Introduction: Unlocking 3D earth systems—Harnessing new digital technologies to revolutionize multi-scale geological models

Driven by the popularity of easily accessible desktop tools such as Google Earth and in-car satellite navigation systems, we are currently experiencing a global geospatial revolution. In parallel, many areas of geoscience now currently routinely use geographic information systems (GIS) software and geospatial data for the visualization and analysis of spatial data. Recent related developments in digital technologies are also heralding significant changes in the way we acquire, visualize, and analyze geological field data. These new methods have the potential to improve the geospatial analysis of earth systems, comparable to the way in which advances in geochronologic and chronostratigraphic methods have increased our temporal constraints. A GSA Penrose Conference held in Durham, UK, in September 2006, brought together about 50 delegates whose contributions provided a detailed view of a wide variety of digital field technologies, and showed the current state-of-the-art in the application of geospatial methods across many diverse branches of geoscience (McCaffrey et al., 2007). This *Geosphere* themed issue contains a number of papers based on contributions made at the conference. A field excursion held in conjunction with the conference was a catalyst not only for "on-the-outcrop" discussion, but also an opportunity for acquisition of data that appears in two of the papers presented here (e.g., Bond et al.).

Geospatial data has long been available from global to regional scales, but the advent of portable, field-based hardware has introduced the ability to routinely analyze outcrop-scale geospatial data. Most of the contributions in this volume are primarily concerned with data at the outcrop scale, corresponding more closely to the scales of observation typically associated with traditional geological field mapping. Consequently, several of the papers address different facets of terrestrial laser scanning (mobile ground-based lidar), since this is proving to be a powerful, rapid and versatile method of acquiring a very detailed, precise 3D image of the surface of the outcrop. Other technologies for data acquisition covered in this volume also include differential Global Positioning Systems (Fiore et al.), digital photogrammetry, laser rangefinders, and remote imagery (Martin and Stofan). Collectively, the technologies discussed here have effectively eliminated the scale gap that used to exist between remote sensing methods (by definition, these previously precluded contact with the outcrop) and basic field geology (McCaffrey et al., 2006.) Importantly, the new digital methods are *not* a substitute or replacement for careful observations and geological interpretations made on the outcrop; rather, the papers presented here show ways in which the new technologies can provide a significant enhancement when integrated with a traditional field-based approach. Furthermore, McCaffrey et al. and Whitmeyer et al. show how the new methodologies, including 3D visualization, can also greatly enhance teaching of earth systems.

A fundamental advantage of digital acquisition methods is that observations and data can be precisely georeferenced, which is a prerequisite for modern 2D and 3D spatial analysis. A group of papers in this volume help to emphasize that the new technologies have widespread use beyond the creation of photo-realistic virtual copies of real-world outcrops. These examples show how spatially referenced data can be used as the basis for detailed quantitative analysis of specific geological attributes. Fiore et al. use detailed measurements of folded layers to test the geospatial relationship between fold geometry and fracturing. Wawrzyniec et al. use terrestrial laser scanning (TLS) of landforms to quantify rates of erosion. Labourdette and Jones also use TLS to derive lateral and vertical facies variations and changes in channel morphology. Quantitative parameters such as these are invaluable in providing well constrained input for modeling of the subsurface (Paton et al.; Venteris), and are of major importance in reservoir modeling in the hydrocarbon industry (Enge et al.).

The breadth of contributions at the conference suggests that the directions of future development in geospatial technologies will be many and varied. One urgent requirement is to increase the size of models that can be rendered in real-time in a visualization system. An important approach to this is to optimize the way in which large point-cloud data sets are filtered and meshed. Bonnaffe et al. document a method to overcome the problem of meshing those parts of a surface that are significantly oblique to the orientation of data acquisition. Another area of future development in airborne and mobile ground-based lidar involves multi-spectral analysis using lasers of different wavelength and/or different types of detection equipment. Bellian et al. explore the potential that this approach can offer. Martin and Stofan extend the reach of digital technologies beyond earth systems to show the applicability of these methods to the study of planetary geology.

Quantification of error and documentation of uncertainty are of fundamental importance, but have not always been readily addressed during traditional field studies. Bond et al. show that digital technologies can help to quantify spatial error, although this also highlights the ongoing difficulty in expressing and visualizing the uncertainties associated with the processes of geological interpretation. One of the main conclusions at the Penrose Conference was that quantifying uncertainty remains one of the major challenges facing both academic and industrial geoscientists today.

TERMINOLOGY, DEFINITIONS, AND ACRONYMS

Most of the digital technologies addressed here have their origins in the surveying, engineering and geomatics industries, and have subsequently been adopted in an ad hoc way by many different branches of science and technology. Because of this, it is perhaps not surprising that there is some ambiguity in terminology and inconsistency in usage of a number of common terms. For the sake of clarification, we have adopted the following definitions.

The term lidar (also Lidar, LiDAR, LIDAR) is an informal acronym used to denote "light detection and ranging." Although use of the term can be found in relation to a number of contrasting types of instrument (including equipment to measure aerosols and particles in fluids such as air and water), within the context of this themed issue, lidar always implies a laser scanning survey instrument used to survey a topographic surface. Lidar equipment has been successfully mounted and used in a variety of different vehicles and vessels, from satellites to motor vehicles, but

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unless there is a clear statement to the contrary, airborne lidar systems are mounted in a plane or helicopter, whereas mobile ground-based lidar systems are mounted on a surveying tripod. Also, laser scanning is taken to be synonymous with lidar. Terrestrial laser scanning and terrestrial lidar scanning are both initialized to TLS, and are equivalent to ground-based lidar. ALS is airborne laser/lidar scanning. Depending on the grammatical context, the acronyms TLS and ALS can denote the instrument (i.e., scanner), the verb (i.e., scanning) or the data collected (i.e., the scan).

THE DIMENSIONALITY OF GEOSPATIAL DATA

One topic that generated considerable debate at the Penrose Conference concerned the dimensionality of geospatial data, particularly in relation to the most appropriate way to describe the nature of detailed outcrop data sets, such as those acquired with terrestrial lidar. A number of delegates expounded clear and forthright views on this subject, and some expressed an opinion that the matter was too obvious to warrant further discussion. However, a number of views, though firmly held, appeared to be conflicting. The underlying problem is that new digital technologies have sometimes blurred the boundaries of definitions that were originally developed and used by traditional field geologists. Although these issues are largely just a question of semantics, there is an advantage in aiming to have a consistent nomenclature, and because of this we look at the issue of dimensionality in more depth in a separate discussion article. However, we do note that most pixel or raster based approaches to geospatial analysis are generally considered to be 2.5D (Bonham-Carter, 1994) meaning that the data (z) varies as a function of its position within a regular x-y grid. In most cases, z is elevation, but it could be any other spatial attribute (e.g., chemical concentration, slope, etc.). This is particular meaningful because virtually all commercially and publicly available geographic information systems software cannot accept an image or data file where a single x-y pair has more than one z value. This limitation precludes the use of these software packages to process mobile ground-based scanner data or model the full 3D nature of many real examples and is largely due to the limited computational power most users have in processing data in a full 3D, or voxel file structure.

LOOKING FORWARD

Digital field technologies are revolutionizing geoscience. An unprecedented quality and richness of data can now be gathered from the outcrop, through a combination of rapid and precise acquisition of georeferenced data, efficient data integration, 3D visualization, and geospatial analysis. Presentations at the Penrose Conference, and papers in this *Geosphere* themed issue, illustrate the impact that these developments have already had upon quantitative research into earth processes, geological modeling, geoscience education, and commercial activities including hydrocarbon exploration.

Inevitably, digital technologies develop rapidly. We hope this snapshot of the current state-of-the-art as recorded by the following papers will rapidly become obsolete. Future conferences are already being planned to address continued progress; join the GEOMOD-LIDAR-L and LIDAR listservs to keep updated on these and other developments. (Sign-up information for these listservs can be found via Google search by entering keywords "GEOMOD LIDAR UNM" and "ASU LIDAR.")

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Tim F. Wawrzyniec
UNM Lidar Lab, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 89131, USA

Richard R. Jones
Geospatial Research Ltd., Earth Sciences, University of Durham, Durham DH1 3LE, UK

Ken McCaffrey
Jonathan Imber
Reactivation Research Group, Earth Sciences, University of Durham, Durham DH1 3LE, UK

Nick Holliman
e-Science Institute, University of Durham, Durham DH1 3LE, UK

Robert E. Holdsworth
Reactivation Research Group, Earth Sciences, University of Durham, Durham DH1 3LE, UK