Nonlinearity and holism in geological systems – Some reflections

Ranen Sen and Saradindra Chakrabarti*

Geological science represents a nonlinear system with scaling properties. It embodies a 'system' because the features that it demonstrates are developed from a set of components/elements like the original materials, their composition, initial conditions, pressure, temperature, stress, strain, topological transformations, chemistry, materials transport, temporal factor, etc. that work together to bring about the 'whole'. We see the geological entity as a whole with its relationship to its environment.

Keywords: Geology, holism, nonlinear systems, scaling.

THE term 'systems' is often applied indiscriminately. People use 'systems' to cover a broad range of meanings, from anything that links up with something else, to a list of topics that all relate to computer, education and achieving change. This overgeneralization not only undermines the distinct power of 'systems', but also raises the question whether most people know what the word 'system' really means. The systems theory as mentioned above never made the leap into mainstream consciousness and thus became a lost art until now. The new age – the 'Systems Age' – has just begun. Today technology mainly focuses on systems linking and interface.

Concept

In geology or any other science and technology, when one component of a system changes, it affects many other systems components and may even alter the entire system. Similarly, when an entire system changes, it has a necessary effect on other systems, because there are points of relationship and interdependence that extend through and across systems and link them in various ways. Let us focus on the earth itself and consider the statement 'Geology of the earth is a chaotic mess of unrelated and isolated events and conditions'. Does this statement make sense? There is no unrelatedness and isolation in any geological event, say, the tsunami. The features in combination reflect a whole phenomenon – there is so much of interlinking and interdependency of components or elements. Structure cannot be isolated from petrology – mineralogy. Depositional environment and later temperature–pressure modifications play an important role as individual interlinked components. The time factor is also vital in the holistic scenario. It has been observed that the oldest rocks which have undergone intense tectonism and metamorphism through the longest period have become a cauldron of massive (used in the sense of quantity only) sulphides. Younger rocks may not show the same level of reserves. It is explicitly a difference of the systems matrix which deals with variations of interrelationships of processes and patterns.

A 'system' is a logical genus suitable to the treatment of wholes, where components or elements as in geological science are distributed in a dimensional domain. Dimensional domain is a necessary condition for both relationships and systems. In geology, the domain itself enters into the relationship. Moreover, the 'wholes' cannot be compared to additive aggregates. Summation does not play any part whatsoever in the formation of wholes. In a system, it is significant that the parts and their related characteristics fit into one whole. The system cannot be derived from the parts; the system is an independent framework in which the parts are placed. In a system, the members may, from the holistic viewpoint, not be significantly connected with each other, except with reference to the whole. For a geological region, petrology may not be individually directly interlinked to structure. But when we reflect on the total geological fabric, these two parts become significant in the way of interrelatedness and interdependency to unfold the pattern absorbed by the fabric.

The hierarchy of systems thus elucidates the interrelationship and interdependence of systems and the impact that systems have on one another. The hierarchy, therefore, validates the concept of 'systems within systems'. The 'whole' geological system will hence contain the sedimentary system, the petrological system, the structural system and the tectonic system. We begin to see how characteristic events belonging to systems are connected and we are forced to look holistically to comprehend the phenomenon and unroll the events in their togetherness.

The authors are in the Department of Applied Geology and Environmental System Management, Presidency College, Kolkata 700 073, India.
*For correspondence. (e-mail: ranensen@gmail.com)

Pagel, in one of his famous comments on nonlinearity in the 20th century, said that 'life is nonlinear and so is everything else of interest'.

All geological events are primarily nonlinear phenomena. If it were not nonlinear, we would have not observed variations in fold geometry pattern along the regional dip or strike. If it were linear, we would have always come across only one style of folding, say disharmonic folds in the region. There would have been no other fold patterns that could be observed in the said linear system.

Similarly, if we analyse waves, we find those with the profiles of solitary waves would disperse in the linear theory, but nonlinearity counterbalances the dispersion to produce waves of permanent shape. We introduce a nonlinear version of the Klein–Gordon equation (as it is simpler than the Koteweg–de Vries equation).

We take

$$\phi_{tt} - \phi_{xx} + v'(\phi) = 0, \qquad (1)$$

where $v'(\phi)$ is some reasonable nonlinear function of ϕ, which is chosen as the derivative of the potential energy $v(\phi)$. Equation (1) arises in a variety of situations. For example, with $v'(\phi) = \sin\phi$, we get clues to many natural phenomena.

Equation (1) also explains dislocations in crystals where the occurrence of $\sin\phi$ is due to the periodic structure of rows and atoms.

Nonlinearity is evolutionary, more so in crystallography. However, this evolution depends upon topology. Let us take the fluorite mineral from Amba Dongri, Gujarat. Usually the linear crystals contain various rare earths in the lattice rendering pink, violet, etc. to the mineral. However, molecular oxygen may create lattice defects (nonlinearity is discernible due to topological transformation) in the crystal and the absorption spectrum shows yellow. Thus fluorite presents a yellow colour due to nonlinearity in the crystal lattice (because of lattice distortion).

Matsumoto *et al.*[1] have reported on the crystallization and second and third order optical nonlinearity of GeO–SiO_2 glass poled with ArF laser irradiation. Their study suggests that the large second harmonic generation (SHG) in glass is not induced from inert second-order nonlinearity of the crystallites, but the main origin of the induction is the associated effective second-order nonlinearity with the formation of the space charge field. Thus nonlinearity is a general phenomenon of the universe from very small size to large scales of matter.

Nonlinearity is also the essence of the characteristics of metamorphic facies change. And in both cases we see the effectiveness of scaling (scaling pointing to a strict order and invariance under certain transformations of scales). It is of interest to know also that this phenomenon of metamorphic facies change also brings up the possibility of second-order phase change with its known characteristics, i.e. a continuous change of state but a discontinuous change of symmetry, symmetry increasing with temperature. Coal to diamond is a classic example of second-order phase change. Transition from muscovite schists to sillimanite schists depicts the same characteristics in metamorphic rocks.

When we attempt to uncover the geology of a particular space, the informal web of relationships that has integrated well and fits together in support of creating the holistic regional scenario must be elucidated. The word 'fit' is only applicable here in the sense that the basic purpose of these components is to work in conjunction with other components to help the specific region create a specific geological framework; without integration, and fit, the geological fabric would lack the synergy.

Let us now discuss the Bauxite deposit in Madhya Pradesh (MP). Gallium which is extracted throughout the world along with aluminium from the bauxite resources, is reportedly not present in an economically extractable quantity in these deposits. The bauxite ores here primarily are of low quality, since it is normally reported that higher the content of aluminium, more is the gallium (Al – atomic radius = 1.43 Å, Ga – atomic radius = 1.41 Å both crystallize in the cubic system; symmetrical and positively charged; Ga replaces Al by substitution). Al being low here, Ga is not generally enriched. This is why MP bauxites have no forward linkage to the Al production industry. However, the most interesting phenomena in MP is that most of the high-grade patches of bauxite in the region do not contain enough Ga for extraction. The question thus arises: why is Ga enrichment selective? Investigations have detailed the general geology, mineralogy, size and grade of the deposits, etc. along with the probable origin of bauxite. But since inter-linkage framework (i.e. systems framework) was not in the perspective, it was not investigated why some bauxites contain Ga, while some do not – a vivid example of nonlinearity. The pertinent questions are: (a) Wherefrom is Ga being transported here, and what could be the origin? (b) Is the Ga enrichment process a part of a continuous process or a specific process? (c) Is it related to any tectonic framework? (d) Detailed structural mineralogy has not been revealed and no model attempted to check how Ga could arrange itself in the crystal structure – could it be in camouflaged positions? (e) Is there any other chemical element present which may be economically exploited? (f) Do we know anything about the geological history and geochemistry?

We find that mutuality among the above elements/ components in the total system is not understood; thus even if the deposit is in the country, Japan imports it. MP is happy that their low quality bauxite is being exported, earning foreign exchange.

Geology must, therefore, be studied in an all-embracing approach so there is a realization of the synergy. A systems perspective is perhaps the modality to come to grips with.

Synthesis

Geology is a holistic study of the earth. It views the earth as a single (environmental) system consisting of lithosphere (including surficial processes), biosphere, hydrosphere and atmosphere with an evolutionary lifespan of 4 billion years. It is the cardinal science, not because of theoretical and experimental purity, but because only geology grapples with the full complexity of a world in which nothing exists in isolation – a world in which there are no independent variables – each one is interdependent and interrelated – a world of systems. Systems dynamics is all about relationships. From a geo-science perspective, questions concerning the earth and our relationships to it are not just about biology, chemistry or physics. Questions are about a biological perspective that sees life in the context of a long, complex evolutionary process that has both responded to changes in the earth and profoundly changed the earth. They are about understanding the responses of minerals, rocks and soils to ever-changing mechanical, thermal, hydrologic and atmospheric conditions. Geology has a systems framework of complete multidisciplinary and interdisciplinary integration of scientific knowledge that is essential to the geological perspective and geological thinking. Geology is not simply about the past, it is also about change and continuity. Most of all, it is about the long run. What society needs to learn from geology is that we cannot impose short-term thinking on long terms or adopt policies that do not recognize that the earth is embedded in an on-going evolutionary change. Understanding of geological systems is an antidote to the fragmented and piecemeal thinking that is specialist-centred thinking about the environment, our relationship with the earth and of science in general. The perspective inculcated by geological understanding is as rare as it is vitally necessary in our society. Earth's environment and man's relationship to those environments cannot be comprehended in isolation. Environmental conditions that exist today are embedded in and reflect processes that can only be understood at time spans extending far beyond the short window of human experience, far beyond experiments run under laboratory conditions and for time-spans that are geologically instantaneous. A geological perspective shows that the human influence is paltry compared to changes that the earth has experienced. Ignorance of a geological systems understanding vis-à-vis the earth leaves us without the knowledge or wisdom to know how to think. Geology tells us that geological processes like ecological processes are historical events; their magnitude, structure, cause and consequence have been and are highly variable. And they are nonlinear.

The issues facing human civilization require synthesis and systems thinking to know all the components – geological, biological, chemical and physical (which make the earth's environment), both ancient and modern. Likewise, the geological knowledge as applied to specific local geologic conditions is essential for those concerned with natural hazards, civil engineering problems, impacts of global change, responsible utilization of the earth's natural resources, pollution and waste disposal, environmental planning and monitoring. Theories or belief systems that do not recognize the earth as a complete integrated system can never adequately prepare the human species to responsibly interact with the earth.

Geology reminds us that we have to think in the long run about our conditions. We must develop the ability to evaluate earth processes with all its inter-linkages and at all scales of observation, from the microscopic to the global to those occurring from microseconds to billions of years and that range to every environmental extreme. Geology (vis-à-vis environment) is the discipline that is able to prepare people's minds to deal with these complexities, ambiguities and life-as-we-know-it threatening problems. Geology looks at the earth holistically enough to solve practical problems of resource and environmental management. Many heads of government, leaders of corporations, business managers and economic theorists have little understanding of how the earth operates or have a real understanding of the environmental issues we confront. All who have been educated need to think about problems from a holistic earth systems perspective, rather than the narrow parochialism of human-centred concerns.

1. Matsumoto, S., Fujiwara, T., Seno, Y., Hirose, Y., Ohama, M. and Ikushima, A. J., Crystallisation and optical nonlinearity in GeO–SiO_2 glass poled with ArF excimer-laser irradiation. *J. Appl. Phys.*, 2000, **88**, 6993–6996.
2. Haines, S. G., *Systems Thinking and Learning*, HRD Press, Mass, USA (printed in Canada), 1998, pp. 1–218.
3. Mandelbrot, B. B., *The Fractal Geometry of Nature* (updated and augmented), W.H. Freeman & Co, New York, 1977, pp. 1–468.

Received 19 January 2007; revised accepted 11 October 2007