

The basics of systems geology

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Definitions for systems geology

What are systems and systems geology?

A system is a set of interacting parts that function as a whole. The systems view involves methodical study of the linkages or interfaces between the component parts. A systems approach may be appropriate for much of the systematic collection of regional geological data and its coordination, interpretation and dissemination as undertaken by geological survey organisations world-wide. Systems geology is seen as a systems view of geology re-based on the cyberinfrastructure, embedding geology as a subsystem in the systems approach to global knowledge.

What is the system approach to global knowledge?

E-scientists have set out a clear vision of a comprehensive knowledge system supported by the evolving cyberinfrastructure of computing, communication and information technologies (Foster and Kesselman, 2003¹, De Roure et al., 2005², Bizer et al., 2009³). Their vision opens the prospect of a structure of shared systems for extensive areas of science. Each system can be studied as a set of interacting parts that function as a whole, including the linkages or interfaces among its components and their context. Developments, such as cloud computing, apps, and personal technology, have built on and extended (but do not displace) the vision, and emphasise the need to provide flexibility in presentation.

What is the cyberinfrastructure?

Advances in e-science and the technologies of information, computing and communication are creating the so-called advanced cyberinfrastructure⁴, which along with geoinformatics⁵, can provide geologists with better ways to obtain, process, interpret and communicate their knowledge. It can represent their thinking more fully and extend their understanding, notably by supporting the systems view. It can make the various techniques of geoinformatics available for more systematic geological investigation, exploiting the synergy of mutually reinforcing methods.

What are the objectives of the systems approach?

The target is a comprehensive system where all component parts work together – with one another and with the wider systems in which they are embedded. It should help to overcome inappropriate barriers between types of information, and between regions, disciplines, and organisations. Objectives are to provide users with more powerful scientific methods, more comprehensive information resources, and rapid delivery of information to meet user requirements for relevance and presentation.

¹ Foster, I., Kesselman, C. (eds), 2003. *The Grid: Blueprint for a new computing infrastructure*, 2nd ed. Morgan Kaufmann, San Francisco. 748pp.

² De Roure, D., Jennings, N. R. and Shadbolt, N. R., 2005. The Semantic Grid: Past, Present and Future. *Proceedings of the IEEE*, 93 (3). pp. 669-681. <http://eprints.ecs.soton.ac.uk/9976/>

³Bizer, C., Heath, T., Berners-Lee, T., 2009. Linked data – the story so far. *International Journal on Semantic Web and Information Systems (IJSWIS)*, 5(3), 1-22. DOI: 10.4018/ijswis.2009070101. <http://tomheath.com/papers/bizer-heath-berners-lee-ijswis-linked-data.pdf>

⁴ Cyberinfrastructure: An integrated assemblage of computing, information and communication facilities, deploying the combined capacity of multiple sites to provide a framework to underpin research and discovery, typically with broad access and end-to-end coordination.

⁵ Geoinformatics: The application of information science and technology to geography and geoscience. Sinha et al. 2010: “an informatics framework for the discovery of new knowledge through integration and analysis of Earth science data and applications”.

What is the role of Geological Surveys?

Geological survey organisations world-wide provide a consistent authoritative view of core elements of regional geoscience, generally by means of published maps and accompanying accounts of the near-surface geology. They provide a consistent information base that underpins their impartial advice and avoids needless duplication of effort in a wide range of specific investigations. Surveys worldwide help to maintain and implement shared standards in areas such as stratigraphical, lithological and palaeontological classification and nomenclature, and ontologies⁶ and formats for information exchange. They are well placed for developing systems geology to meet customer expectations for this subsystem of the wider information system.

What is a solid Earth systems model?

A 'solid Earth systems model (sEsm)⁷' was proposed by Loudon (2011⁸, page 71) as a framework⁹ to provide an integrated systems¹⁰ approach to some aspects of regional geology. It considers procedures for collecting, organising, integrating and sharing geoscience information, linked to requirements specified in the business model and to the facilities of the infrastructure, consistent with the e-science vision of linked data. Its aim is to clarify the possibilities and benefits of a comprehensive structure for representing some aspects of information on the solid Earth, in which relevant knowledge can be integrated as a shared, coherent, predictive system, where like can be compared with like and quantitative relationships assessed. As future developments are unknown, the proposals refer to a scenario – a description of a plausible, though uncertain, outcome – open to discussion, criticism and improvement, and helping to identify appropriate priorities and technologies.

⁶ Ontology: A formal representation describing concepts, entities and relationships in a domain of knowledge, typically providing a more detailed and rigorous machine-readable specification than a thesaurus or taxonomy.

⁷ Solid Earth systems model (sEsm): An approach to structuring distributed knowledge of the science of geology to provide an integrated view in the context of sciences of the solid Earth as a whole. A model of the systems of the solid Earth, organised within a framework or metamodel that depicts and clarifies the principal relationships among the findings of geology, providing a multidimensional map to locate and connect ideas, concepts, workflows of investigation and threads of reasoning. The content of the model is distributed information referring to: the three-dimensional disposition and configuration of the present-day observable objects of the solid Earth (where things are and how they are arranged); their observed and interpreted properties, composition and relationships, at all scales; geological processes and the outcomes of their interactions with configurations of objects; events and historical changes throughout geological time.

⁸ Loudon, T.V., 2011. A Scenario for Systems Geology: suggestions concerning the emerging geoscience knowledge system and the future geological map. *BGS Research Report RR/11/05*. <http://www.bgs.ac.uk/systemsgeology/scenario.pdf>

⁹ Framework: A logical structure and guidelines giving a broad overview for classifying and organizing complex information, within which detail can be added as required.

¹⁰ Systems geology: A view of geology re-based on the developing cyberinfrastructure and regarded as a system (a set of interacting parts that function as a whole) embedded in the wider knowledge system.

Benefits of systems geology

Why is the conventional approach inadequate?

When they investigate a new area, geologists claim to take into account all that they know about the geology (see, for example, Harrison, 1963¹¹), in effect taking a systems view. However, the extent to which this knowledge can be communicated is limited by the methods of representation, thereby constraining working procedures and thought patterns. Limitations (which systems geology can overcome) of conventional pre-digital methods for representing the results of geological surveying include the following:

1. A single view of the same geology is inconveniently separated into different documents such as maps, map explanations and scientific papers.
2. Each document is self-contained, published independently, and revised irregularly and infrequently.
3. The edges of map sheets are unrelated to the geology.
4. The maps are two-dimensional, the geology is not.
5. The map scales are fixed, thereby inhibiting the study in scale-space¹² of geological processes and their outcomes.
6. The ability to show detail is uniform throughout a map sheet, although the geological complexity and evidence are frequently concentrated in small areas at any scale.
7. The positions and shapes of lines that represent geological boundaries on the map are influenced by insights and rules of thumb that are seldom communicated to the end-user.
8. Each accompanying memoir or paper is a single linear narrative, whereas the underlying geological thinking can be more appropriately represented as a highly interconnected, scalable network of theories, observations, and hypothetical deductions and reconstructions, where readers can follow signposts directing them along the paths of their own interests.
9. The workflows of investigations, video on-site demonstrations and detailed outcrop photography (think Google Street) and sketches of key points, samples and specimens, could clarify the surveyors' evidence and reasoning, but are not feasible with conventional publication.

¹¹ Harrison, J.M., 1963. Nature and significance of geological maps, in Albritton, C.C. (editor), 1963. *The fabric of geology*. Freeman, Cooper & Co, Stanford, pp. 225-232.

¹² Scale-space: In Geographic Information Systems and maps, scale is the ratio of the distance between two points on a map or image to the corresponding distance on the ground. In the study of scale-space, however, scale may refer to the level of detail detected by eye or instrument across a range of scale from the finest detail discriminated, to the entire image or area of interest. Scale-space theory regards this range as a multi-resolution continuum, zooming in or out to increase or reduce the amount of detail using a filtering process. It studies the range of scales over which types of object and geological processes exist and operate.

Why consider systems geology?

The benefits potentially include:

1. Systems geology can represent geology as a holistic¹³, object-oriented¹⁴, system, forming an important component of Earth systems science in the global knowledge system.
2. It can build on a systematic framework to collect, organise, exchange and integrate geological information, following shared standards to ensure wide compatibility.
3. It can accommodate a more extensive, accurate and comprehensive representation of geological thinking, integrated across information types, dimensions and levels of detail.
4. It can maintain comprehensively documented, evaluated, predictive geology, substantiated by records of investigational procedures and observational evidence.
5. Its contents can be kept up-to-date by revision of superseded modules and their links.
6. It can integrate methods to collect, filter¹⁵, analyse, interpolate¹⁶ and simulate¹⁷ data.
7. It can consolidate and integrate information across objectives, disciplines, organisations and geographical regions.
8. It can provide more flexible delivery, depiction and visualisation of information, selectable by users to match their specific needs.

Why is information architecture involved?

Information architecture is concerned with the representation, evaluation and evolution of information in an orderly, coherent structure that enables it to work for its designed purpose and meet user needs. The architecture is based on an infrastructure of widely accepted, flexible and reliable methods for acquiring, evaluating, storing, retrieving, and disseminating information, able to operate across geographical and disciplinary boundaries. Systems geology involves a radical change: from the familiar, conventional infrastructure to the rapidly evolving advanced cyber-infrastructure. To gain the full benefits, the information architecture must be redesigned, and explicitly described for criticism, improvement, and (in due course) implementation.

¹³ Holistic: A view of a system that emphasises its properties and interrelationships acting as a whole, as opposed to the reductionist approach of studying its components in isolation as distinct entities.

¹⁴ Object-oriented: An approach to analysis, design, and classification, which can support many aspects of thinking about objects (representations of real-world or conceptual things or entities of interest in a particular context) and their relationships including linking them along interweaving threads of thought.

¹⁵ Filtering: A process that selectively enhances or reduces specified components of the information stream.

¹⁶ Interpolation: The estimation of values, for example at a point or along a line or surface, in order to predict a value or complete a visualisation.

¹⁷ Simulation: Imitation of the operation of postulated processes in a system and their results; usually to visualise, statistically compare with, or predict real-world occurrences.

Methods in systems geology

How can we gain the benefits of systems geology?

The anticipated benefits stem from infrastructure developments, but must be based on a carefully planned strategy reflecting the needs of the geological community. Global geology can be understood in detail only because world-wide stratigraphical and mapping conventions are long-established and widely followed. Similarly, systems geology can make the relevant knowledge of geologists available throughout the emerging knowledge system only if an appropriate framework for geological systems is designed and implemented. The involvement of informed geologists in many countries, organisations and disciplines will be essential for the successful development of systems geology.

How are other disciplines responding to systems developments?

One recent implementation of the systems approach is the Physiome Project, which investigates the systems of the human body (Clapworthy et al., 2008¹⁸, Physiome Project, 2011¹⁹). Another is Systems Biology which investigates the interactions and dynamic structures of molecules, cells and organs in order to better understand life processes and complex diseases (BBSRC, 2007²⁰, European Science Foundation, 2007²¹, Anteneodo and Da Lux, 2010²²).

How are such global developments funded?

Much of the funding for systems development has come from the host organisations. However, significant costs arise from the need for international and interdisciplinary collaboration. The Physiome Project and Systems Biology each sought major funding from the European Commission. The UK National e-Science Centre (<http://www.nesc.ac.uk/nesc/>) also provides funds to support international collaboration.

How are Earth scientists responding to the systems view?

Within the Earth sciences, global systems models have been proposed or developed with particular reference to the atmosphere, hydrosphere, and some geophysical properties of the solid Earth (The Earth System Modeling Framework, 2011²³, Environmental Systems Science Centre, 2011²⁴). The question of whether there are universal mechanisms that unite phenomena across scales in fluid, solid and chemical mechanics, and whether this could improve understanding of complex processes in the Earth as a whole and the coupling between such processes, is discussed by Ord et al. (2010²⁵).

¹⁸ Clapworthy, G., Viceconti, V., Coveney, P.V., Kohl, P., 2008. Editorial. *Phil. Trans. R. Soc. A* 366, 2975-2978. doi: 10.1098/rsta.2008.0103 <http://rsta.royalsocietypublishing.org/content/366/1878/2975.full.pdf+html>

¹⁹ Physiome Project, 2009. <http://www.physiome.org>

²⁰ BBSRC, 2007. Systems biology (UK Biotechnical and Biological Sciences Research Council). <http://www.bbsrc.ac.uk/publications/corporate/systems-biology.aspx>

²¹ European Science Foundation, 2007. Systems Biology: A grand challenge for Europe. <http://www.esf.org/publications/medical-sciences.html>

²² Anteneodo, C., Da Lux, M.G.E. 2010. Complex dynamics of life at different scales: from genomic to global environmental issues. *Phil. Trans. R. Soc. A* vol. 368, no.1933, 5561-5568 doi: 10.1098/rsta.2010.0286 <http://rsta.royalsocietypublishing.org/content/368/1933/5561.abstract>

²³ Earth System Modeling Framework (ESMF), 2011. <http://www.earthsystemmodeling.org/>

²⁴ Environmental Systems Science Centre, 2011. <http://www.nerc-essc.ac.uk/index.php>

²⁵ Ord, A., Hunt, G.W., Hobbs, B.E., 2010. Patterns in our planet: defining new concepts for the application of multi-scale non-equilibrium thermodynamics to Earth-system science. *Phil. Trans. R. Soc. A*, **368**, 3-8.

How are Geological Surveys involved?

Geology is one small sub-system in a much larger knowledge system, and its system design must be a multidisciplinary, international endeavour. Geological Surveys are well placed, by their role in systematic survey and through long-established links to users and to their global counterparts, to contribute to a task that influences their own future and that of their science. In particular, Geological Survey maps provide a systematic core of geological information, much of which has been digitised and restructured.

How does the systems approach relate to existing geological knowledge?

The systems approach should offer a better match to patterns of geologists' thinking than is achieved by conventional documentation. However, most geological information is recorded in conventional forms. Much of this has already been digitised and reformatted, making it accessible from hyperlinks in a systems representation. Thus, systems modules derived from existing publications can (and should) link to their sources. Reconciliation and integration of information derived from many disparate sources requires a shared framework. It has been proposed, for example, that a systems approach to geology could be based around an explicit framework²⁶ of granularity (level of detail), geographical space and geological time. This could provide a structure for the representation, study and predictive interpolation of configurations (spatial arrangement, pattern, form and shape) of geological objects and processes and their interactions through geological time.

²⁶ Loudon, T.V. and Laxton, J.L., 2007. Steps towards Grid-based Geological Survey: suggestions for a systems framework of models, ontologies and workflows. *Geosphere*, 3(5), 319-336. <http://nora.nerc.ac.uk/1084/>

A time scale for systems geology

When will systems geology be in place?

Implementing systems geology is a process rather than an event. It can be argued that it started long ago and will proceed beyond predictable future developments. Nevertheless, for forward planning we must 'take a view' of the future, developing a basis for interoperability²⁷ of the mutually dependent components in the overall system. The cyber-infrastructure is bringing major changes, the course of its mainstream is clear, and its momentum implies that migration to future mainstream enhancements will be supported. A widely shared cyber-strategy for the geological component (incorporating systems concepts and information architecture) will encourage coordinated development, and deter repetition of effort and expensive back-tracking. As it will take some years to mature, an early start is essential.

When will comprehensive standards be defined?

Many aspects of geology can be brought together by the systems approach. This is more difficult (but may still be essential) where different studies originated within earlier, non-compatible contexts. A full understanding of the context of earlier work requires specialist knowledge (Gahegan, 2007²⁸). However, semantic links²⁹ (Berners-Lee et al., 2001³⁰), can help to clarify the differences between disparate information sources. They are, for example, one of the tools used by GEON³¹, an open collaborative project that is developing cyberinfrastructure for integration of 3 and 4 dimensional earth science data, facilitated by its OpenEarth Framework (OEF). Rigorous implementation of appropriate standards can assist in wider and more complete understanding, in particular for quantitative modelling and statistical analysis. Many standards (such as GeoSciML³²) are already defined and more will emerge as the work continues.

When should a cyber-strategy include systems and architecture?

The information architecture and systems geology are integral parts of a cyber-strategy. The development of each can be considered separately, but they are interdependent and their interactions must be kept in mind. Initially, a cyber-strategy³³ that describes how geologists and geological organisations plan to respond to the advancing infrastructure can consider systems geology only as a scenario³⁴, because of uncertainties in the path of future developments. An explicit

²⁷ Interoperability of information: The ability of concepts, terms or models from various sources to work together, by meeting standards that enable sharing and reuse of information.

²⁸ Gahegan, M., 2007. We can share our resources, but can we share our understanding? GEON Cyberinfrastructure Workshop, November 2007 http://www.geongrid.org/presentations/Gahegan_Understanding.ppt

²⁹ Semantic Web: Berners-Lee et al. (2001) described the Semantic Web as an extension woven into the structure of the existing Web, in which information is given well-defined meaning, improving the ability of computers and people to work in cooperation.

³⁰ Berners-Lee, T., Hendler, J. and Lassila, O., 2001 (May). The Semantic Web. *Scientific American*, **284** (3).

<http://www.scientificamerican.com/article.cfm?id=the-semantic-web>

³¹ GEON <http://www.geongrid.org/>

³² CGI (Commission for the Management and Application of Geoscience Information), 2009. GeoSciML. http://www.cgi-iugs.org/tech_collaboration/geosciml.html

³³ Cyber-strategy: A plan describing how organisations or individuals intend to respond to the current and future development of the cyberinfrastructure.

³⁴ Scenario: A description of a plausible, though uncertain, outcome.

scenario (such as Loudon, 2011³⁵) can be evaluated, and aspects can be discussed, criticised, amended, extended, adjusted and tested in pilot projects. It is therefore timely to consider a provisional cyber-strategy for systems geology and its information architecture. As it develops, a revised and improved scenario should help to define the objectives and guide the cyber-strategy for systems design (mapping a route to the evolving goal), its implementation (building the facilities to get there), and migration (moving relevant information).

When will the benefits of a cyber-strategy appear?

Decisions about some systems geology projects can be purely tactical, setting aside considerations of their long-term relevance as: not known, not tested, not relevant, or not important. Exploratory pilot studies may fall into this category, and are essential for understanding future possibilities. Alongside experimental investigations of geoinformatics techniques, development of a cyber-strategy is essential to ensure a viable, sustainable, comprehensive approach to systems development. It must be based on a clear identification of the objectives and priorities, taking full account of developments in the cyberinfrastructure. Just as the work of stratigraphic committees³⁶ in the 1970's led to a step change in the coordination of stratigraphic classification, terminology and procedure, so also a determined international, inter-disciplinary effort over the next few years could give a firm base for the global validity and acceptance of systems geology. Benefits should appear as the work progresses. Maintaining a coherent overview is essential, but the rate of progress will differ from topic to topic. Major developments, such as designing and building a solid Earth systems model, call for a strategic approach on which tactical projects can build. They must be integrated with the current development of the cyber-infrastructure and its applications. Long-term international and interdisciplinary collaboration can ensure that geology will take its place in the overall development. An initial step is to develop a clear vision for the future involvement of geology.

When will there be a coordinated view of systems geology?

The work of Geological Surveys involves much international collaboration and is directly concerned with a coordinated³⁷ authoritative account of regional geology – a central element of systems geology. Their work on modernising the geological map³⁸ has led to coordinated representations in Geographic Information Systems, presenting the user with a limited systems view. Around this core, other systems aspects can develop, such as: comprehensive, accessible databases of stratigraphical and geological time relationships³⁹; structured authoring of modular, explanatory text providing single sources for inclusion in many documents⁴⁰; and quantification, statistical analysis, and predictive process-based models of field observations. Current practice is the only basis from which future systems can evolve. The emerging systems must be capable of linking back to conventional representations, and highlighting discrepancies that require elucidation by the user. The rate of

³⁵ Loudon, T.V., 2011. A Scenario for Systems Geology: suggestions concerning the emerging geoscience knowledge system and the future geological map. *BGS Research Report RR/11/05*. <http://www.bgs.ac.uk/systemsgeology/scenario.pdf>

³⁶ Hedberg, H.D. (editor), 1976. *International stratigraphic guide: a guide to stratigraphic classification, terminology and procedure*. Wiley-Interscience, New York.

³⁷ OneGeology – Making geological map data for the Earth accessible. <http://www.onegeology.org/>

³⁸ BGS, 2011. UK Geology: applied geoscience, survey and research <http://bgs.ac.uk/research/UKGeology/>

³⁹ Chronos – Geologic time ... connects a wide variety of research endeavours... <http://www.chronos.org/>

⁴⁰ Information architecture for systems geology. <http://www.bgs.ac.uk/systemsgeology/architecture.pdf>

development of individual topics is unclear, but there is an urgent need to clarify strategic issues in order to reduce duplicated effort and later backtracking.

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- Physiome Project, 2009. <http://www.physiome.org>

Glossary

Cyberinfrastructure: An integrated assemblage of computing, information and communication facilities, deploying the combined capacity of multiple sites to provide a framework to underpin research and discovery, typically with broad access and end-to-end coordination.

Cyber-strategy: A plan describing how organisations or individuals intend to respond to the current and future development of the cyberinfrastructure.

Filtering: A process that selectively enhances or reduces specified components of the information stream.

Framework: A logical structure and guidelines giving a broad overview for classifying and organizing complex information, within which detail can be added as required.

Geoinformatics: The application of information science and technology to geography and geoscience. Sinha et al. 2010: "an informatics framework for the discovery of new knowledge through integration and analysis of Earth science data and applications".

Holistic: A view of a system that emphasises its properties and interrelationships acting as a whole, as opposed to the reductionist approach of studying its components in isolation as distinct entities.

Interoperability of information: The ability of concepts, terms or models from various sources to work together, by meeting standards that enable sharing and reuse of information.

Interpolation: The estimation of values, for example at a point or along a line or surface, in order to predict a value or complete a visualisation.

Object-oriented: An approach to analysis, design, and classification, which can support many aspects of thinking about objects (representations of real-world or conceptual things or entities of interest in a particular context) and their relationships including linking them along interweaving threads of thought.

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Scale-space: In Geographic Information Systems and maps, scale is the ratio of the distance between two points on a map or image to the corresponding distance on the ground. In the study of scale-space, however, scale may refer to the level of detail detected by eye or instrument across a range of scale from the finest detail discriminated, to the entire image or area of interest. Scale-space theory regards this range as a multi-resolution continuum, zooming in or out to increase or reduce the amount of detail using a filtering process. It studies the range of scales over which types of object and geological processes exist and operate.

Scenario: A description of a plausible, though uncertain, outcome.

Semantic Web: Berners-Lee et al. (2001) described the Semantic Web as an extension woven into the structure of the existing Web, in which information is given well-defined meaning, improving the ability of computers and people to work in cooperation.

Simulation: Imitation of the operation of postulated processes in a system and their results; usually to visualise, statistically compare with, or predict real-world occurrences.

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Systems geology: A view of geology re-based on the developing cyberinfrastructure and regarded as a system (a set of interacting parts that function as a whole) embedded in the wider knowledge system.