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CARBONATE GEOBODIES: HIERARCHICAL CLASSIFICATION AND DATABASE – A NEW WORKFLOW FOR 3D RESERVOIR MODELLING

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Quantitative data on geobodies are crucial for reservoir modelling. Although abundant quantitative data are available in the literature for siliciclastic depositional systems, equivalent data for carbonate systems are scarce. In this paper we introduce a new approach to the management of quantitative data on carbonate geobodies which is based on a hierarchical classification scheme. The classes to which a carbonate geobody are assigned are: (1) depo-time (i.e. geological age); (2) depo-system (i.e. type of carbonate platform); (3) depo-zone (i.e. facies belt or zone); (4) depo-shape (i.e. geometry of the geological body); (5) depo-element (i.e. architectural elements present); and (6) depo-facies (litho- and biofacies). This hierarchical classification is complemented by a set of rules for modifying depo-shapes which refer to their spatial distribution and patterns of interaction.

Based on this classification, an extensive database has been developed which can be used for 3D reservoir modelling. The database holds more than 600 case studies from outcrop analogues and the subsurface and also from satellite images of modern carbonate settings. The database can be used as the basis for a new workflow for reservoir modelling which uses multiple-point statistics (MPS). MPS makes use of training images to capture and reproduce facies patterns and geometries during stochastic simulations.

The application of this new approach is demonstrated by modelling a Cretaceous outcrop reservoir analogue from southern France. The use of MPS allows the generation of geologically realistic and complex facies distributions in the model based on the simplified training images.

INTRODUCTION

Modelling subsurface petroleum reservoir heterogeneities requires quantitative data on the dimensions, shapes and orientations of structures and geobodies. These kinds of data may be acquired using suitable outcrop analogues or modern equivalents. An important step forward in the understanding of reservoir heterogeneities was the introduction of the concept of the architectural element and the notion of hierarchies in scales of architectural units and bounding surfaces, which was first developed for siliciclastic rocks (e.g. Miall and Tyler, 1991). A similar approach for carbonates is only now being established (e.g. Pomar and Kendall, 2008; Harris, 2010; Palermo *et al*., 2010; Rankey and Reeder, 2011). One reason for this may be that the shapes of carbonate geobodies,

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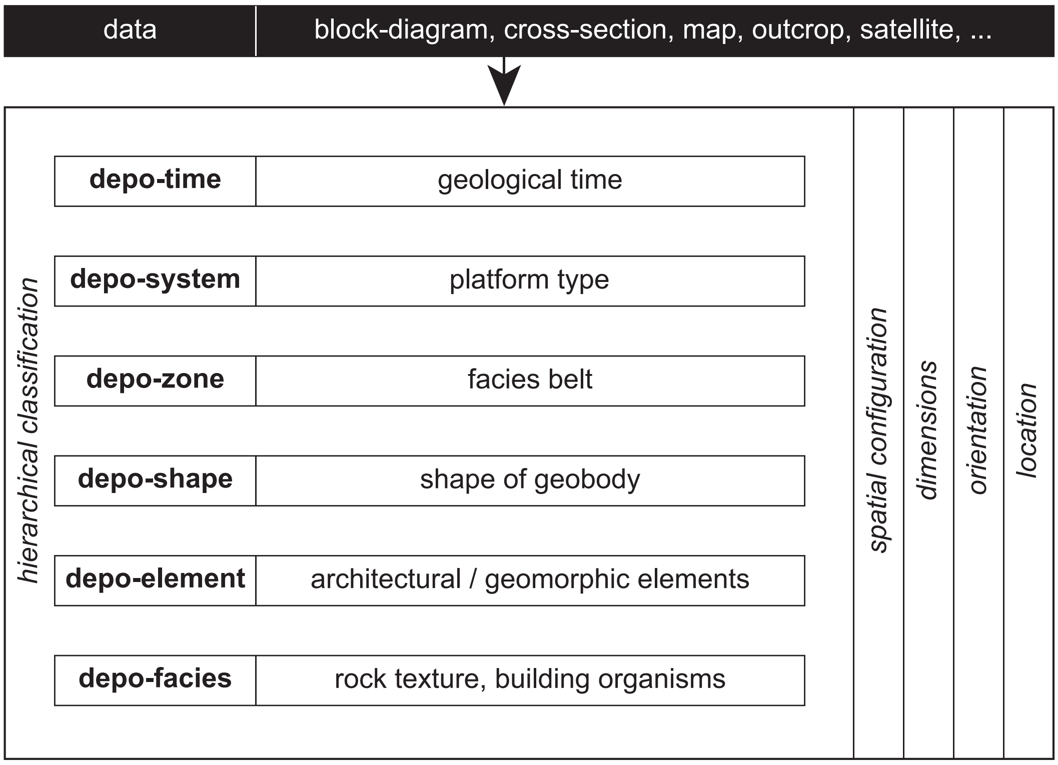


Fig. 1. Table summarising the new hierarchical classification of carbonate geobodies, showing both the hierarchical categories and the terms used as modifiers for spatial configuration (dimensions, orientation and location). The new terminology (depo-time, depo-system, etc.) is compared to terms used in previous studies.

and the factors controlling them, are more complex than they are for siliciclastic rocks (e.g. Schlager, 2003; Pomar and Hallock, 2008).

This paper presents a new approach to investigating this complexity which is based on a hierarchical classification of carbonate geobodies and a set of rules to characterize their spatial distribution. Existing classification schemes for carbonate bodies are often ambiguous. In order to improve them and to facilitate communication with reservoir engineers, the new approach uses a novel descriptive terminology. While some recent classification schemes have focussed on modern carbonate systems (e.g. Morgan and Harris, 2008), the new classification can be applied to both modern and also ancient carbonate environments. The system seeks to identify the dimensions, shape and internal structures of carbonate geobodies.

In reservoir modelling, rapid access to data is important. The new classification is the basis for a web-based database system (referred to here as *Carbdb*) which can supply quantitative data rapidly to a reservoir modeller. Characterizing carbonate geobodies by means of a hierarchical classification scheme sets *Carbdb* apart from other archival compilations of ancient carbonates (e.g. Kiessling and Flügel, 2002; Kenter and Harris, 2005).

The transfer of three-dimensional sedimentary features from analogue studies to stochastic reservoir models is limited when conventional variogram-based techniques are used. A better reproduction of shapes can be achieved by object-based algorithms which however may be difficult to condition. Multiple-point statistics (MPS) combines the benefits of both approaches and allows three-dimensional facies arrangements to be reproduced while at the same time honouring data from a large number of wells (Daly and Caers, 2010). Conceptual training images depict the desired geometries of facies patterns. MPS incorporates the structures from the training image during the simulation while taking account of additional data such as facies probability models. MPS has only recently been applied to carbonate systems (e.g. Levy *et al*., 2008; Rankey and Harris, 2008; Carrillat *et al*., 2010), although its application to clastic systems has a longer history (e.g. Strebelle and Journel, 2001; Strebelle *et al*., 2002; Harding *et al*., 2005; Strebelle and Levy, 2008).

We established a new workflow for building carbonate reservoirs: data from *Carbdb* is imported to the reservoir model by means of MPS. The workflow is demonstrated using a Cretaceous outcrop reservoir analogue from southern France. MPS with multiple training images was used to model different reservoir geobodies, such as mounds and fans.

An initial presentation of this approach was delivered at the EAGE conference in Barcelona (Jung *et al*., 2010).

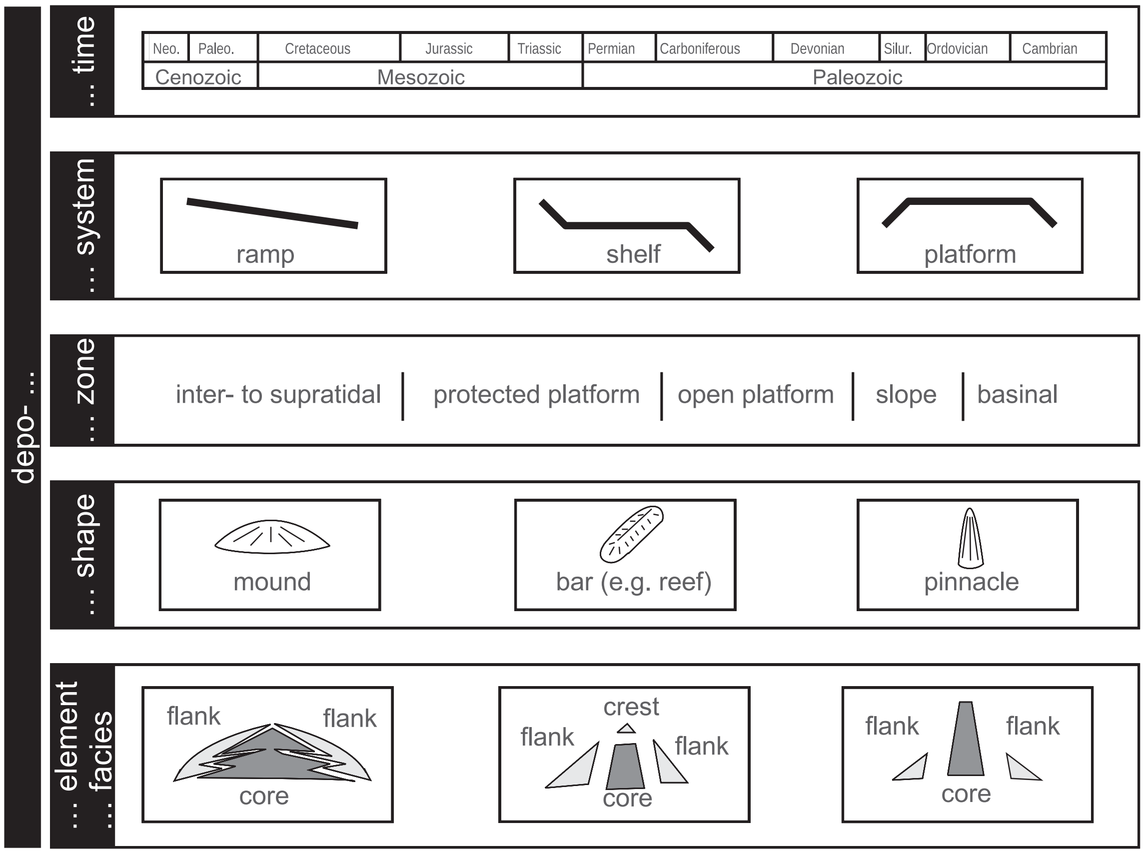


Fig. 2. Summary of the hierarchical categories used in the new classification scheme. Three major classes of *depo-system* are recognised (ramp, shelf and isolated platform) and five *depo-zones* (facies belts). Various types of *depo-shapes* are located in the depo-zones and can in turn be subdivided into component *depo-elements*. Depo-shapes are illustrated in Fig. 3.

HIERARCHICAL CLASSIFICATION OF CARBONATE GEOBODIES

The present classification scheme for carbonate geobodies consists of two elements which in combination permit any geobody to be described: (i) the hierarchical classification itself (Fig. 1); and (ii) a set of complementary rules which describe modifications of geobody shape, dimensions, geometries and spatial distribution patterns. This approach can be applied to both ancient and modern carbonates. In this paper, there is a focus on depositional carbonate bodies as opposed to diagenetic or structural bodies. Carbonate geobodies can be classified according to the following factors (Figs. 1 and 2):

(1) depo-time, i.e. geological age;

(2) depo-system, i.e. the type of carbonate platform (e.g. ramp or shelf);

(3) depo-zone, i.e. the facies belt or zone hosting the geobody;

(4) depo-shape, i.e. the 3D geometrical characteristics of the geobody;

(5) depo-element, i.e. the architectural elements or "building blocks" of the depo-shape; and

(6) depo-facies, i.e. lithofacies.

Carbonate sediments are the product of more varied processes than siliciclastic deposits, which are in general controlled by hydrodynamic processes. Early studies (e.g. Heckel, 1974; Wilson, 1975; Wilkinson, 1979; James, 1983) and more recent research (e.g. Markello *et al*., 2008) have identified geological age ("*depo-time*") as a strong control on carbonate depositional patterns. Evolutionary processes have resulted in a variety of carbonate-producing organisms leading to a wide variation in carbonate facies, architectural patterns, geobody types and platform morphologies. Even the presence of carbonate sandbodies may vary as a function of geological age (Wilkinson *et al*.,1985).

The *depo-system* at the second level of the classification (Fig. 2) refers to the three major types of platform: ramp, shelf and isolated platform (e.g. Ahr, 1973; Tucker *et al*., 1990). Derivatives of the major platform classes are assigned to the parent class, e.g. an epeiric ramp is classified as a ramp.

Subdivisions of depo-systems are *depo-zones* which are equivalent to facies belts and represent regions to which certain rules can be applied: the behaviour, shape and spatial relationships of a carbonate geobody may be linked to specific positions in a facies belt (Wilson, 1975). Each depo-system

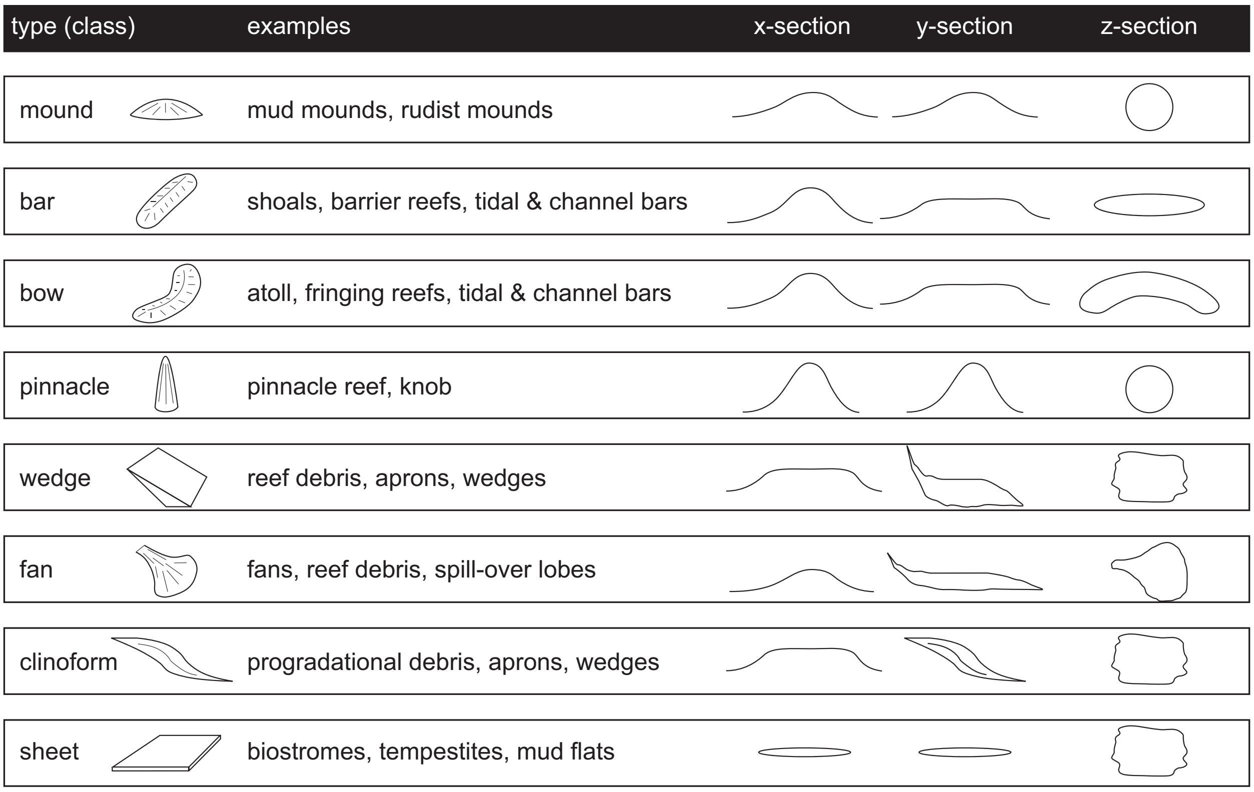


Fig. 3. Classes of *depo-shape* recognised in the new classification scheme. Different types of build-up may be classified with the same shape as it is a purely geometrical description. Deviations from an ideal shape are taken into account by rules describing external physical forces which control the nature of the shape.

can be subdivided into one of five *depo-zones* which are from land- to basinward: inter- to supratidal, protected platform, open platform, slope and basin (Fig. 2).

Carbonate geobodies (*depo-shapes*) occur typically in particular facies belts (depo-zones). The depo-shape is the measurable geometric shape of a geobody (Fig. 3). A depo-shape describes the geobody's geometrical characteristics without conferring any geological meaning on it. Classification of geobodies in terms of their external shape assigns each to one of several classes (e.g. mound, bar or bow: Fig. 3). Since the classification of shapes is purely geometric, a patch reef for instance could be classified as a mound-shaped depo-shape. The randomness of nature and the complexity of controlling factors which influence the final depo-shape cannot be fully captured by the classification. Typically, classification schemes embrace only selected features. Therefore deviations from these predefined classes are covered by a set of extra rules which are described below.

Depending on the type of the depo-shape, a further classification into *depo-elements* (architectural elements, facies associations) is possible (Fig. 2). The depo-elements form the "building blocks" of the depo-shapes. For example, the depo-shape "mound" may be built up of depo-elements such as cores and flanks (Fig. 2). Depo-elements can be further subdivided into *depo-facies* which describe, for example, rock texture, bioclastic components and porosity.

Modern analogues provide a valuable resource for understanding genetic processes in carbonates. The classification was applied to a number of depo-systems (ramp, shelf and isolated platform) which are present in the Arabian Gulf (ramp), Great Barrier Reef (rimmed shelf) and Bahamas and Maldive Islands (isolated platform). Mapping was based on Landsat-7 satellite imagery using NASA Worldwind software (Fig. 4).

A different notation for the categories *depo-shape* and *depo-element* was applied during mapping to account for the fact that the shapes of modern geobodies conform only to temporary "snapshots" in the sedimentary record. Thus depo-shapes correspond to first-order geomorphic elements, and depo-element to second-order geomorphic elements (Fig. 4). Second-order features are hosted by first-order features by analogy with parasitic folds. However, ultimately the interpreted analogues are stored using the unified notation applicable to both ancient and modern carbonates, i.e. depo-shapes and depo-elements.

CLASSIFICATION OF SPATIAL DISTRIBUTION OF CARBONATE GEOBODIES

Location in space (in 2D and 3D) is clearly an important specification while positioning a depo-shape

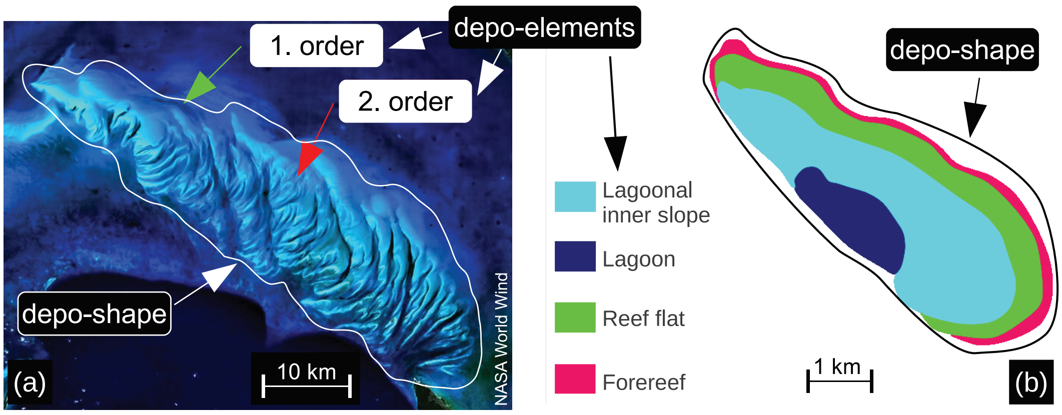


Fig. 4. (a) Landsat-7 image of a shoal body, Schooner Cay, Bahamas. First- and second-order geomorphic elements (depo-elements) are distinguished and together make up the depo-shape (i.e. the geobody). (b) Geomorphic classification of a shelf reef from the Great Barrier Reef. The first-order depo-shape is made up of component depo-elements.

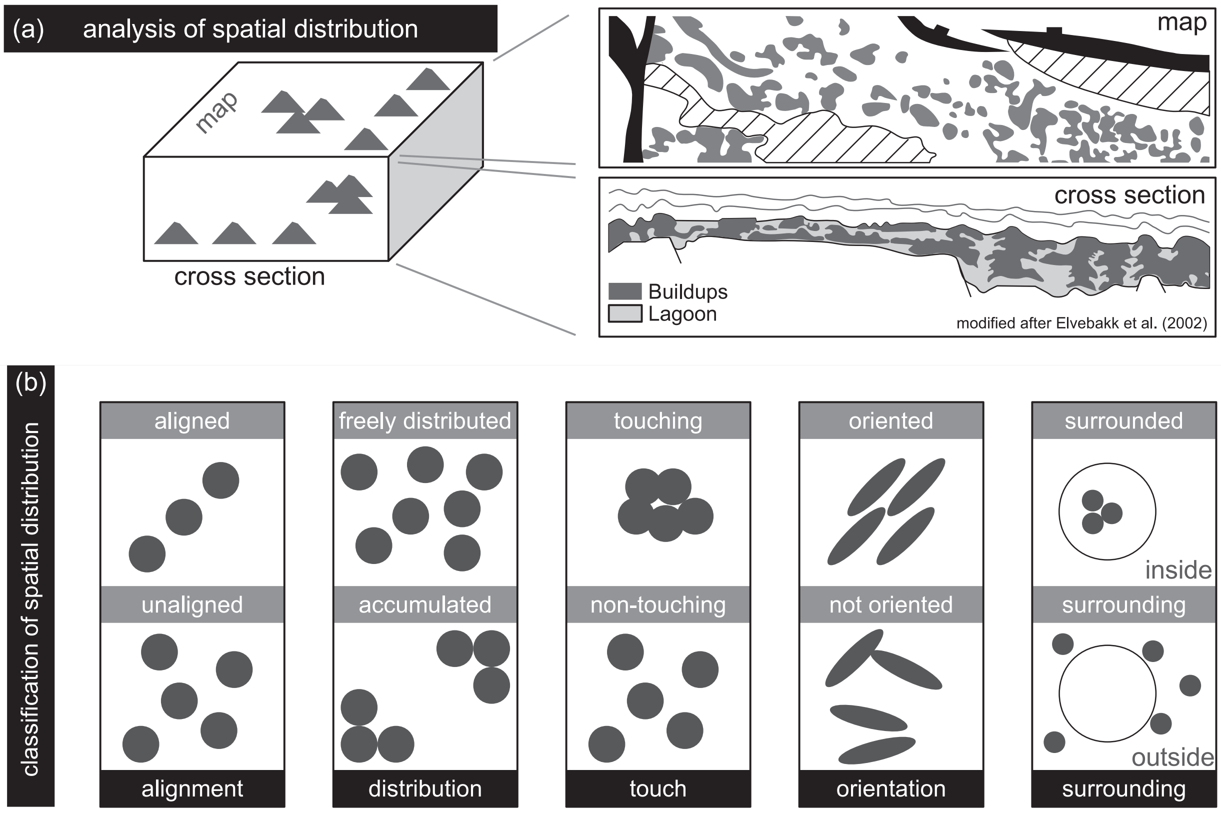


Fig. 5. (a, above) Cartoon showing how depo-shapes (geobodies) may occur in different patterns in map- and cross- section view. The three-dimensional spatial configuration of a depo-shape is controlled by both physical processes (Fig. 6) and sequence-stratigraphy (Fig. 7). (b, below) Five classes for the spatial distribution of geobodies can be distinguished (see text for details).

in a grid for reservoir simulation, as is its relationship to other depo-shapes. Observed patterns range from a random distribution (e.g. Elvebakk *et al.*, 2002) to systematic alignment (e.g. Wheeler *et al.*, 2006) or touching (e.g. Wendt *et al.*, 1993). Five principal classes of spatial distribution are used here (see Fig. 5), namely: (i) aligned / non-aligned; (ii) touching / non-touching; (iii) surrounded / surrounding; (iv) freely distributed / accumulated; (v) oriented / non-oriented.

The spatial distribution of depo-shapes originates from sequence stratigraphy and locally acting forces. Sequence stratigraphy involves both global and local controls.

In addition to global-scale controls caused by the effects of geological time on evolutionary patterns and by tectonics and eustatic sea level changes, local controls may also influence individual geobodies. Local controls on carbonate geobodies such as

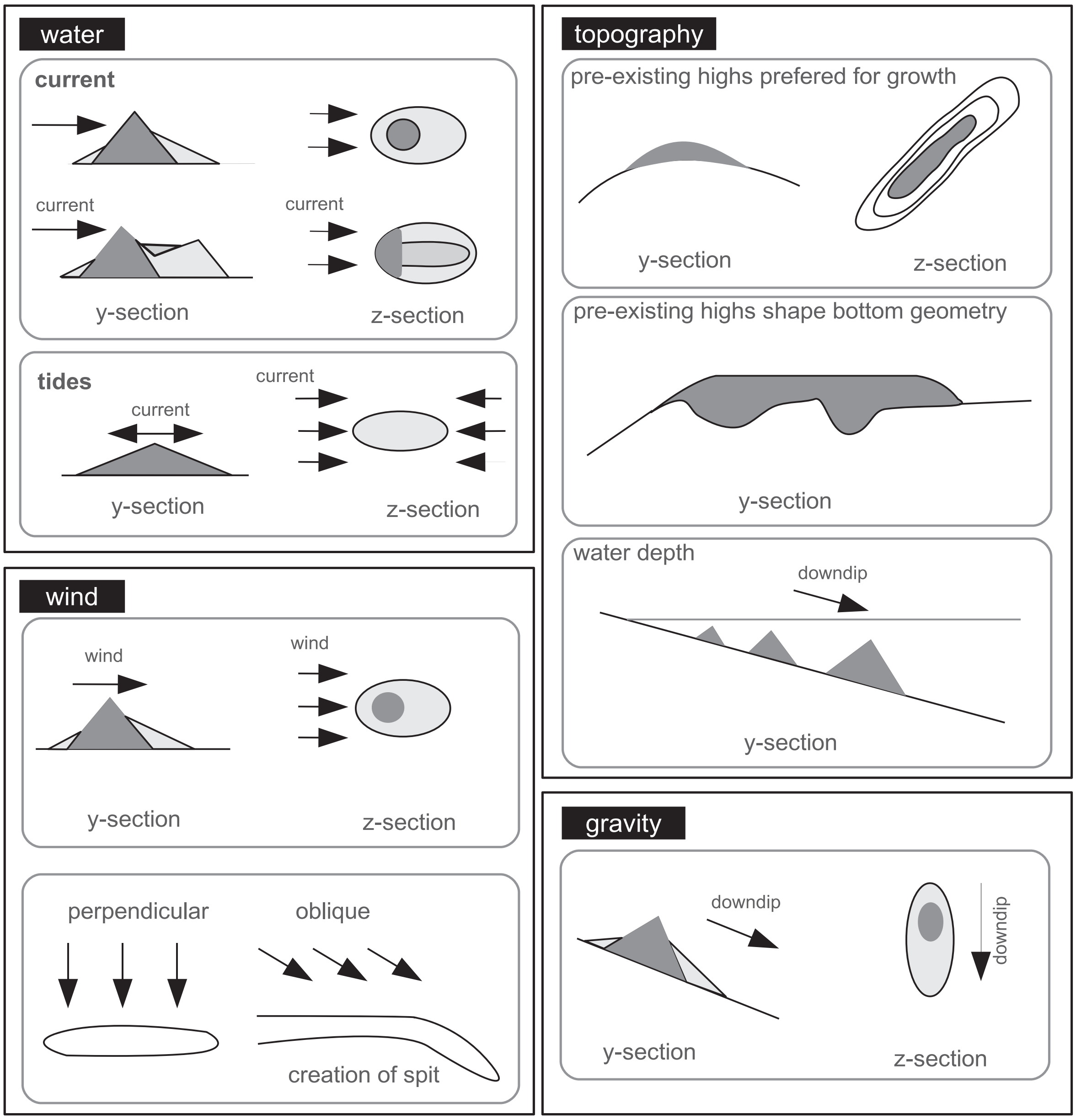


Fig. 6. Cartoons showing the physical processes controlling the growth and shape of a carbonate geobody. The darker-grey regions correspond to zones of major carbonate production, whereas the paler-grey areas correspond to areas dominated by carbonate debris. External factors (hydrodynamic processes, wind, topography and gravity) control the growth of carbonate-producing organisms as well as the distribution of the debris (c.f. Ginsburg and Lowenstam, 1958; Purser and Evans, 1973; Tucker, 1985).

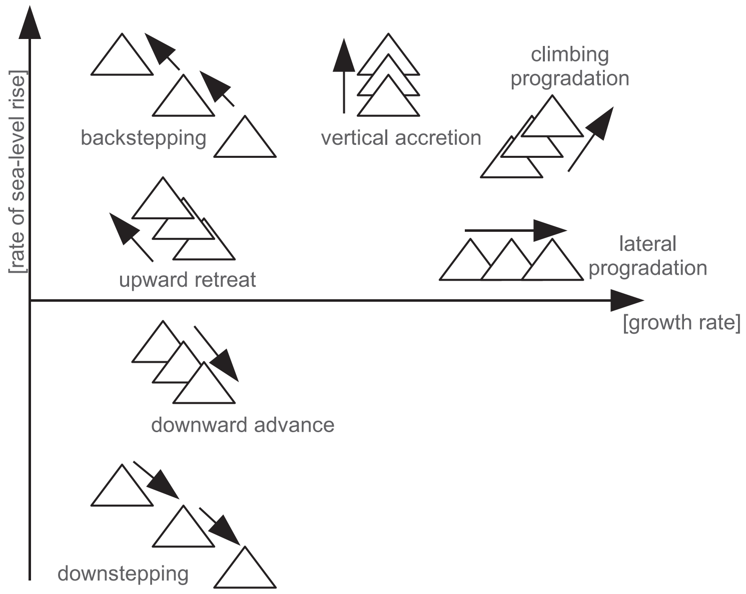
changes in sediment supply and accommodation space can control the depo-shape of an individual geobody and also the spatial distribution of groups of geobodies (Fig. 6). Growth, inter-growth and patterns of down- or back-stepping (Fig. 7) may lead to distinct and classifiable spatial configurations (Fig. 5). Local controls determine the internal proportions (size of depo-elements) and final geometry of the depo-shape (e.g. Ginsburg and Lowenstam, 1958; Purser and Evans, 1973; Tucker, 1985).

By analogy with the spatial constraints used to classify clastic depositional environments, e.g. wing-like extensions of sandstone bodies (Surlyk, 1987) or crevasse-splays of channels, a set of rules is proposed here for carbonates. For example, spill-over lobes are attached to an adjoining geobody such as a carbonate shoal (Fig. 8); and spits are commonly found at the tips of shoals or barrier reefs. The pathways of sediment transportation provides a first-order control on the spatial relationship of depo-shapes.

A HIERARCHICAL DATABASE FOR CARBONATE GEOBODIES: *CARBDB*

Reservoir modellers need data on carbonate geobodies and this can be based on outcrop observations, cross-sections, maps and conceptual

Fig. 7. Sequence stratigraphic growth patterns are generated by fluctuations in sea level and the carbonate growth rate. The arrangement of the depo-shapes in space may range from overlapping to touching to separate. The triangle (a lateral section) represents any of the depo-shapes in Fig. 3 (figure modified after Tucker and Wright, 1990).



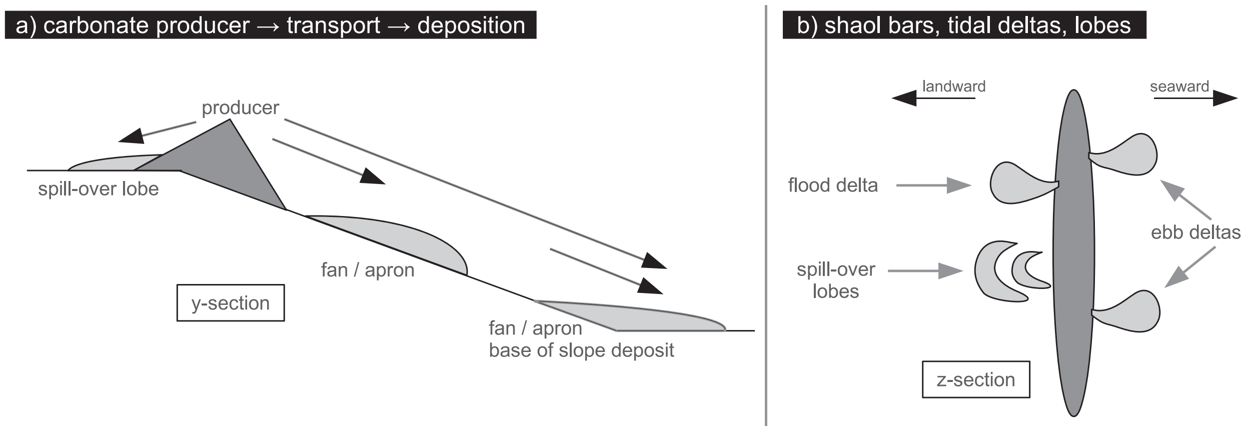


Fig. 8. Cartoon diagrams illustrating that carbonate geobodies are biological build-ups as well as physical accumulations of carbonate particles. (a) Diagram showing the spatial relationship between the producer / source of the particles, the transport path and the final depositional body. (b) Diagram showing a typical spatial configuration of carbonate geobodies which can be observed both in modern carbonate systems as well as in the geological record.

diagrams. Databases on complex topics have progressed in recent years from simple data accumulations to knowledge management systems (Alavi and Leidner, 2001). *Carbdb* is a tool for an interdisciplinary audience of reservoir modellers which can capture data on depo-shapes, manage it and retrieve relevant case studies rapidly with an intuitive visual search mask resembling the hierarchical classification scheme (Fig. 9). *Carbdb* was developed as a web-application which allows users to work simultaneously from different locations. Other benefits of web-applications are a reduction of the software requirements of the user's machine to a simple web browser. Since the programme and the database reside in a single server, users are able to work with the latest version of the software and the data with no updates necessary. "Web 2.0" developments have facilitated user contributions and interactions (O'Reilly, 2005) and these methods are now available for scientific applications (e.g. Henning and Reichelt, 2008; Ullrich *et al*., 2008; Sinha *et al*., 2010) and to industry (McAfee, 2006). These techniques have been incorporated to involve the user through tags and comments, and by interlinking items and uploading material. The *Carbdb* system has been set up using non-proprietary and standardised data formats and runs on Free and Open Source Software in order to ensure the long-term compatibility and sustainability of the system (e.g. Hall, 2010). The system set-up is based on the server edition of Ubuntu and is commonly referred to as LAMP (Linux, Apache, MySQL, PHP). The programme itself is written in PHP. The data in the form of variables resides in the MySQL database, whereas binary objects (e.g. images, PDF documents) are stored separately. A more detailed technical description is beyond the scope of this paper.

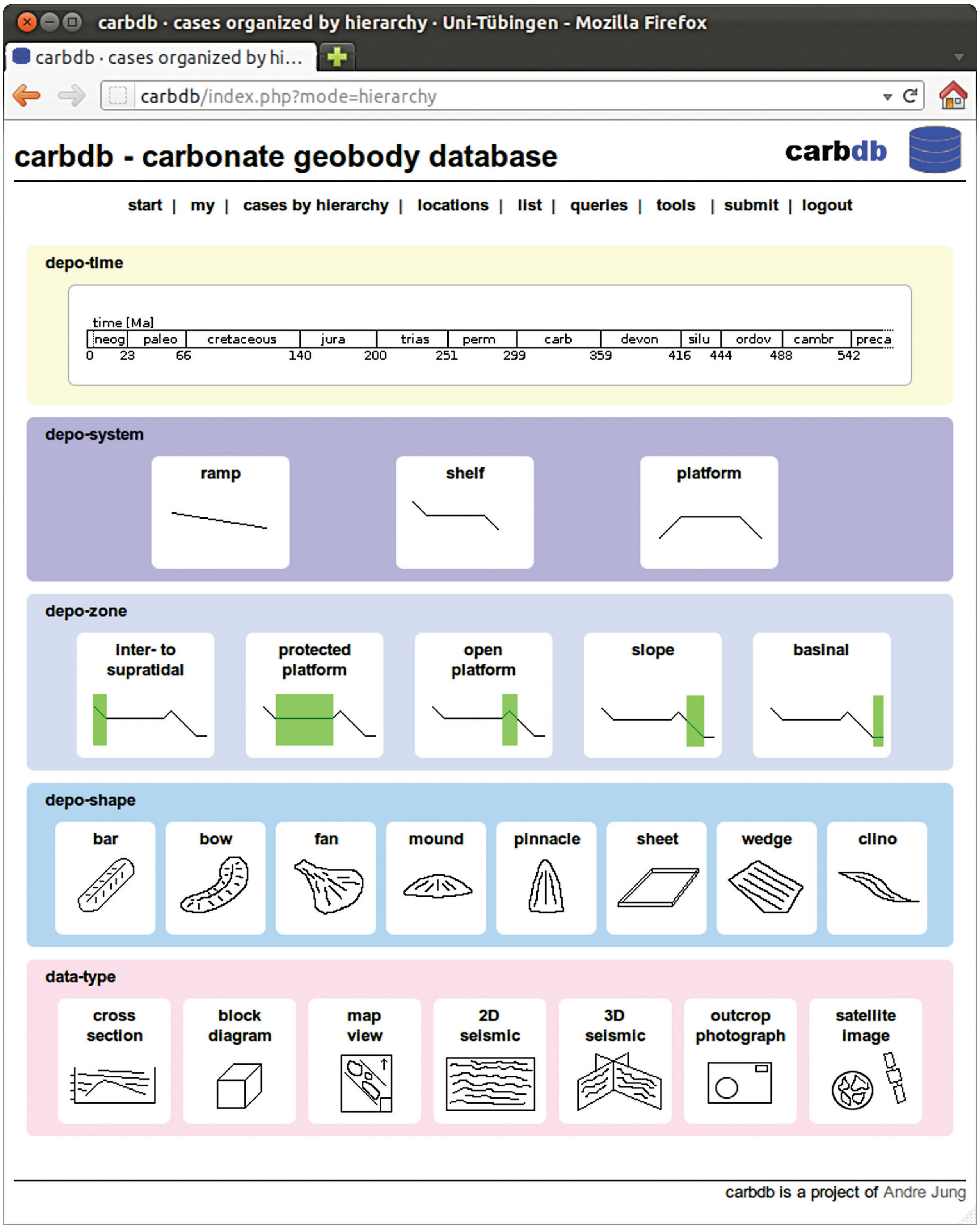


Fig. 9. Visual search interface of the *Carbdb* database using the hierarchical classification scheme for quick access to the stored case studies. Search criteria can be combined in an arbitrary fashion. Thus, it is possible for example to search for "bar-shaped" depo-shapes in the open platform depo-zone and to constrain the results to a particular geological time period. Screenshot taken from a client workstation accessing *Carbdb* with Mozilla Firefox on the Ubuntu operating system.

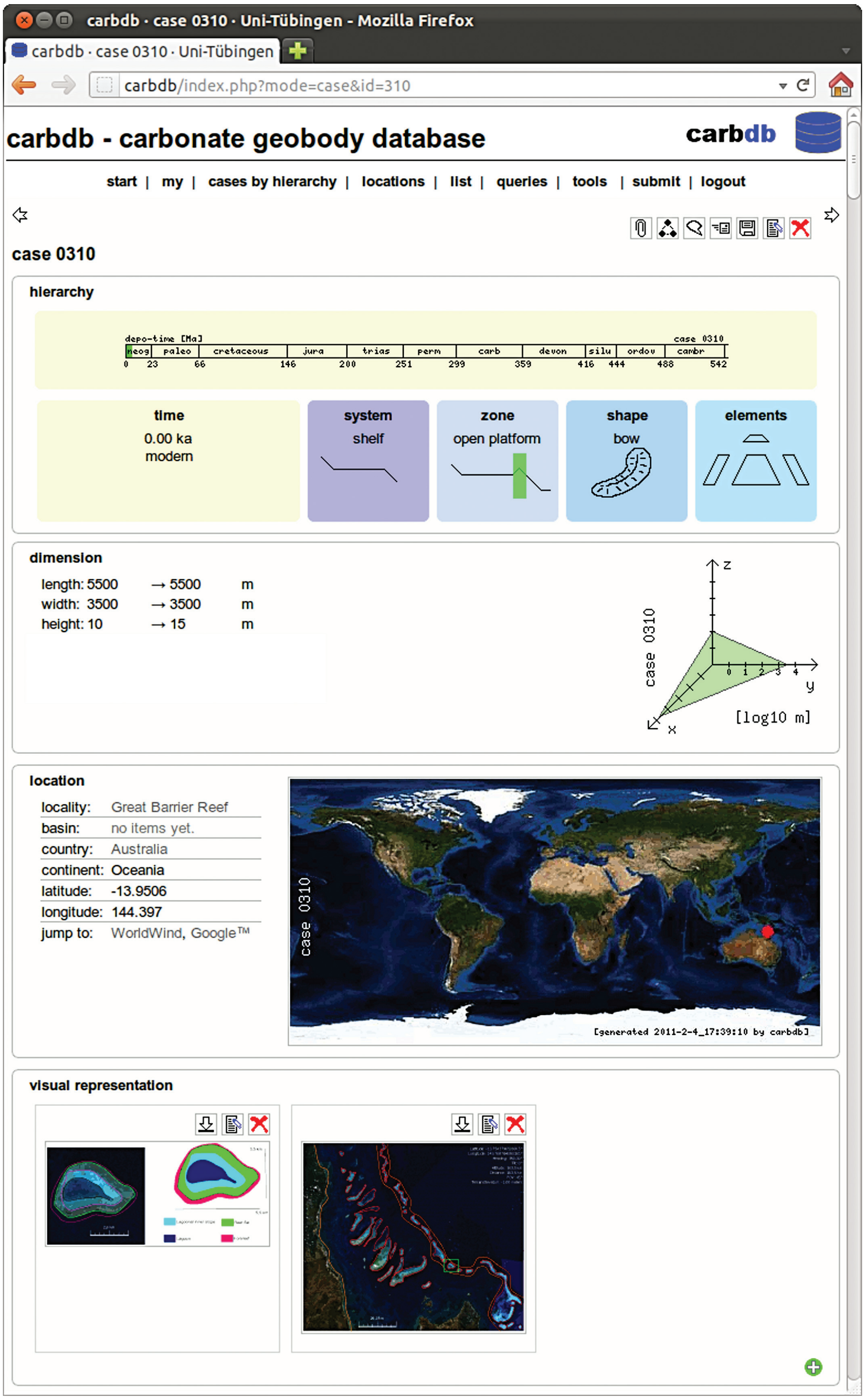


Fig. 10. Example of a data-sheet in the *Carbdb* data base. Data on each case study is processed and prepared to provide relevant information for reservoir modelling. Additional information not presented on this page includes: type of building organism, carbonate texture, and data from neighbouring case studies, classification of spatial distribution, etc. Screenshot taken from a client workstation accessing *Carbdb* with Mozilla Firefox on the Ubuntu operating system.

Carbdb is designed to provide a geologic and pragmatic user experience through hiding raw database queries from the users and delivering an intuitive usage. *Carbdb* guides the user through multiple dialogues asking for the required data when new case studies are captured (e.g. publications, outcrop studies). Once the data resides within *Carbdb*, the user can add images, drawings, maps, etc. to provide new users of the data-set with a better understanding of it. Each case study in *Carbdb* is presented in a unified way to allow browsing and comparison of depo-shapes (Fig. 10). The original data (e.g. in a publication) remains attached to captured data, allowing users to evaluate it in detail. While geologic expert knowledge is required to understand, classify and extract data from arbitrary sources, data handling in *Carbdb*, such as data import and use of the stored data (browsing, searching), does not require specialised training. Currently, the database system holds more than 600 case studies relating to both ancient and modern carbonate geobodies. Case studies in *Carbdb* that have successfully served as analogues for modelling studies may be improved by the uploading of outcomes, such as property models and training images.

APPLICATION TO 3D RESERVOIR MODELLING: A NEW WORKFLOW

A new workflow has been developed in which the hierarchical classification and its implementation in the database was applied to reservoir modelling. This section focuses on modelling at the level of depo-zones and depo-shapes using multiple-point statistics (MPS). Following an introduction to MPS, the workflow is described and illustrated. Although the workflow is applicable to any kind of property modelling, we consider MPS as the most appropriate of the stochastic algorithms available as it facilitates the import of geological concepts – from *Carbdb* or from any other source.

Multiple-point statistics (MPS) is a stochastic modelling approach which combines the strengths of both pixel-based and object-based techniques (Daly and Caers, 2010; Caers and Zhang, 2002). Falivene *et al*. (2006) provided a comparative overview of stochastic algorithms including MPS. MPS acquires information about depositional geometries from training images. A training image is a three-dimensional conceptual representation of an assumed depositional pattern. While simulating the depositional patterns derived from the training image, MPS also honours hard data derived from wells. MPS is also able to integrate "soft" data such as three-dimensional probability models. Building training images manually (e.g. interactive facies modelling) is time-consuming and may violate geostatistic principles as demanded by MPS based on the SNESIM algorithm (Strebelle, 2002). However, specialized software can be used for the rapid, automated generation of training images based on the desired parameters, e.g. TiGenerator (Maharaja, 2008) a plug-in to SGeMS (Remy *et al*., 2009). Object-based simulators which are present in most reservoir modelling software can also be used to generate training images. Inputs for such software can be delivered by the *Carbdb* database.

MPS permits the simulation to be conducted in a hierarchical manner. A reservoir can be divided into depo-zones and a different training image may be used for each region (Zhang, 2008). The training image contains the depo-shapes, their depo-elements and their component depo-facies. MPS allows the same facies type present in different training images to connect across the boundaries between depo-zones. This is of particular advantage when adjacent depo-zones share one or more facies types.

The modelling workflow is shown in Fig. 11 and comprises the following general steps. The steps may vary depending on the requirements of the individual reservoir model.

Step 1: Evaluate the available information on the reservoir/case to be studied and modelled, including: data (wells, seismics, etc.), interpretations and conceptual considerations. Use this knowledge to identify and classify geobodies according to the classification scheme;

Step 2: use information on classification from Step 1 to find matching case studies in *Carbdb* with quantitative data;

Step 3: upscale well logs (if available);

Step 4: add additional hard data;

Step 5: build training-images in a hierarchical fashion (using data from step 2) comprising depo-shapes, depo-elements, and depo-facies;

Step 6: build depo-zones;

Step 7: create probability models;

Step 8: create properties for rotation and scaling;

Step 9: run the simulation, integrating the results of steps 3-8.

The workflow for modelling a reservoir begins with a hierarchical classification of the available data (Fig. 11). This ordered information is then used to interrogate the *Carbdb* database. The hierarchical search functionality gives quick access to relevant case studies containing quantitative data. Both the available information and the data from the database are used to prepare the MPS simulations in a hierarchical fashion: depo-shapes and subordinate elements are represented in the training images, and the training images are assigned to the appropriate depo-zones which in turn build the reservoir.

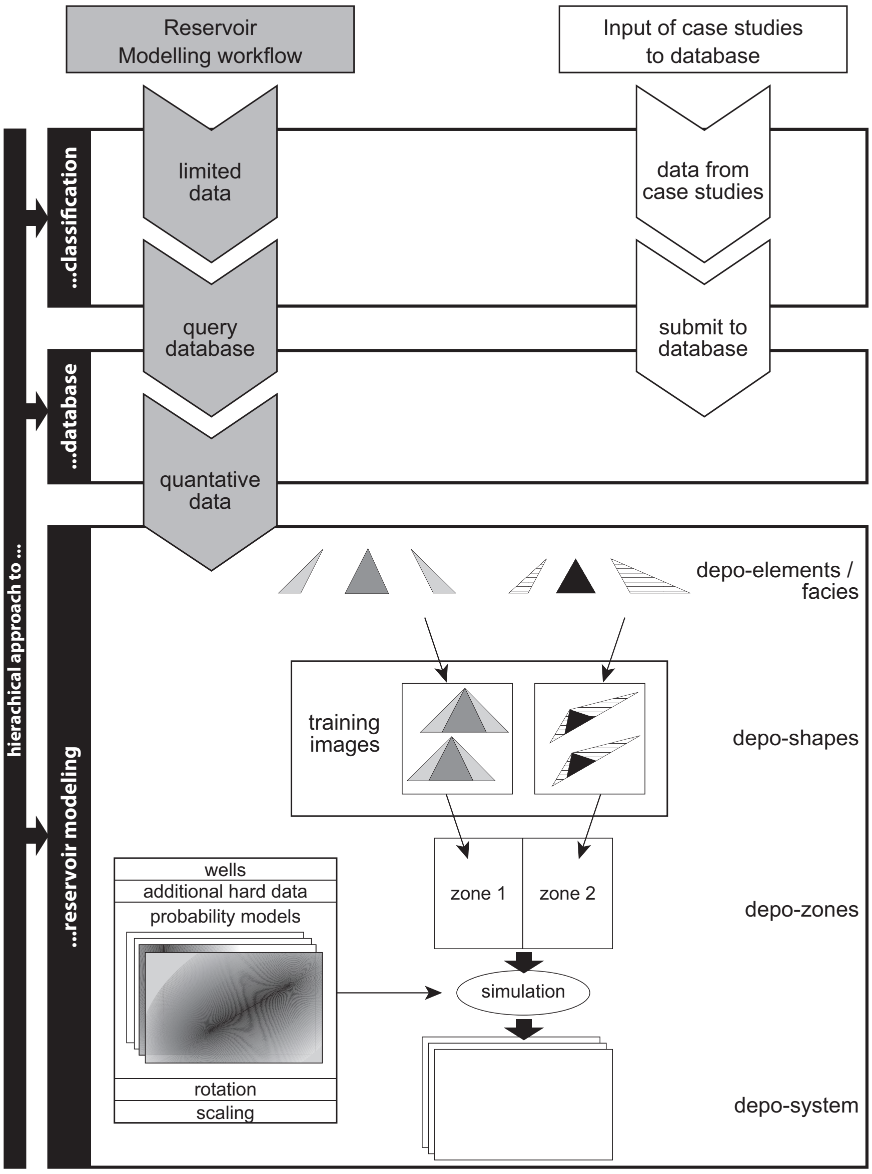


Fig. 11. Conceptual diagram of the hierarchical approach to the three elements of the workflow: classification, database and modelling. Grey pathway: in the modelling workflow, the classification is used to find and transfer data from analogues to the reservoir. White pathway: the classification is likewise used to classify and store data about analogues in the database.

The depo-zones can be built either in a deterministic or a stochastic way. Facies probability models control the location of individual facies. They can be derived from seismic data, palaeo-topographic/bathymetric data, or from the conceptual depositional model. The facies probability models do not have to be co-located with the depo-zones. In this way, facies trends extending across multiple zones can be realized.

WORKFLOW DEMONSTRATION: A CRETACEOUS CARBONATE PLATFORM

In order to illustrate the transfer of qualitative and quantitative data from the *Carbdb* database to a modelling case study, publicly available data was used from an outcrop in southern France. This outcrop analogue comprises a Cenomanian (shelf type) carbonate platform which can be subdivided into three depo-zones: open platform, slope and basin (Fig. 12). Detailed studies of this outcrop have been published (e.g. Philip, 1993; Gari, 2008). *Carbdb* was used to retrieve data on appropriate depo-shapes for each zone. In the open-platform environment, rudist reef mounds can be expected to occur (Carannante *et al*., 2007). These reef mounds occur irregularly in patches. Debris and breccia from these rudist reefs was transported downslope, leading to the formation of lobes and fans of resedimented debris (Bourchard, 1986). The lobes extend across two depo-zones from the slope into the basin. Mound shapes have also been observed, but have a more arched character than the up-slope rudist mounds, and are bigger in size. Their

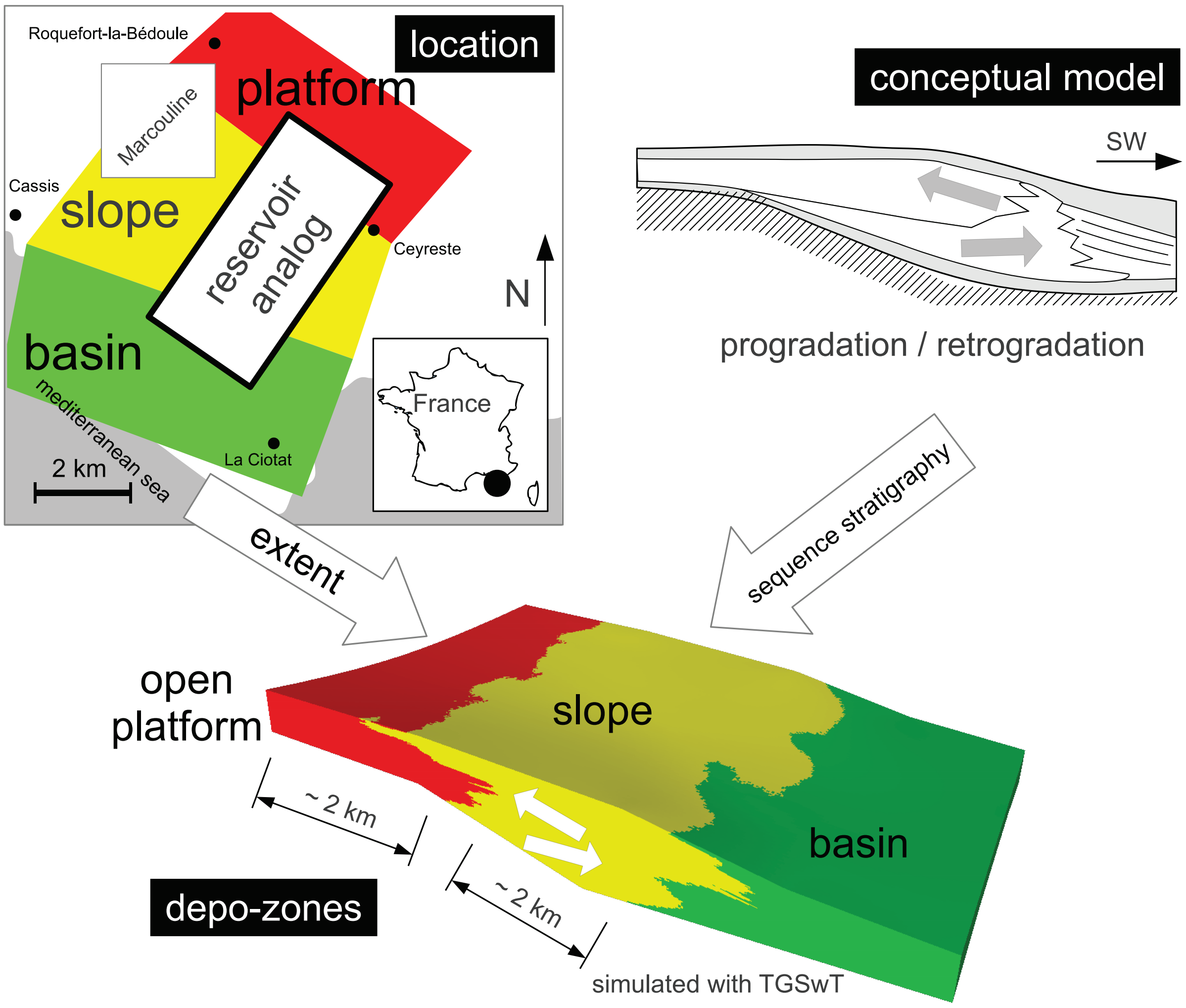


Fig. 12. An outcropping Cenomanian carbonate patform in Southern France was used to demonstrate the application of the hierarchical classification and the database to reservoir modelling. The location and extent of the depo-zones is based on work by Philip (1993) and Gari (2008).

origin is a matter of debate (Fouilhe, 2001; Dovera *et al*., 2006; Gari, 2008). For the purpose of this workflow, it is only important that a depo-shape with different characteristics (geometry, dimensions) is introduced for the slope zone. The inventory of depo-shapes for this demonstration comprises:

• "Mound" deposhape;
Rudist mounds in the depo-zone "open platform";
Mound shapes in the depo-zone "slope";
• "Fan" deposhape in the depo-zones "slope" and "basinal".

According to the hierarchical scheme, the full classification proceeds as follows:

depo-time: Cenomanian;
depo-system: shelf;
depo-zone: open platform;
depo-shape: mound;
depo-zone: slope;
depo-shape: mound, fan;
depo-zone: basin;
depo-shape: fan.

Building the reservoir model with MPS consists of the following steps (Fig. 13):

(i) create a training image for each of the three depo-zones with data from the *Carbdb* database; (ii) simulate the transitions between the depo-zones with "Truncated Gaussian Simulation with Trends" (TGSwT); (iii) build facies probability models based on conceptual considerations; and (iv) run the simulation. For the purpose of this workflow demonstration, the simulations were not conditioned to any hard data.

Firstly, the database is queried for data to build the training images (Fig. 13a). As the available data has been classified, the visual search mask of *Carbdb* can be used to find case studies matching these criteria. For instance, the combination of "Cretaceous" plus "shelf" plus "open platform" plus "mound shape" will bring up results which are classified accordingly. The depo-shapes for the other two depo-zones were extracted from *Carbdb* in the same way. Outcrop photographs and interpretations derived from the literature via the database portray the geometries and dimension of the mounds and show the development of mound complexes. Different types of two-dimensional data (e.g. cross-sections, maps) have different orientations and allow the three-dimensional shape of the mounded bodies to be inferred.

With this information concerning the geometry and dimensions, the next step is to build the three-dimensional training images (Fig. 13b). Because each of the three depo-zone hosts one training image, three training images were built:

(A) *open-platform depo-zone*: rudist reefs form mound-like depo-shapes and overlap in some areas; the training image aims to resemble this geological concept. The depo-shapes in the training-image overlap and may form areas where multiple mounds accumulate;

(B) *slope depo-zone*: mound-shaped bodies and fan-shaped lobes. The mound depo-shapes are not overlapping. The lobes are assumed to surround the mounds but not to cross-cut them. These consideration were taken into account when generating the training image;

(C) *basinal depo-zone*: only lobes are present in this zone and the training image therefore only depicts lobes. The lobes correspond to the lobes in training image B.

Training image A was generated with TiGenerator in SGeMS (Maharaja, 2008). The mound shapes in training image B were generated with TiGenerator in SGeMS, and the lobe/fan shapes were added with object-based simulation in the reservoir modelling software. Training image C was generated with object-based simulation within the reservoir modelling suite. The dimension of the cells in the training image grid correspond to those used later in the simulation grid. A training image with 125000 cells (50 x 50 x 50) has proven to be adequate in the present case. Each of the three training images is assigned to one depo-zone (Fig. 13c). The width of the depo-zones and their overall pro-/ or retrogradational shape is partly based on previous work (Fig. 12) and is simulated with Truncated Gaussian Simulation with Trends. Based on the concept of complexes of depo-shapes caused by antecedent topography in particular regions of the reservoir, multiple three-dimensional probability models (Fig. 13d) were generated to assist the location of facies within the grid.

(1) A first probability model is prepared for the two elements/facies forming the small mound shapes in the open-platform depo-zone. Three areas of high probability on the upper platform edge are defined with a higher density of rudist mounds.

(2) The second probability model controls the two elements/facies forming the mounds in the slope depo-zone. Two somewhat larger areas of high probability result in an accumulation of mounds with an area of low mound density in between.

(3) The third probability model controls the lobe shape present in the training images A and B (Fig. 13b) which are assigned to the slope and basin depo-zones. A low probability suppresses the occurrence of lobe shapes in the upper slope. The high probability in the basinal area allows for a high abundance.

MPS integrates the training image and probability models during the simulation. The final realizations (Fig. 13e) show a close reproduction of the depo-shapes from the training image, as well as the desired accumulation in certain areas. Furthermore, in comparison to the training image, an increase in complexity is observed by amalgamation of single shapes to complexes.

DISCUSSION

The methods introduced in this paper address the import of geological observations into reservoir property models. Deterministic as well as stochastic reservoir facies modelling requires quantitative data on carbonate geobodies. Data from analogue studies to be used in reservoir modelling is available from various sources including publications. However, finding relevant case studies and extracting the required data is time-consuming. The classification for carbonate geobodies presented here allows analogue studies to be classified and managed efficiently, including quantitative data. The subdivision of depositional environments into their elements allows the "building blocks" required as input for the construction of reservoir facies models to be identified. The classification scheme is not bound to a database application but may be applied to any other collection of analogue studies on carbonate geobodies.

The hierarchical classification has proven applicable to most case studies. However, some geobodies are situated between two classes of depo-shapes. Examples would be mounds which are about to amalgamate to mound ridges developing a bar shape. Future use of the classification will show if more classes are required or if, by contrast, some classes can be removed from the scheme.

Managing hundreds of analogue studies with *Carbdb* following the hierarchical classification provides access to the data by geological means not only by raw database queries. The introduction of the new shape-oriented nomenclature is intended to broaden the audience to include engineers and geostatisticians. Further developments of *Carbdb* and training image generating software could provide the user with a seamless integration. As of now, unified preparation of the data of analogue studies in *Carbdb* allows the manual transfer of geological data to training images to be compared and facilitated.

Property modelling aims to populate the unsampled space between hard data (e.g. wells) with geologically meaningful depositional patterns. This can be done either in a deterministic or stochastic fashion. The presented workflow addresses both and promotes the reservoir to be built in hierarchical fashion. Using the same scheme for classification, management and modelling of carbonate geobodies allows the rapid transfer of quantitative data about depositional patterns to reservoir models. Future porosity and permeability models could be used to evaluate dynamic characteristics of the facies model, e.g. depending on different training images.

CONCLUSIONS

A hierarchical classification of carbonate bodies forms the basis for the *Carbdb* database which includes some 600 entries on carbonate systems from outcrops, the subsurface and modern environments. *Carbdb* has been assembled in order to make available appropriate analogues of carbonate reservoir bodies as input data for static reservoir models. A workflow is proposed for carbonate reservoir modelling drawing on the *Carbdb* database and using multiple-point statistics (MPS). This workflow offers the following benefits to the reservoir modeller:

1. For each case to be studied, the hierarchical classification offers a simple search function. The classification starts with depo-time (i.e. age), depo-system, depo-zone, then depo-shape, depo-element and finally depo-facies. The advantage of this uniform terminology is that it is not burdened with pre-existing and often ambiguous definitions. The terminology is intuitive and is intended to be comprehensible to both the geoscience and engineering communities.
2. Quantitative data on relevant case-studies can be retrieved rapidly from the database system. The database is web-based and can be accessed by multiple users simultaneously.
3. Training images for MPS can easily be generated by using geometries, dimensions and distribution patterns of geobodies from the *Carbdb* database.
4. Static reservoir models can also be built in a hierarchical fashion. General models highlighting depo-zones can be divided into their component depo-shapes, depo-elements and depo-facies, depending on the degree of detail required.

The workflow is illustrated with reference to an application to a Cretaceous carbonate reservoir analogue from southern France.

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REFERENCES

AHR, W.M., 1973. The carbonate ramp: an alternative to the shelf model. *Transactions - Gulf Coast Association of Geological Societies*, **23**, 221-225.

ALAVI, M. and LEIDNER, D.E., 2001. Review: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues. *MIS Quarterly*, **25**(1), 107-136.

BOURCHARD, P., 1986. Un modele de talus carbonatee d'origine recifale : exemple du complexe cenomanien de Cassis-La Bedoule (Sud-Est de la France). Stratigraphie - Sedimentologie - Diagenese. Universite d'Aix-Marseille 1, Marseille, France (Universite de Soutenance).

CAERS, J. and ZHANG, T., 2002. Multiple-point Geostatistics: A Quantitative Vehicle for Integrating Geologic Analogues into Multiple Reservoir Models. In: GRAMMER, G.M., HARRIS, P.M., EBERLI, G.P. (Eds.): Integration of Outcrop and Modern Analogues in Reservoir Modelling. *AAPG Memoir* **80**, 383-394.

CARANNANTE, G., RUBERTI, D., SIMONE, L. and VIGLIOTTI, M., 2007. Cenomanian carbonate depositional settings: case histories from the central-southern Apennines (Italy). In: Cretaceous Rudists and Carbonate Platforms: Environmental Feedback. *SEPM Special Publication*, 11-25.

CARRILLAT, A., SHARMA, S.K., GROSSMANN, T., ISKENOVA, G. and FRIEDEL, T., 2010. Geomodelling of Giant Carbonate Oilfields with a New Multipoint Statistics Workflow. In: Proceedings of Abu Dhabi International Petroleum Exhibition and Conference, 1-4 November 2010, Abu Dhabi, UAE. DOI: 10.2118/137958-MS

DALY, C. and CAERS, J., 2010. Multi-point geostatistics - an introductory overview. *First Break*, **28**(9), 39-47.

DOVERA, L., CAERS, J. and BORGOMANO, J., 2006. MPG Simulation of Facies Thicknesses Interpreted through Sequence Stratigraphy – Application on a Carbonate Outcrop. In: Proceedings of the 10th European Conference on the Mathematics of Oil Recovery. EAGE.

ELVEBAKK, G., HUNT, D.W. and STEMMERIK, L., 2002. From isolated buildups to buildup mosaics: 3D seismic sheds new light on upper Carboniferous-Permian fault controlled carbonate buildups, Norwegian Barents Sea. *Sedimentary Geology*, **152**(1-2), 7-17.

FALIVENE, O., ARBUES, P., GARDINER, A., PICKUP, G., MUNOZ, J. A., and CABRERA, L., 2006. Best practice stochastic facies modeling from a channel-fill turbidite sandstone analog (the Quarry outcrop, Eocene Ainsa basin, northeast Spain). *AAPG Bulletin*, **90**(7), 1003-1029. DOI:10.1306/02070605112.

FOUILHE, A., 2001. Le complexe de resedimentation de la formation de la Marcouline (La Bedoule, Provence, France): Temoin d'une plateforme carbonatee de Cenomanien Moyen. Universite Laval. Masters thesis, *unpublished*.

GARI, J., 2008. Developpements en geologie numerique d'affleurement et modelisation stratigraphique 3D: Exemple de la marge carbonatee du bassin Sud-Provencal

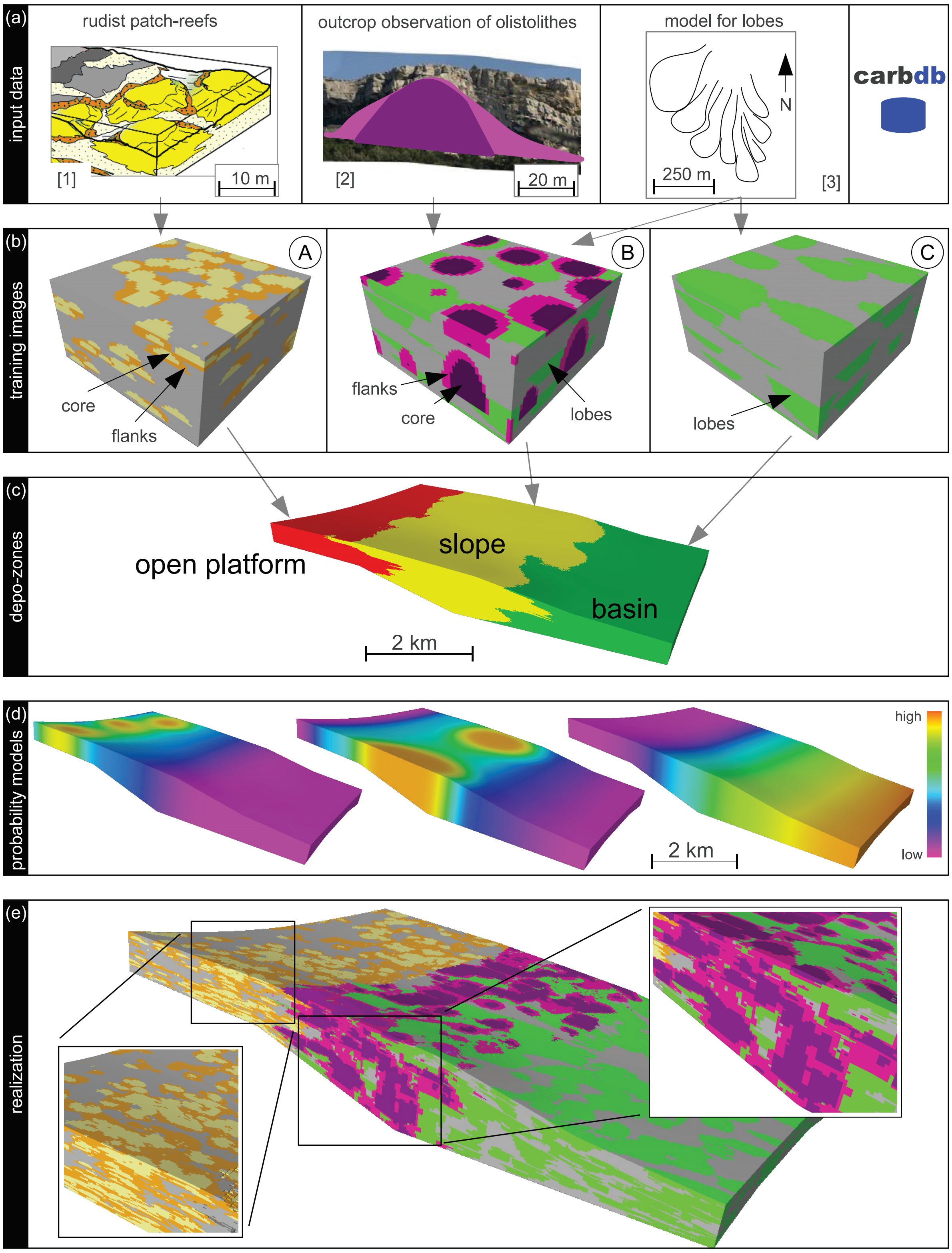

Fig. 13. This chart shows the proposed workflow as applied to a Cenomanian carbonate platform. (a) The *Carbdb* database is queried for data on depo-shapes. (b) For each depo-zone, one case study is evaluated and data on dimensions, geometry and spatial distribution are used to construct training images. (c) The depo-system is subdivided into three depo-zones which were generated stochastically. (d) Three-dimensional probability models permit the facies density to be modelled; if more than one facies type forms one depo-shape, the same probability model can be re-used for each facies type. (e) The final realizations reflect the patterns from the training images as well as the trends from the probability models; by the amalgamation of the depo-shapes from the training images, the final realizations gain in complexity. References: [1] Carannante *et al.*, 2007; [2] Gari, 2008; [3] Bourchard, 1986.

au Cretace Superieur (SE, France). Universite de Provence. Ph.D thesis, *unpublished*.

GINSBURG, R.N. and LOWENSTAM, H.A., 1958. The Influence of Marine bottom Communities on the Depositional Environment of Sediments. *Journal of Geology,* **66**(3), 310-318.

HALL, M., 2010. The future is open for business: open source tools for the geoscientist. *First Break*, **28**(6), 119-123.

HARRIS, P.M., 2010. Delineating and quantifying depositional facies patterns in carbonate reservoirs: Insight from modern analogs. *AAPG Bulletin*, 94 (1), 61-86.

HARDING, A., STREBELLE, S., LEVY, M., THORNE, J., XIE, D., LEIGH, S., PREECE, R. and SCAMMAN, R., 2005. Reservoir Facies Modelling: New Advances in MPS. In: Geostatistics Banff 2004. Quantitative Geology and Geostatistics. Springer Netherlands, 559-568.

HECKEL, P.H., 1974. Carbonate Buildups in the Geologic Record: A Review. In: Reefs in Space and Time - Selected Examples from the Recent and Ancient. *SEPM Special Publication*, 90-154.

HENNING, V. and REICHELT, J., 2008. Mendeley - A Last.fm For Research? In: ESCIENCE '08 Proceedings of the 2008 Fourth IEEE International Conference on eScience (7-12 December 2008, Indianapolis). 327-328. DOI:10.1109/eScience.2008.128

JAMES, N. P., 1983. Reef Environment. In: SCHOLLE, P.A., BEBOUT, D.G. and MOORE, C.H. (Eds), Carbonate Depositional Environments. *AAPG Memoir* **33**. 346-462

JUNG, A., AIGNER, T., PALERMO, D., NARDON, S. and PONTIGGIA, M., 2010. A Hierarchical Database on Carbonate Geobodies and its Application to Reservoir Modelling using Multi-point Statistics. In: 72nd EAGE Conference & Exhibition incorporating SPE EUROPEC, Barcelona, Spain.

KENTER, J.A.M. and HARRIS, P.M., 2005. Web-based Outcrop Digital Analog Database (WODAD): A Public Relational Database Archiving Carbonate Platform Margins in the Geological Record. In: Geophysical Research Abstracts. European Geosciences Union.

KIESSLING, W. and FLÜGEL, E., 2002. Paleoreefs - A database on Phanerozoic reefs. In: Phanerozoic Reef Patterns. *SEPM Special Publication*, 77-92.

LEVY, M., HARRIS, P.M. and STREBELLE, S., 2008. Multiple-Point Statistics (MPS) / Facies Distribution Modelling (FDM) of Carbonates – an Isolated Platform Example. Search and Discovery. *Available at:* http://www.searchanddiscovery.com/documents/2008/08059levy/ [Accessed January 12, 2010].

MAHARAJA, A., 2008. TiGenerator: Object-based training image generator. *Computers & Geosciences*, **34**(12), 1753-1761.

MARKELLO, J.R., KOEPNICK, R.B., WAITE, L.E. and COLLINS, J.F., 2008. The Carbonate Analogues through Time (CATT) Hypothesis and the Global Atlas of Carbonate Fields - A systematic and predictive look at Phanerozoic Carbonate Systems. In: LUKASIK, J., SIMO, J.A. (Eds), Controls on Carbonate Platform and Reef Development. *SEPM Special Publication*, 15-45.

McAFEE, A.P., 2006. Enterprise 2.0: the dawn of emergent collaboration. *Engineering Management Review, IEEE*, **34**(3), 38.

MIALL, A.D. and TYLER, N. (Eds), 1991. The Three Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery. *Concepts in Sedimentology and Paleontology*, **3**, 309 pp. SEPM. DOI: 10.2110/csp.91.03.

MORGAN, W.A. and HARRIS, P.M. (Eds.), 2008. Developing Models and Analogues for Isolated Carbonate Platforms - Holocene and Pleistocene Carbonates of Caicos Platform, British West Indies. *SEPM Core Workshop* 22.

O'REILLY, T., 2005. What Is Web 2.0 - Design Patterns and Business Models for the Next Generation of Software. *Available at*: http://www.oreillynet.com/pub/a/oreilly/tim/news/2005/09/30/what-is-web-20.html [Accessed April 30, 2009].

PALERMO, D., AIGNER, T., NARDON, S., BLENDINGER, W., 2010. Three-dimensional facies modeling of carbonate sand bodies: Outcrop analog study in an epicontinental basin (Triassic, southwest Germany). *AAPG Bulletin*, **94** (4), 475-512.

PHILIP, J., 1993. Late Cretaceous Carbonate-Siliciclastic Platforms of Provence, Southeastern France. In: SIMO, J.A., SCOTT, R.W., MASSE, J.P. (Eds), Cretaceous Carbonate Platforms. *AAPG Memoir* **56**. 375 - 385.

POMAR, L. and KENDALL, C.G.S.C., 2008. Architecture of Carbonate Platforms: A Response to Hydrodynamics and Evolving Ecology. In: Lukasik, J. and Simo, J.A. (Eds), Controls on Carbonate Platform and Reef Development. *SEPM Special Publication* **89**, 187-216.

POMAR, L. and HALLOCK, P., 2008. Carbonate factories: A conundrum in sedimentary geology. *Earth-Science Reviews*, **87**(3-4), 134-169.

PURSER, B.H. and EVANS, G., 1973. Regional Sedimentation along the Trucial Coast, SE Persian Gulf. In: PURSER, B.H. (Ed.), The Persian Gulf. Springer, 211-231.

RANKEY, E.C. and HARRIS, P.M., 2008. Remote Sensing and Comparative Geomorphology of Holocene Carbonate Depositional Systems. In: Lukasik, J. and Simo, J.A. (Eds), Controls on Carbonate Platform and Reef Development. *SEPM Special Publication* **89**, 317-322.

RANKEY, E. C. and REEDER, S. L., 2011. Holocene Oolitic Marine Sand Complexes of the Bahamas. *Journal of Sedimentary Research*, **81** (2), 97-117.

REMY, N., BOUCHER, A. and WU, J., 2009. Applied Geostatistics with SGeMS: A User's Guide, Cambridge University Press.

SCHLAGER, W., 2003. Benthic carbonate factories of the Phanerozoic. *International Journal of Earth Sciences*, **92**(4), 445-464.

SINHA, A.K., MALIK, Z., REZGUI, A., BARNES, C.G., LIN, K., HEIKEN, G., THOMAS, W.A., GUNDERSEN, L.C., RASKIN, R., JACKSON, I., FOX, P., McGUINNESS, D., SEBER, D. and ZIMMERMAN, H., 2010. Geoinformatics: Transforming data to knowledge for geosciences. *GSA Today*, **20**(12), 4-10.

STREBELLE, S., 2002. Conditional Simulation of Complex Geological Structures Using Multiple-Point Statistics. *Mathematical Geology*, **34(**1), 1-21.

STREBELLE, S. and JOURNEL, A., 2001. Reservoir Modelling Using Multiple-Point Statistics. In: Proceedings of SPE Annual Technical Conference and Exhibition, 30 September-3 October 2001, New Orleans, Louisiana. DOI: 10.2118/71324-MS.

STREBELLE, S. and LEVY, M., 2008. Using multiple-point statistics to build geologically realistic reservoir models: the MPS/FDM workflow. In: ROBINSON, A., GRIFFITHS, P., PRICE, S., HEGRE, J., and MUGGERIDGE, A. (Eds), The Future of Geological Modelling in Hydrocarbon Development. *Geological Society London Special Publication,* **309**(1), 67 -74.

STREBELLE, S., PAYRAZYAN, K. and CAERS, J., 2003. Modeling of a Deepwater Turbidite Reservoir Conditional to Seismic Data Using Principal Component Analysis and Multiple-Point Geostatistics. *SPE Journal*, **8** (3), 227-235.

SURLYK, F., 1987. Slope and deep shelf gully sandstones, Upper Jurassic, East Greenland. *AAPG Bulletin*, **71**(4), 464-475.

TUCKER, M.E., 1985. Shallow-marine carbonate facies and facies models. In: Brenchley, P. J. and Williams, B. P. J. (Eds), Sedimentology Recent Developments and Applied Aspects. *Geological Society London, Special Publication*, **18**(1), 147-169.

TUCKER, M. E., WILSON, J. L., CREVELLO, P. D., SARG, J. R., and READ, J. F. (Eds), 1990. Carbonate Platforms. IAS *Special Publication* **9**. Wiley.

TUCKER, M.E. and WRIGHT, V. P. 1990. Carbonate Sedimentology. Blackwell Publishing.

ULLRICH, C., BORAU, K., LUO, H., TAN, X., SHEN, L. and SHEN, R., 2008. Why web 2.0 is good for learning and for research: principles and prototypes. In: Proceeding of the 17th international conference on World Wide Web. WWW '08. ACM, 705–714.

WENDT, J., BELKA, Z. and MOUSSINE-POUCHKINE, A., 1993. New architectures of deep-water carbonate buildups: Evolution of mud mounds into mud ridges (Middle Devonian, Algerian Sahara). *Geology*, **21**(8), 723-726.

WHEELER, A.J., BEYER, A., FREIWALD, A., HAAS, H., HUVENNE, V.A.I., KOZACHENKO, M., OLU-LE ROY, K. and OPDERBECKE, J., 2006. Morphology and environment of cold-water coral carbonate mounds on the NW European margin. *International Journal of Earth Sciences*, **96**(1), 37-56.

WILKINSON, B.H., 1979. Biomineralization, paleo oceanography and the evolution of calcareous marine organisms. *Geology*, **7**(11), 524-527.

WILKINSON, B.H., OWEN, R.M. and CARROLL, A.R., 1985. Submarine hydrothermal weathering, global eustasy and carbonate polymorphism in Phanerozoic marine oolites. *Journal of Sedimentary Research*, **55**(2), 171-183.

WILSON, J.L., 1975. Carbonate Facies in Geologic History. Springer.

ZHANG, T., 2008. Incorporating Geological Conceptual Models and Interpretations into Reservoir Modelling Using Multiple-Point Geostatistics. *Earth Science Frontiers*, **15**(1), 26-35.