. R. 2004. Soil science and geology: connects, disconnects and new opportunities in geoscience education. *Journal of Geoscience Education*, **52**, 191–196. The permission of the Journal of Geoscience Education for its usage here is gratefully acknowledged. Robert Ridky, Educational Coordinator for the USGS, provided useful dialogue and much appreciated encouragement. Any use of trade, product or firm names in this report is for descriptive purposes only and does not imply endorsement by the US government.

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