Spatial models of carbonate platform anatomy

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Summary

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Carbonate platforms are highly particular sedimentary systems that are formed by a series of complex, variable and interrelated intrinsic processes such as production, erosion, transport, deposition, early cementation and corrosion, and strongly influenced by external processes like relative sea level (eustasy and subsidence) changes, local and regional tectonic regime, ecological changes, climate variations, and burial fluid migration styles controlling late diagenetic modification. The result of the interplay between such intrinsic and extrinsic processes is reflected in the architecture of carbonate depositional systems and the type of facies and textural make-up of internal sedimentary bodies, which is termed stratal anatomy. Quantitative morphological analysis of stratal anatomy, therefore, can be used to capture proxy data on depositional processes and their evolution within a sedimentary system. Such analysis leads to the establishment of rules and concepts on carbonate sediment accumulation and provides an important tool for predicting the anatomy of sedimentary rock bodies in the subsurface. As more than half of the world's hydrocarbon reserves are in carbonate sediments, improving the predictability of their stratal anatomy is of prime economic importance. In addition, they contain major fresh-water aquifers and also hold significant ore deposits. Moreover, carbonate sedimentary systems are highly sensitive recorders of oceanographic processes and the relative oscillation of sea level through time, and as such may offer valuable insight into how ancient earth environments responded and adapted to climatic change.

With the advent of accurate and affordable high-resolution positioning equipment it has now become possible to efficiently extract quantitative morphological information from large-scale outcrops. These systems make use of global positioning systems or laser applications and ensure correct registration of geological observations in 3D space. Such data can subsequently be used to build realistic geological models, so-called digital outcrop models. The models can be visually interrogated from any perspective and provide the possibility for quantitative analysis. Furthermore, the models significantly improve and enhance original outcrop observations that would have been more difficult to appreciate from outcrop without the digital approach. Quantitative spatial appreciation of outcrop systems has gained momentum over the last decades as an important tool for assessing predictability and reducing uncertainty in the subsurface. It is the application of digital outcrop modeling techniques that is the subject of the first part of this thesis.

A second source for information on stratal anatomy is reflection seismic data. Seismic data present a logical source because they provide ”continuous” anatomical proxy information, although remotely sensed. The translation of a geophysical image into a geological formation, however, is obscured by methodological difficulties and the non-uniqueness in interpretation of the seismic signal. Therefore, understanding the controls of petrophysical properties of porous media is a key issue in interpreting seismic images and acoustic logs of sedimentary sequences. Carbonate sediments present special challenges in this respect due to their complicated pore structure and susceptibility to diagenetic alteration. In the second part of the thesis the relationship between geological parameters, such as rock texture, and acoustic properties is investigated.

The thesis is arranged in a modular fashion. Chapter 2 lays out the methodology and workflow for efficiently capturing and integrating digital field data in digital outcrop models. Subsequently, in Chapter 3 the recent advances and current practice in the use of spatial geologic outcrop data in analog studies is discussed. The format of such data is treated as well as the most commonly used geostatistical algorithms. This gives an insight in the way in which spatial geologic outcrop data is of use in improving the knowledge on the processes of carbonate sediment accumulation, and in enhancing the techniques of pattern replication of facies in subsurface reservoirs.

The methodology and workflow set up in the first chapters is applied to three case studies in Spain and Morocco. The Spanish Sierra del Cuera is an upper Carboniferous high-relief steep-flanked carbonate platform which was rotated 90° to vertical in a thrust slice. Orthorectified aerial photographs provided insight in the depositional architecture of the platform and traced stratal surfaces offered information on the spatial distribution of lithofacies which allowed establishing an accurate model of microbial boundstone dominated carbonate platform margins (Chapter 4). The Moroccan Djebel Bou Dahar is a lower Jurassic carbonate platform which evolved in a rift basin. At present-day the platform is exposed as exhumed topography and of exceptional outcrop quality. The platform architecture was controlled by active syndepositional tectonics. It evolved in several stages from a wide-spread low-relief system into an isolated steep-flanked carbonate platform. Digital field data were acquired in two detailed study windows in a high-rising slope environment (Chapter 5) and across an outer-platform shoal-barrier complex (Chapter 6). Subsequently, the stratal anatomy was digitally reconstructed in digital outcrop models and used to asses the spatial distribution of lithofacies, derive quantitative stratigraphic information and to statistically assess the predictability of lithofacies stacking.

Finally, in Chapters 7 and 8, controls on acoustic wave propagation in sedimentary rocks, and the effects of saturation on acoustic wave propagation in carbonate rocks, are discussed. The Poisson's ratio (a specific P-wave over S-wave ratio) is introduced as an important discriminator of critical rock texture classes. It shows a strong correlation with depositional and diagenetic parameters, as well as particular changes in acoustic behavior as a result of fluid saturation. A better understanding of the mechanisms controlling the acoustic behavior would ultimately enhance the geological interpretation and extraction of rock characteristics from reflection seismic images.

Quantitative concepts and rules are essential for improving the predictability of (remote) carbonate stratal anatomy (e.g. in subsurface reservoir evaluation) and for the general advancement of the field of sedimentology. Precise and accurate anatomical information on sedimentary bodies, their internal bedding geometries, and physical characteristics is essential for reconstructing depositional models, flow models for hydrocarbon reservoirs and aquifers, remediation of contaminated aquifers and the reconstruction of basins, to name just a few applications. With the rapidly increasing demand for potable water and energy resources, the need for such data will only increase in the future.