Geoscience Canada

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Volume 11, numéro 3, september 1984

URI : https://id.erudit.org/iderudit/geocan11_3fea01

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Éditeur(s)

The Geological Association of Canada

ISSN

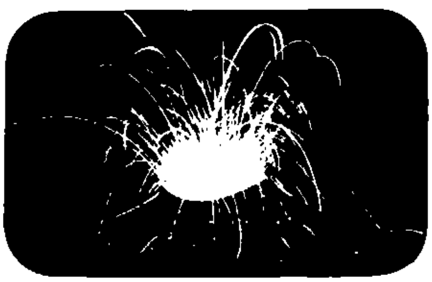
0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

Maill, A. D. (1984). Pyroclasts:: Basin Analysis: Is It Science? *Geoscience Canada*, *11*(3), 140–141.

Features



Pyroclasts

Basin Analysis: Is It Science?

A.D. Miall

Geologists have consistently displayed an inferiority complex about the value of geological data. For much of the late nineteenth century the teachings of uniformitarianism were in doubt because of Lord Kelvin's calculations about the earth's heat sources, which put serious constraints on the maximum possible age of the earth. Then radioactivity was discovered. More recently geologists resisted their own observations about the geological matches between now distant continents because geophysicists such as Harold Jeffrys said continental drift was impossible.

In our university curricula we insist that students majoring in geology take heavy doses of mathematics, physics and chemistry before they plunge into their courses in advanced geology. It is certainly the case that many areas of geology have become increasingly laboratory oriented. Petrologists need to know basic physical chemistry, structural geologists need to understand the physical properties of materials, paleontologists need a grounding in statistics, and so on. But there remains a core of distinctly geological skills which many would not accept as "scientific", with all the negative value judgments this rejection implies. For example, much useful research in sedimentary geology and basin analysis has been accomplished based on little more than a qualitative use of basic science. We have to distinguish here between, 1) the application of known theories and models of sediment behaviour to the analysis of a new basin, and 2) the development of new theories and models themselves. A scientific background is far more important in the second case, but even here much first-class research work remains to be done by the mathematical simpleton and the chemical incompetent.

Basin analysis, as discussed here, is taken to mean the investigation and documentation of stratigraphy, depositional environments, paleogeographic evolution and relationship to contemporaneous tectonics of a given sedimentary sequence. There are two major elements to such an analysis: an understanding of depositional systems and an appreciation of stratigraphic architecture. Both are subjects requiring spatial skills – the ability to visualize and explain objects and processes in three dimensions. Such skills commonly are emphasized to students studying basic structural mapping, but they are equally important to those engaged in basin analysis. Three-dimensional thinking can only be achieved with practice, like most other skills.

Recent advances in seismic techniques have resulted in the evolution of a subject called seismic stratigraphy. High-quality regional seismic lines can now display the internal structure of entire basins to depths of several kilometres, and the architecture now being documented is far more complex than anyone would have imagined. We have learnt that the Law of Superposition of Strata is quite misleading. Many basins are filled by sideways progradation of dipping depositional surfaces, building giant wedges hundreds or thousands of metres high called clinoforms. Alluvial fans, deltas, reefs with their talus slopes, continental margins and submarine fans are good examples. Very few environments accumulate sediment in the classic layer-cake manner. Superposition, as such, is one-dimensional and a quite inadequate law on which to base an interpretation. More important is a knowledge of the complexity of stratigraphic geometry and its dependence on the way in which sediment is transported and deposited. This, in turn, requires a sound understanding of sedimentary environments and depositional systems. Clinoforms and other architectural units wedge out, showing onlap and offlap stratigraphies; these result from erosional and depositional processes, tectonics and sea-level change. We now know that sea level has been changing by hundreds of metres almost continuously, at least throughout the Phanerozoic, and this has had profound effects on sedimentary patterns from coastal plains to the deepest oceans. On scales of tens to hundreds of metres sediments display lensoid, mounded, channelled, wedge-shaped or lobate geometries. These are best displayed on regional seismic lines, hence the term "seismic facies". These shapes reflect the influence of marine currents, sediment gravity flows or channel meandering in the erosion and dispersion of detritus. Biogenic carbonate sediments, too, have their own distinctive geometries.

The skill of the basin analyst is to reconstruct and make sense of this complexity. Petroleum exploration companies run regional seismic lines, which reveal many of the broader outlines of the basin, but without these (and even with) reliance must be placed on scattered outcrop and drill-hole information to flesh out the detailed picture.

One of the most widely used techniques in the study of sedimentary environments is vertical profile analysis. In vertical section many stratigraphic units show characteristic sequences, which commonly are repetitive (cyclic).Interpretation of these depends on Walther's Law, which states that only those facies occurring side by side in nature can occur together in vertical sequence (except where erosional breaks intervene). By studying the individual components of a cyclic sequence a few metres or tens of metres thick a basin analyst can reconstruct a depositional system perhaps tens of kilometres across that migrated through the basin. For clastic sequences variations in grain size, bed thickness and scale of hydrodynamic sedimentary structures are the most useful criteria for environmental interpretation – hence the terms "thickening-and-coarsening upward" and "thinning-and-fining upward" cycles. Environmental interpretation depends largely on such mesoscopic to macroscopic facies studies, and is very much a "field science". These observations require only a hand lens and metric scale to collect the necessary data, in core or outcrop. Laboratory studies, such as analysis of grain size or geochemistry are quite unnecessary, and because of the simplicity of the observations, they have been regarded as not very scientific, and downgraded or even ignored by many workers.

The study of fluid dynamics and sediment mechanics has added immeasureably to the interpretation of clastic rocks. In fact, modern clastic sedimentology owes its existence largely to two major breakthroughs, the turbidite concept of the nineteen fifties and the flow regime concept, developed in the sixties. Both concepts are empirical in origin, based on field observation and flume experimentation. Theoretical documentation came much later, and the work is still far from complete. The empirical work, however, has given sedimentologists powerful tools for the interpretation of sedimentary structures, allowing the building of facies models based largely on a qualitative understanding of the relationship between water flow rates, turbulence and sediment grain support mechanisms. The investigation of sedimentary structures continues, with much work remaining to be done on hummocky cross-stratification and large bed forms in tidal and shelf environments. Basic facies information from field outcrops figures largely in this work, alongside the mathematical modelling of the specialists in fluid dynamics and sediment mechanics. In fact, without the careful facies studies the theoreticians would not know what to model, so that this distinctive field geological skill is clearly of first importance.

There is no question that the theoretical, quantitative aspects of clastic sedimentology are increasing in importance, and require an ever more sophisticated understanding of mathematics and physics, both to understand current developments and to form a basis for new research. But the fact remains that to exploit these developments in exploring new basins, or developing a better understanding of the relationship between depositional systems, sea level change and stratigraphic architecture – the large scale aspects of basin analysis – requires only a qualitative, descriptive or intuitive understanding of sediment mechanics.

Consider, for example, the study of sedimentation on continental margins, including continental slopes, submarine canyons and fans. At present there is a major gap in our understanding of this environment because of a data problem. Seismic and side-scan sonar techniques can illustrate stratigraphic architecture and sea-bottom physiography down to scales of a few tens of metres, but they cannot yet tell us much about the sediments themselves. Outcrop studies of ancient rocks tend to be confined to a few sections representing small fragments of a continental margin, or to long sections with little lateral control, and thus lacking in architectural detail.Therefore, we know a lot about sediment gravity flow processes from the point of view of instantaneous sedimentation behaviour and the resulting facies, but much less about longitudinal changes in flow characteristics and the broader scale of canyon-fill and submarine fan architecture. Debates about submarine fan facies models have raged, as a result. The basin analyst, armed with qualitative and three-dimensional skills, has much to contribute by studying networks of cores and outcrops and relating facies and vertical profile data to the seismic and sonar images. This is important, basic research, and of considerable relevance to those most interested in the larger picture – petroleum companies exploring the offshore.

The status of knowledge about the continental shelf is much the same, offering similar opportunities for important basin analysis research. In the case of on-shore environments, our greater ability to study facies in the making and relate them to existing geomorphic patterns and processes has given us a much better grasp of basin development. However, even here, we lack information on long-term patterns of river behaviour, and there is a need for basin analysis research on three-dimensional networks of cores or outcrops to evaluate the various styles of fluvial architecture.

The style and composition of a basin fill tells us a great deal about the behaviour of the crust on which it rests and from which its clastic detritus was derived. Basin analysis is therefore useful in the study of orogeny and magmatism and plays an important part in the reconstruction of plate tectonic history of the continents. Studies of Precambrian sediments are shedding much light on the history of the crust. For example, they have helped document the development of stable cratonic continental masses during the evolution of the crust from Archean to Proterozoic time.

Basin analysis is a unique geological discipline, involving its special methodology of observation and interpretation. It has its own value in what it can tell us about the history of the earth and the clues it provides for locating stratabound fuel and mineral resources. But is it science? The question only exists if we allow the word "science" to be used as the password to some exclusive, priestly sect. Does the answer really matter?