Introduction

Carbonate rocks commonly exhibit evidence of former processes associated with the formation and subsequent breakdown of karst. Preserved and fossilized karst and karst-related structures are termed paleokarst, and are a common feature in carbonate reservoirs worldwide (e.g. James and Choquette 1988; Fritz et al 1993; Lucia 2008; White et al 1995; Soudet and Rolando 1994; Cook 2002; Yan 2002; Colpaert et al. 2007; Sayago et al. 2012). A comprehensive approach for handling paleokarst in industrial reservoir geo-models is however lacking. The aim of the present paper is to outline some concepts that could contribute towards improving facies modelling in paleokarst reservoirs, in particular with respect to spatial distribution.

A paleokarst reservoir will exhibit characteristics inherited from the original karst system as well as features and properties derived from its subsequent collapse, infill and diagenesis. This complex pattern of 3D heterogeneities is superimposed on the original depositional and tectonic structure of the host rock and produces highly complex reservoir architectures with hard-to-predict property distributions. Typical features may include permeability variations spanning four orders of magnitude, a lack of porosity/permeability relationships, complex, varied pore shapes and sizes, dual-permeability and “low-resistivity pay” with difficult-to-predict spatial changes, and high sensitivity to fluid properties (Choquette 2012). Commonly encountered problems in reservoirs containing paleokarst structures include drill-stem drops and mud-loss while drilling, and unexpected water breakthrough, poor sweep during production and erratic pressure behavior (Agar and Hampson 2014), which affect both safety considerations and running recovery estimates throughout the lifetime of a field.

Theory

Modelling and forecasting of properties in paleokarst reservoirs is highly challenging. Given that many paleokarst features are on sub-seismic scale, well data commonly is sparse, and paleokarst typically exhibits extreme spatial heterogeneity, data-driven modelling, where model algorithms are generated from statistical guidelines extracted from data analysis, is problematic, as the statistical content of the underlying data may not be adequate or representative.

Concept-driven modelling, on the other hand, requires a good conceptual understanding of processes and products involved in the formation of paleokarst reservoirs, where concepts are based on a combination of outcrop observation and an understanding of physical/chemical processes forming the observed structures. Alternative conceptual model can be derived from the data analysis and produce a set of forecasts based on the uncertainties associated with the underlying reservoir concept and conditioned to available well data and seismic on relevant scales. Although concept-driven models tend to be strongly deterministic, they nevertheless are better suited to capture key characteristics of paleokarst systems (such as connectivity) that will not necessarily be evident when analyzing sparse (and possibly non-representative) well data and seismic data with limited resolution.

Presently there are no dedicated tools or workflows for generating concept-driven paleokarst models in standard industrial reservoir modeling software such as Petrel or RMS. There are two fundamental prerequisites for establishing such workflows for forecasting purposes: 1) the ability to render realistic paleokarst geometries in geocellular models at relevant (i.e. manageable) scales, and 2) a classification scheme for paleokarst-related facies, based on their process of formation. Following are some concepts and guidelines pertaining to the latter, which may form a framework for modelling spatial distribution of paleokarst facies.
Existing classification schemes, (e.g. Loucks 1999), although providing a template for textural classification breccia and sediment types observed in paleokarst systems, only address forecasting of the spatial distribution of these facies to a limited extent. Forecasting of reservoir architecture and properties using stochastic modelling methods requires the use of constrainable parameters to yield constrainable outcomes. Thus, models including paleokarst facies should be linked to quantifiable and constrainable parameters controlling the distribution of these facies.

Taking paleo-cave systems as an example, the distribution of facies elements is primarily controlled by the scale and configuration of the initial karst cave system, its stability, and hydrological development.

Karst system configurations are controlled by several factors: 1) host rock properties, such as rock type, facies distribution, stratigraphy and diagenetic state; 2) structural geology, including faults, fracture pattern and stratal orientation; 3) fluid chemistry; 4) time; and 5) position during formation (i.e. epigene or hypogene systems). Development of epigene systems is closely tied to climate, topography, base level and whether the karstification happens at the surface or at depth; whereas hypogene systems are largely disconnected to near surface process but closely tied to deep hydrothermal fluid flow pathways. For most reservoirs these factors can to some extent be identified and parametrized, and can provide constraints for stochastic modelling of likely configuration of the karst cave systems while it was active (e.g. Collon-Drouailllet et al 2012; Jouve et al. 2017). The karst system configuration forms the starting point and can provide constraints for a definition of paleokarst facies and their spatial distribution. Paleokarst facies thus include any preserved element of the initial karst system, sediment infill and products related to subsequent breakdown and degradation processes following the deactivation of the active karst system.

For cave systems, breakdown is closely tied to the stability of the cavity, which in turn will facies types and distribution. Presence and distribution of fractures, stratification (bed thickness and mechanical strength), passage shape and width, and overburden load are the primary controls of cave stability (e.g. Bakun-Mazor et al. 2009; Parise & Lollino 2011). Open cavities can be preserved down to several km burial depth, and remain empty or be filled by sedimentary breccia, sediments and/or cements/speleothems. Infills of such cavities will most likely not experience normal compaction during burial.

Partial collapse of a cavity generates local collapse breccias, which may be deposited either directly on the cave floor or on top of pre-existing sediments fills. Interbedding of collapse breccia with sediment fills and presence of breccia pipes can indicate roof collapse occurring while the drainage in the system was still active. Part of the initial cavity is preserved.

Total collapse implies cavities being filled entirely with collapse breccia, sometimes on top of preexisting sediments. The collapse expands the cavity upwards and may continue until the breccia infill reaches the roof and stabilizes it. In these case transition from collapse-breccia infill through mosaic- and crackle breccia to intact host-rock can be expected, and collapse structures can propagate into the overburden.

An example of how to link the stability (or state) of the paleocave to expected paleokarst facies is shown in Figure 1. Probabilistic maps of initial karst configurations and expected stability of these configuration during burial can serve as conditioning factor when performing stochastic modelling of facies distributions.

**Conclusions**

Constraints for stochastic modelling spatial distribution of paleokarst facies can conceivably be derived from a combination of forecasting the likely configuration and scale of the initial karst system and perform an assessment of the stability of different part of the cave system during subsequent
burial. Both elements provide a means to constrain lateral distribution of facies in paleokarst systems for reservoir modelling purposes.

**Figure 1** Example schematic of paleokarst facies subdivision based on cavity stability.

**References**


