Paper 2

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SEISMIC FACIES ANALYSIS BASED ON 3D MULTI-ATTRIBUTE VOLUME CLASSIFICATION, DARIYAN FORMATION, SE PERSIAN GULF

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Interpretation of recently acquired 3D seismic data from the adjacent Sirri C and D oilfields in the SE Persian Gulf indicates that a 3D interpretation of seismic facies is crucial to resolve the internal stratal geometries of the Aptian Dariyan Formation. This carbonate formation passes southward into the Shu'aiba Formation, a prolific reservoir rock of similar facies in the UAE. Lack of exposures and limited cored intervals have forced reliance on the seismic data for evidence of the depositional environment and the internal architecture of potential reservoir rocks. The progradational nature of the Dariyan Formation and the occurrence of carbonate build-ups within it make this stratal geometry complex. The complex internal heterogeneity of the build-ups and presence of seismic noise make mapping of the build-ups in 3D space using conventional seismic interpretation tools difficult, despite the availability of high-quality 3D seismic data covering the area.

The high quality seismic and limited well data from this field is one of the few datasets of this kind presented in the literature. A procedure for the hierarchical multi-attribute analysis of seismic facies using Paradigm's SeisFacies software is used in this study to provide a 3D interpretation of the stratal patterns. Principal component analysis reduces the noise and redundant data by representing the main data variances as a few vector components in a transformed coordinate system. Cluster analysis is performed using those components which have the greatest contribution to the maximum spread of the data variability. Six seismic attribute volumes are used in this study and the result is a single 3D classified volume.

Important new information obtained from within the Dariyan Formation gives new insights into its stratigraphic distribution and internal variability. This method of processing seismic data is a step towards exploring for subtle stratigraphic traps in the study area, and may help to identify exploration targets.

INTRODUCTION

Stratal geometries and patterns in the Aptian Dariyan Formation (James and Wynd, 1965) in the SE Persian Gulf are not well documented. The lateral equivalent Shu'aiba Formation forms a major carbonate reservoir in the Arabian Peninsula and has been intensively studied (Alsharhan, 1985; Calavan *et al*., 1992; Hughes, 2000; Terken *et al*., 2001; Fisher *et al*., 1997; Immenhauser *et al*., 2001; Duffy Russell *et al* , 2002; van Buchem *et al*., 2002b; Borgomano *et al*., 2002; Pittet *et al*., 2002; Hillgärtner *et al*., 2003; Montenat *et al*., 2003). The internal heterogeneity of this carbonate interval and the low impedance contrast between rock units make horizons difficult to trace. Therefore, in terms of seismic data analysis, which is the main focus of this study, a horizon-based interpretation approach has failed to provide a truly 3D interpretation that can be visualized in 3D space.

Mapping the complex geological features of this formation in 3D space using a single seismic attribute volume is almost impossible. A single attribute volume resulting from numerical calculations can include patterns of similar points which are of diverse origin. Seismic data are highly redundant; therefore, post-

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stack attributes derived from the data tend to be redundant. Noise as a significant component of seismic data can link the meaningful patterns and prevent them from being imaged in isolation. Consequently, any attribute volume must be analyzed to exclude spurious data. However, the remaining portion is not a unique solution.

The aim of this paper is to demonstrate how a synthesis of different 3D attribute volumes can be used to reveal meaningful variability within the seismic data from the Dariyan Formation and to provide a 3D interpretation. In 3D seismic facies classification, the results can be displayed in map view (two-dimensional representations) or can be projected over 2D sections. In 2D representations, 3D geological features are superimposed one upon another. Application of proportional or stratal slices (Posamentier *et al*., 1996; Zeng *et al*., 1998a, 1998b) throughout the classification volume provides important geological information and detail, reflecting the true shape, connectivity and heterogeneity of the main features of interest, as is shown in this work for rudist build-up geometries.

Principal component analysis (PCA) is used to perform dimension reduction (Gurney, 1997) of a multivariate dataset by compressing the bulk of the variances in the seismic data into as few vector components as possible.

A hierarchical method is used for the seismic facies classification. In the hierarchical classification, different seismic attribute volumes are integrated and divided into clusters of similar pattern. Cluster analysis (i.e. discovering clusters of similar pattern) after data reduction characterized the input data volumes as population subsets of multi-dimensional clouds. The results are generated and displayed as a volume in 3D space so that the true shapes and relationships of the geobodies can be analyzed.

The generated volume and 3D facies patterns appear to be more diagnostic than the original seismic reflection data and /or single attribute volumes. Inspection of these patterns in combination with well data resulted in a more confident correlation and seismic stratigraphic interpretation, and improved our understanding of the development of the internal geological features of the Dariyan Formation in the study area at tne *Sirri C* and *D* oilfields.

GEOLOGICAL SETTING

The study area is located in the SE portion of the Persian Gulf in the territorial waters of Iran (Fig. 1a). The limits of the area are defined by the limits of a 3D seismic dataset covering two salt-driven domal structures (*Sirri C* and *D*: Fig.1A) with an areal extent of 300 sq. km.

During the Mesozoic, the Persian Gulf was located at the NE edge of the Arabian Plate (Glennie, 2000), and extensive carbonate platforms covered the area. Carbonate deposition was frequently interrupted by subaerial exposure and the influx of siliciclastics attributed to tectonic movements of the Arabian Shield and eustatic sea-level fluctuations (Sharland *et al*., 2001).

The Aptian Dariyan Formation (Fig. 2) correlates with the lower and middle parts of the Shu'aiba Formation which are prolific reservoirs in the UAE (Calavan *et al*., 1992; Terken *et al*., 2001; Fisher *et al*., 1997; Duffy Russell *et al*., 2002; van Buchem *et al*., 2002b). This laterally extensive, shallow-marine carbonate platform consists mainly of mud-supported and some grain-supported limestones with rudist debris (Fisher *et al*., 1997; van Buchem *et al*., 2002b). The overall regional setting during deposition of the Dariyan Formation was a shelf to shallow-basin complex, resulting in progradational mounds. A lowstand or shelf margin wedge of the equivalent Shu'aiba platform (Bab Sand Member, Fig.2) is observed in the UAE (Aldabal and Alsharhan, 1989; Fischer *et al*., 1997) but is probably thinly developed in the study area. An offshore development of calcareous shales with rudist debris occurs in this area and corresponds to the lower Dariyan Formation.

The deposition of the Dariyan Formation corresponds to a 3rd order sea-level highstand (Sharland *et al*., 2001). The basal limestones overlying the transgressive argillaceous limestones and greenish grey shales of the Barremian Gadvan Formation (Fig. 2) may be correlated with the K70 MFS of Sharland *et al*. (2001). Overlying this, two progradational units separated by a backstepping unit resulting from a flooding event are recognized from wireline logs and core description reports (*IOOC unpublished)*. The uppermost section reflects a continued reduction in water depths that ended with a relative sea-level fall in the late Aptian recognized as a regional unconformity over the entire Middle East (Harris *et al*., 1984). Deeper marine shales of the Kazhdumi Formation overlie this exposure surface.

Two horizons can be mapped with confidence through the entire 3D dataset in the study area: the top-Dariyan (Fig. 1b) and the top-Gadvan Formations. Both surfaces are characterized by high impedance contrasts that result from the juxtaposition of Dariyan carbonates with (i) Kazhdumi shales at the top; and (ii) the upper shaly part of the Gadvan Formation at the base. It is difficult to map additional horizons within the Dariyan Formation with any confidence.

In the UAE, exploration and development wells indicate that reservoir quality in the Shu'aiba Formation is closely related to primary depositional facies, with the best quality encountered in prograding

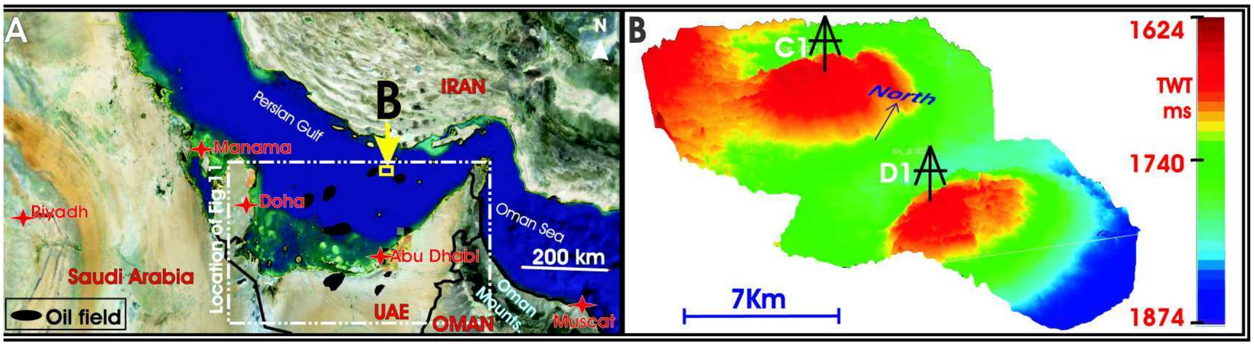


Fig. 1. (A) Location map of the study area in the SE Persian Gulf (arrow) and nearby oilfields (refer to Fig.11 for details). (B) Time structure map of the Dariyan Formation (Aptian) showing two salt-driven domal structures and the location of wells *C1* and *D1*.

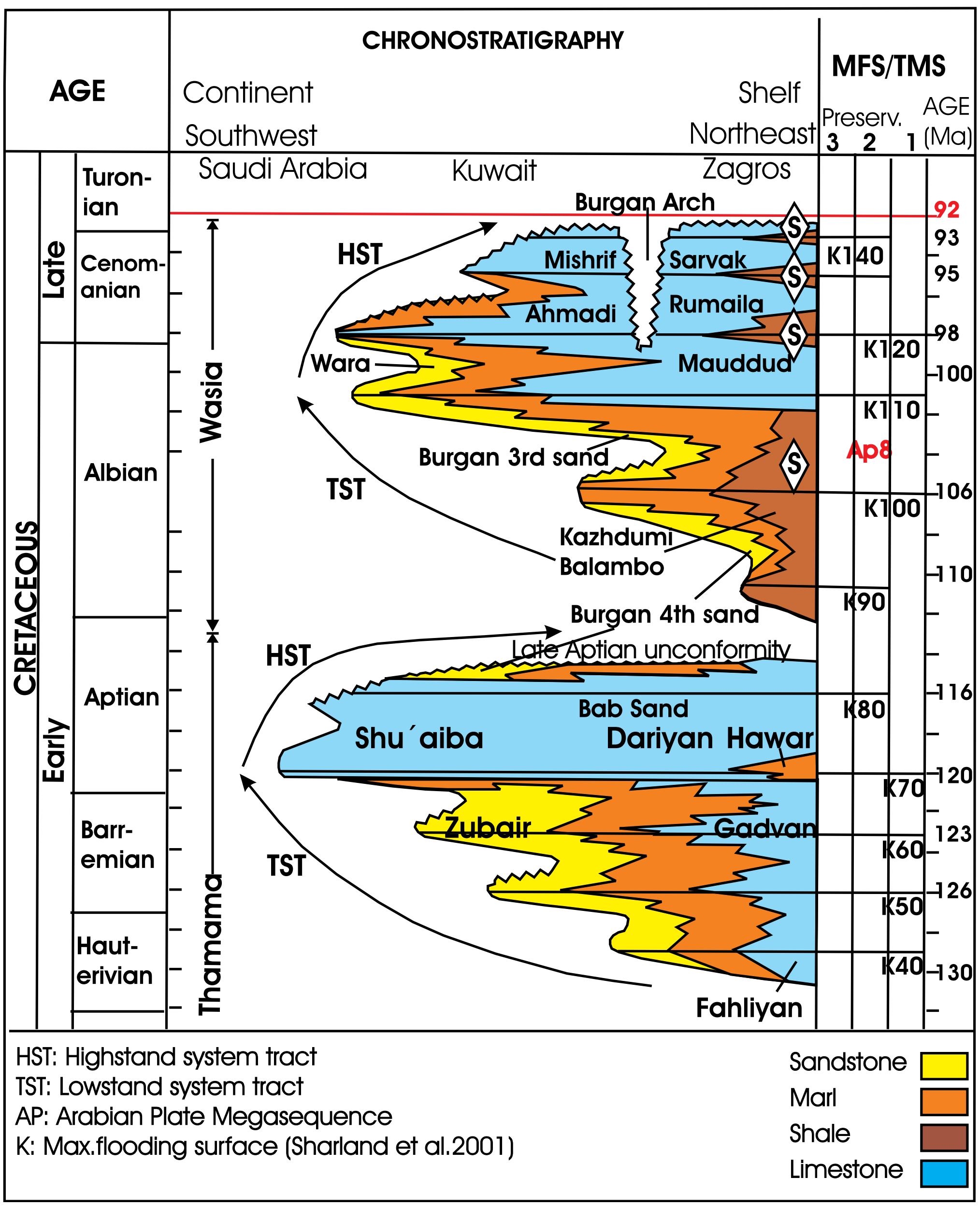


Fig. 2. Chronostratigraphy of the Cretaceous in the Middle East region (after Sharland *et al.*, 2001). The studied interval, the Dariyan Formation, correlates with the Shu'aiba Formation in Saudi Arabia, UAE, Kuwait and Oman. Deposition of the Dariyan Formation corresponds to a 3rd order highstand during the Aptian (see text for details).

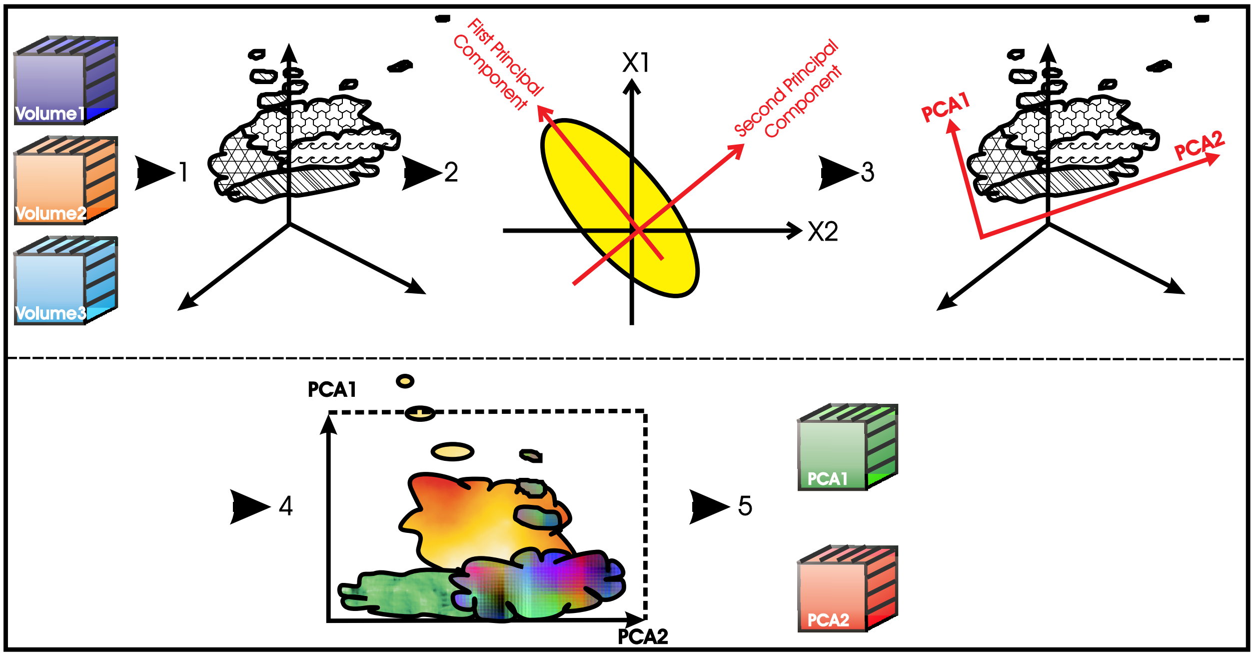


Fig. 3. Schematic diagram of PCA analysis showing how a 3D plot of three data volumes (standardized) can be reduced to two PCA components.

The correlation matrix of the input data volumes is decomposed into a summation of Eigen vectors and values. The variance as a function of the covariance matrix and projection weights is greatest along the maximum elongation trend of each component. By imposing a standardization constraint, maximization of variance is achieved by orthogonal rotation of the principal axes. Redundant data which do not contribute to the maximum spread of the data clouds are eliminated by this method.

carbonates and/or carbonate build-ups (e.g. Calavan *et al*., 1992; Fischer *et al*., 1997; Borgomano *et al*., 2002; Droste and van Steenwinkel, 2004).

Previous high-resolution sequence stratigraphy studies based on well and outcrop data of the Shu'aiba Formation (Witt and Gokdag, 1994; van Buchem *et al*., 2002b; Droste and van Steenwinkel, 2004) in Oman and the UAE have shown that the Lower Cretaceous Shu'aiba platform consists of well-defined progradational clinoform belts with complex internal geometries. The existing horizon maps at the top (Fig. 1B) and base of the laterally-equivalent Dariyan Formation show variability only at the top and base of the study section and not within it. In the present study, multiple attribute seismic classification in combination with a data reduction technique (PCA) is used to investigate possible similar complexities within the Dariyan Formation and to interpret them in the studied area.

Oneof the wells studied penetrated the entire Dariyan Formation, and the second penetrated the upper half of the formation. Both wells were drilled to assess the younger Mishrif reservoir (Farzadi, 2006). Although they penetrated the Dariyan Formation, they did not target the scattered build-ups within it. The wells did not provide an optimal test of the interval, but they provided valuable information for sequence stratigraphic purposes.

MATERIALS AND METHODS

Data

In this study, a seismic cube covering 300 sq. km was used for the analysis. The seismic data that were acquired by Fugro-Geoteam AS over the *Sirri C* and *D* structures (Fig. 1) during November and December, 2001 had a bin size of 12.5 x 12.5m, 40 fold coverage, a sampling interval of 4ms and record length of 6 seconds. These pre-stack time-migrated seismic data have a broad frequency bandwidth with a dominant frequency in the range of 37-40 Hz within the Dariyan Formation, which is located at relatively shallow depths (2,630-2,740m interval at the *C1* location, 1,650-1,850 ms TWT throughout the area).

Wireline logs and limited core description reports from the two vertical wells, one of which penetrated the entire interval while the other penetrated the upper half of the formation were used for the interpretation. Faunal content palaeologs allowed the temporal and spatial relationships of events to be estimated.

Methods:

Principal component analysis (PCA)

Principal component analysis (PCA) is a statistical technique for performing dimension reduction (Kendall, 1975; Gurney, 1997). This mathematical procedure examines the pattern space and finds the

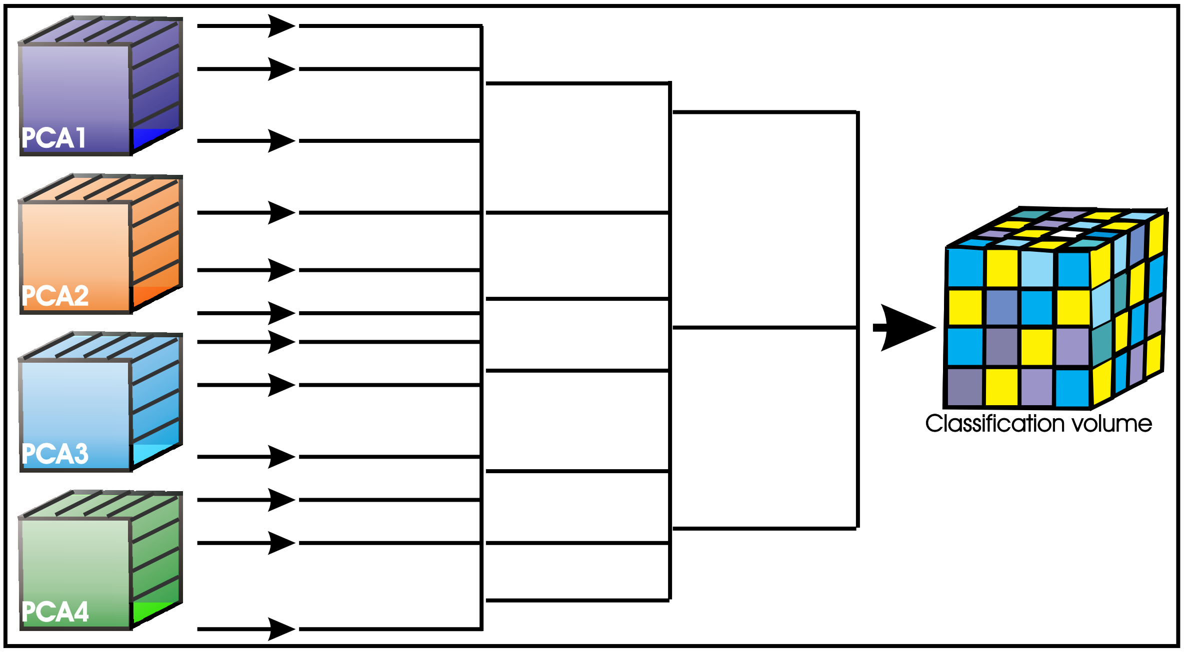


Fig. 4. Hierarchical classification of input data volumes (seismic attribute volumes). The true dimensionality of the data, which is much smaller than the large number of seismic samples, is recognized (PCA result). Each value of the original data is assigned to the cluster to which it best correlates. The clusters are sorted in a progressive sequence and a single data volume is generated.

principal directions of variances within multi-dimensional data. A large number of input attribute volumes (this study) dramatically increases data redundancy. Noise and redundant data (components with the least contribution to the data variability) must be minimized (using PCA) as they link the geologic features and destroy their isolation. Attempts to reduce the data by manually removing redundant attributes may cause loss of information not immediately recognized as valuable by the interpreter (Linari *et al*., 2003).

In PCA, the data are cross-plotted and the main trends of the cross-plot are identified (Fig.3). N-dimensional cross-plots of the seismic data show organization of a limited number of elongated subclouds (clusters). This indicates that the true dimensionality of the data is much lower than the large number of samples would suggest. These principal directions represent the heterogeneity of the multi-dimensional data clouds (clusters). In order to describe the data more effectively, the co-ordinate axes are rotated such that the new X-axis lies along the direction of maximum variance, resulting in distinct discrimination along this axis. In this way the data is presented in a more efficient co-ordinate system. Transformation is linear, as co-ordinate rotation is a linear transformation. Although each point still needs two co-ordinates in the transformed system, the most important feature is contained in the single dimension (X'). In a multi-dimensional distribution of the clusters, the required angle of rotation is not known. To find the optimal transformation, the system looks for a transformation in which the variance along one of the new axes is at a maximum while orthogonal rotations are allowed. The bulk of the variance in the data is then compressed into a few vector components (Eigen vectors) labelled in order of decreasing data variability. In other words, the data matrix is decomposed into a summation of Eigen vectors and Eigen values (singular value decomposition; Mari *et al*., 1999). The Eigen vector of a data matrix gives a direction in which a linear transformation is simply a scaling, and the amount of scaling is the associated Eigen value. Each component is analyzed based on its Eigen value and its contribution to the maximum spread of the data cloud. Those components with an Eigen value close to or greater than 1 are generally selected as they are assumed to have the greatest contribution to the maximum spread. The first component contains the largest data variance resulting from co-ordinate rotation; the second component contains the largest part of the remaining variance, and so on. The first few vector components in the transformed co-ordinate system are the principal components and the required transformation is obtained by PCA (Gurney, 1997). The essential information about the dataset is contained in the first few principal components, which will be used for facies classification. The selected components are then projected onto the principal axes, thus reducing volume, noise and redundancy for the classification process (Fig.3).

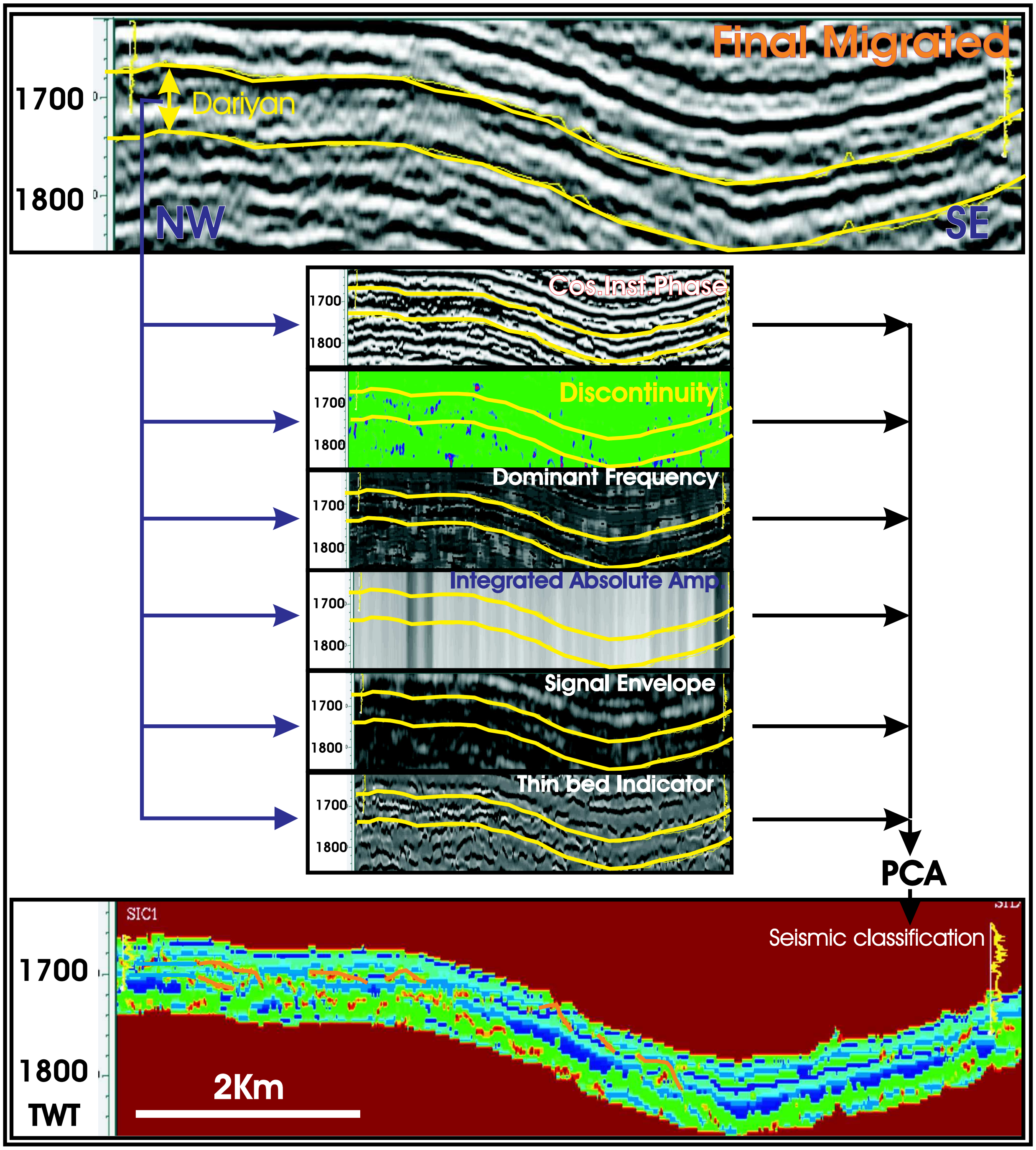
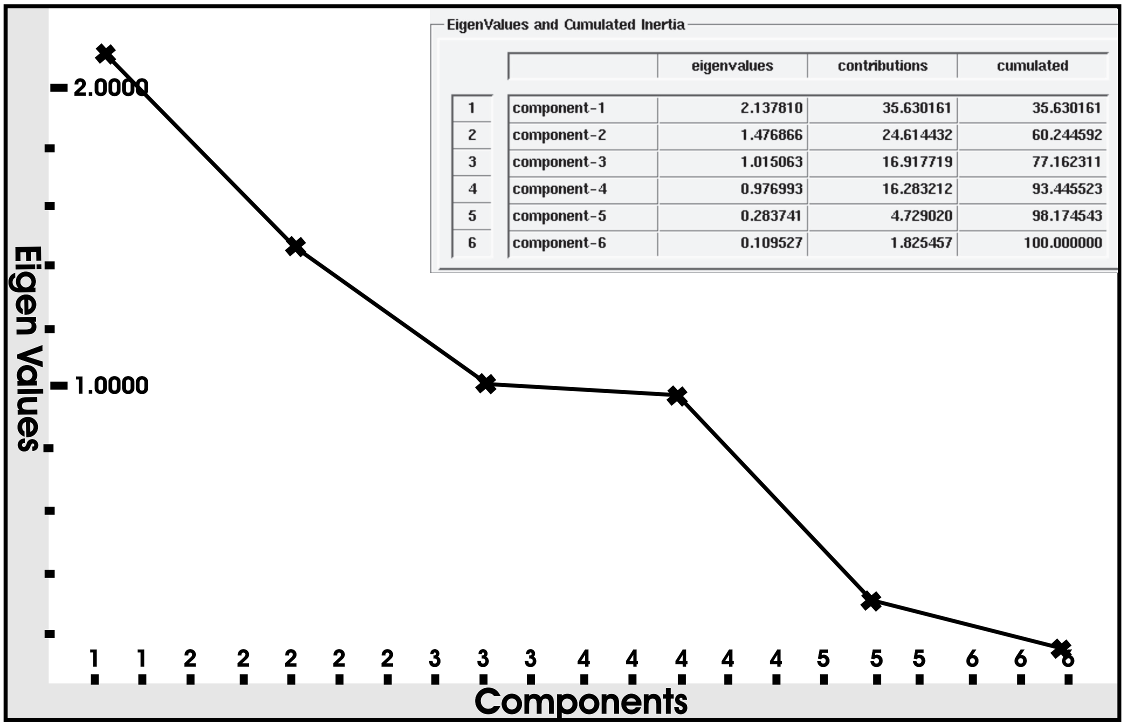


Fig. 5. Multi-attribute classification of complex internal features of the Dariyan Formation in the SE Persian Gulf. Six seismic attribute volumes extracted from the study interval (70 ms) were used for the classification. Input attribute volumes (middle) are combined, and after data reduction by PCA, a single seismic facies volume is generated using hierarchical classification. Note the increased definition of the classification result (bottom) compared to the conventional amplitude stack (top).

SEISMIC FACIES CLASSIFICATION

The aim of seismic facies classification is to recognize meaningful variability within the 3D seismic data in order to highlight geologic features, generally hidden within the redundant seismic noise. The use of automatic seismic facies classification techniques and their role in the interpretation process were reviewed by Coleou *et al*. (2003) and Linari *et al*. (2003).

The aim is to build a model of clusters of similar points (grouping similar items together to form nodes or classes) by combining different seismic attribute volumes and to compare them to the actual data values. Each data value is then assigned to the cluster or class to which it best correlates. The 3D distribution of the classes or seismic facies resulting from the classification method makes data useful for geologic interpretation.



		eigenvalues	contributions	cumulated
1	component-1	2.137810	35.630161	35.630161
2	component-2	1.476866	24.614432	60.244592
3	component-3	1.015063	16.917719	77.162311
4	component-4	0.976993	16.283212	93.445523
5	component-5	0.283741	4.729020	98.174543
6	component-6	0.109527	1.825457	100.000000

Fig. 6. Cross-plot showing the Eigen values calculated for the six components. The principal components that contribute significantly to the main elongation trend of the dataset have Eigen values close to 1 or higher. Components with Eigen values less than 1 are usually either redundant data or noise and can be eliminated. The table (inset) shows that the contribution of the first four components to the dataset is 93.4%.

To increase the information available for facies classification, multiple post-stack seismic attribute volumes derived from original seismic data are used in this study. Since seismic attributes with different dimensions are used (e.g. amplitude, impedance and discontinuity), some re-scaling or standardization is necessary, preventing one attribute from having a greater significance than another. Once the correlation matrix of the input attributes is known, the standard linear algebraic technique of PCA reduces data redundancy. Seismic samples from a multivariate dataset are grouped into clusters of similar points using a hierarchical classification system. Cluster analysis is performed in an N-dimensional space where N is the number of seismic attribute volumes. Clusters are discriminated based on the Euclidean distance between each. N-dimensional cross-plots of the seismic data show significant organization as elongated sub-clouds with some branching. In the classification process, it is assumed that two samples are in the same facies class if they are characterized by similar values in all input seismic attribute volumes, and therefore probably correspond to similar geologic environments. A hierarchical classification procedure builds a model of classes or clusters of similar points and compares them to the original seismic data values of the entire cube. Each data value is then assigned to the cluster to which it best correlates (Fig.4). There is a huge number of seismic samples within the data volumes but the true dimensionality of the seismic data is much lower than that indicated by the large number of samples.

Work flow

This study follows the multi-attribute hierarchical classification workflow built into the *Paradigm Seisfacies* software and includes the following steps:

1. Multiple seismic attribute cube generation;
2. performing the PCA analysis and determining the principal components;
3. examining the calculated Eigen vectors and values to determine how many components contribute significantly to the main elongation trend of the dataset, and eliminating those with little contribution (noise and redundant data);
4. projection of the main components onto primary principal axes;
5. processing the data to determine the classes;
6. inspection of the processing results to adjust the number of classes by examining the cross-plots to ensure adequate clustering and minimal overlap;
7. classification of seismic data and single volume generation;
8. visualization, well calibration and interpretation.

In step 1, six attribute volumes are generated (Fig. 5). There is no limit to the number of attribute volumes involved in this method, but the process

Components variable correlation		Dom.Freq.	Cos.Inst.Ph.	Thin.Bed.Ind.	Disccont.	Signal Env.	Int.Abs.Amp.
1	component-1	-0.452270	-0.228529	0.100426	0.308763	-0.565959	-0.563469
2	component-2	0.530798	0.292373	0.150497	-0.532175	-0.385006	-0.422710
3	component-3	-0.011512	0.671727	0.575721	0.456331	0.094489	-0.005437
4	component-4	-0.033590	-0.520077	0.788187	-0.267030	0.183120	0.048115
5	component-5	0.715755	-0.374528	0.000094	0.584123	-0.073483	-0.028698
6	component-6	0.011832	-0.018016	-0.120713	0.026690	0.695414	-0.707567

Fig. 7. Components variable correlation showing the weight of each component on the six input variables. The contribution of each attribute to the PCA components is indicated in this table.

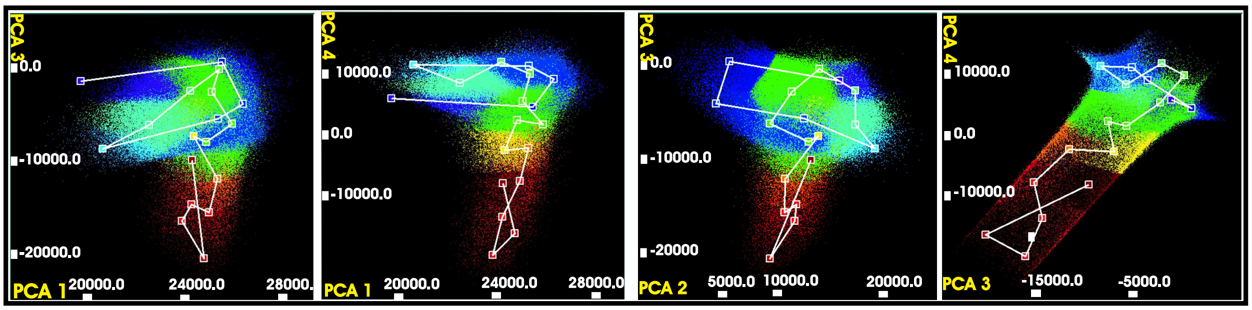


Fig. 8. Two-dimensional cross-plots of data distribution plotted against different principal axes. Note that two classes which are next to eachother in one cross-plot may be some distance apart when viewed on a different cross-plot.

becomes increasingly demanding by increasing the data dimensionality. A constant interval of 70 ms from the top Dariyan Formation was selected for the analysis that covers the entire formation. In step 2, the principal components are determined using N-dimensional cross-plots of the data (as discussed above). In step 3, significant principal components which have Eigen values close to 1 or higher are selected. Components with low Eigen values (less than 1) do not contribute significantly and are generally either redundant data or noise. The contribution of the first four components (out of 6) to the dataset is 93.4% (Fig. 6). Component values are calculated by multiplying the Eigen vector by the square root of the Eigen values. This ensures that the components represent the weighting of the original Eigen values. The table in Fig. 7 gives an indication of the contribution of each block (attribute) to the PCA components. In step 4, the four components are projected onto the principal axis.

Once the data have been projected onto the principal axis, the actual attribute values associated with each volume are replaced by the projected values. In step 5, the data are characterized into meaningful population subsets and a representative (class) is defined for each subset (Fig.8).

Hierarchical classification is sensitive to the number of facies classes processed, so steps 5 and 6 are necessarily iterative. Several modifications to the number of classes are required before a satisfactory result is achieved. Cross-plots showing the facies model classes relative to the data spread are used to determine the appropriate number of classes (Fig.8). The appropriate number and choice of classes is determined by examining the distribution of clusters to achieve minimal overlap between classes. The data should have facies model classes distributed across the entire range with an appropriate density for the data.

The data is projected onto 2D plots (Fig. 8). For a clear understanding of facies model relationships, one needs to look at the distribution plotted against different axes. Two classes may appear right next to each other in one cross-plot, but may actually be some distance apart when viewed on another cross-plot.

The next step (step 7) is to apply the facies classification to the entire dataset to assign individuals (original data points) to the appropriate facies class (subset) based on Euclidean distance. The eighth and final step is the most important and is where the interpreter's skills play a major role in the understanding of the 3D facies classification volume.

FACIES SUCCESSION: WELL CALIBRATION

In this study of the Dariyan Formation, the generated seismic facies data were calibrated with two wells,

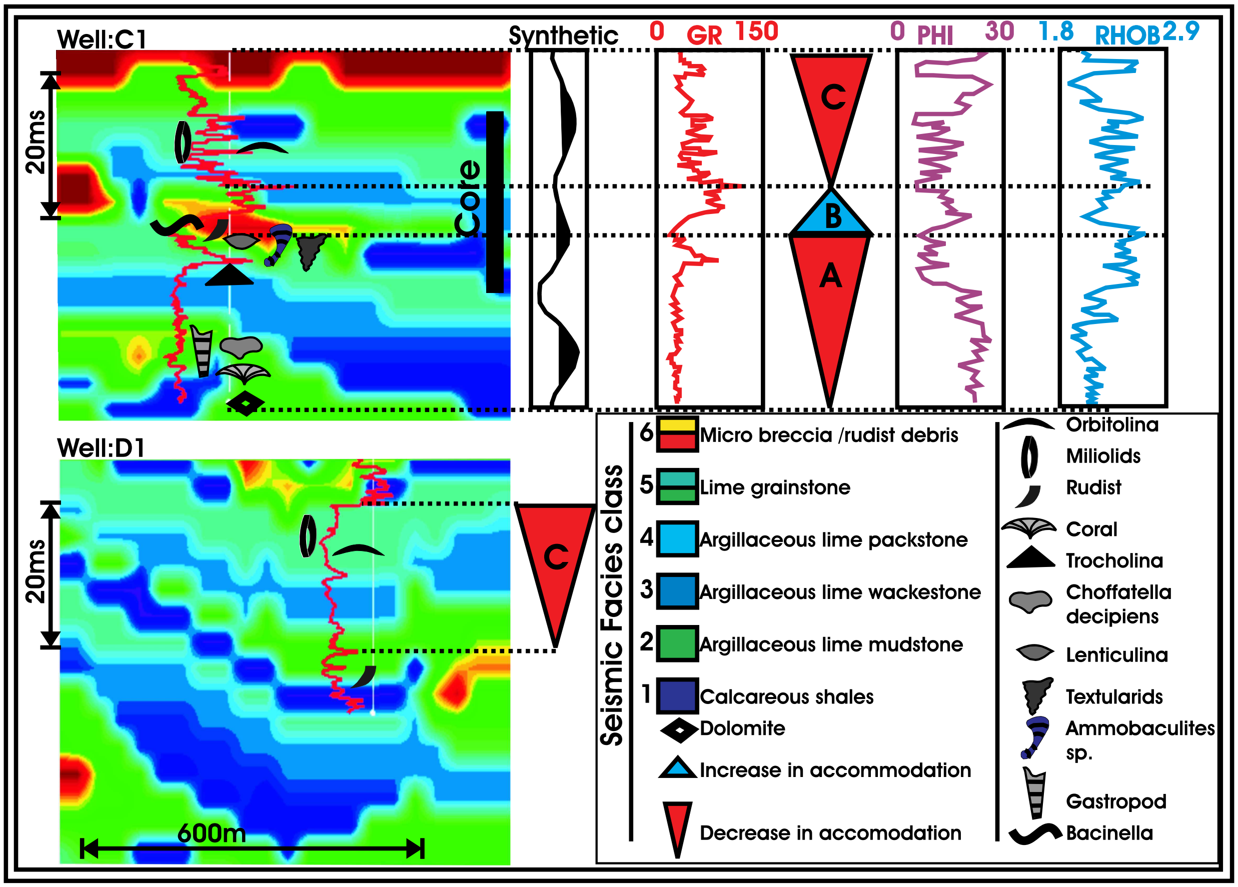


Fig. 9. Well calibration: three fining- or coarsening-upward successions are recognized based on the gamma-ray log. These successions correspond to a 3rd order highstand of relative sea level (Sharland *et al.*, 2001). A synthetic seismogram at the well location, as well as porosity and density logs are shown (upper right) for a comparison between the seismic wiggle trace and the more diagnostic classification data (left) in relation to rock properties. Fossils from core descriptions are projected over the classification data at well locations. Six facies classes are recognized; their 3D distribution is discussed in the text.

one crossing the entire interval and the other only the upper half of it. Palaeontological information obtained from faunal palaeologs and limited core descriptions were used for comparison with detailed biostratigraphic analysis of the time-equivalent Shu'aiba Formation in the UAE (Alsharhan and Kendall, 1991; van Buchem *et al.*, 2002b), Saudi Arabia (Hughes, 2000) and Oman (Pittet *et al.*, 2002; van Buchem *et al.*, 2002b).

Depositional cycles as coarsening/fining upward successions derived from gamma-ray (GR) logs were used to enhance the facies succession analysis. In addition, porosity and density logs available from one well classified vertical variations in rock properties (Fig. 9).

Three GR-derived cycles within the study interval are interpreted as alternating progradational and backstepping units (unit A, B, C: Fig. 9). The lower progradational/aggradational unit is interpreted as a response to rising sea level in the early Aptian (Vail *et al.*, 1977; Koop and Stonely, 1982; Sharland *et al.*, 2001).

Based on core description reports, the sediments in the lower Shu'aiba are mostly mudstones, characterized by mixed, diverse biota including *Choffatella decipiense*, corals and gastropods. The diverse biota, the scarcity of miliolids and the homogeneous facies point to normal, stable marine conditions (Pittet *et al.*, 2002).

Seismic facies no. 1 (Fig. 9) is interpreted to be composed of calcareous shales with rudist debris based on core descriptions (*unpublished IOOC internal reports*). Pittet *et al.* (2002) suggested the possible presence of tempestites as rudist floatstones from outcrop analysis of the Lower Shu'aiba in northern Oman. The development of facies 1 within the undrilled interval beneath well *D1* (Fig. 9) shows the geometry of transported sediments, but this study cannot explain if this facies is related to tempestite deposition.

The gamma-ray log corresponding to the lower progradational unit A shows a relatively flat response indicating vertical aggradations, probably the result of more rapidly increasing accommodation space

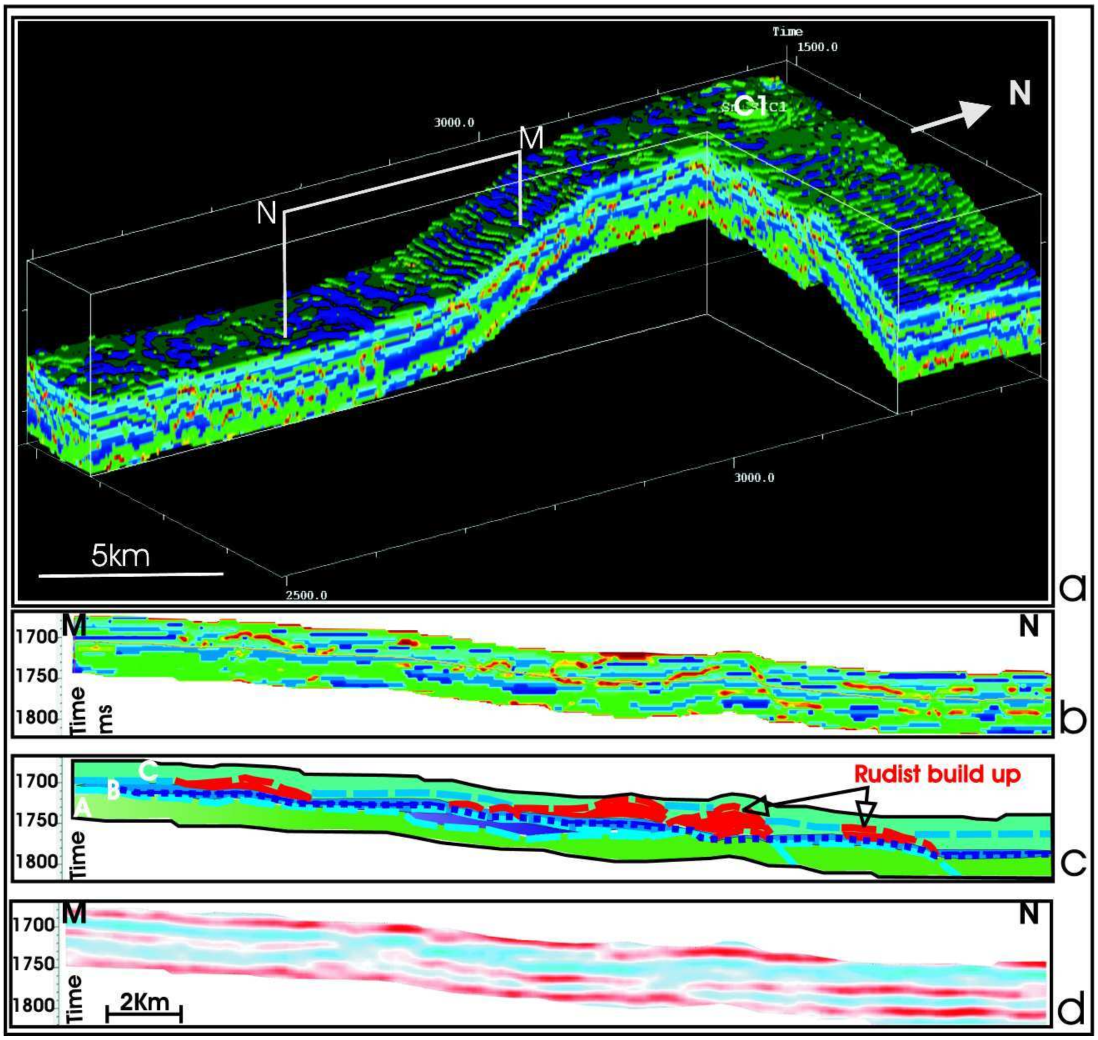


Fig. 10. 3D view of the classification data (a) and a section (b) through it showing the interpreted carbonate build-ups (c) highlighted by facies 6 (red and yellow). Letters (A, B and C) show the corresponding depositional cycles (see Fig. 9). A section through the conventional seismic data with the same orientation (d) is shown for comparison.

during the early highstand. This unit is defined by two seismic facies (2 and 3: well *C1*, Fig. 9).

Unit B is a backstepping succession associated with rapid marine transgression over a large platform. It contains microbreccia and grainstones consisting of rudist debris suggesting deposition in high-energy locations on the shallow crests of rudist biostromes. The occurrence of *Bacinella* (Pittet *et al*., 2002) within this facies supports the interpretation of a very shallow depositional environment. Seismic facies 6 is associated with unit B. Interpretation of seismic facies 6 suggests that it is related to isolated build-ups, which occur sparsely throughout the study area.

The Dariyan platform backstepped in response to rapid sea-level rise (Sharland *et al*., 2001; van Buchem *et al*. 2002b) towards the NW. Abundant *Trocholina*, textularids, *Lenticulina* and *Ammobaculites* in association with the rudist debris correspond to this rise. In the lower part of the lower Shu'aiba in Oman (Pittet *et al*., 2002), micro-encrusters commonly build low-relief biostromes. In the middle – upper part of the lower Shu'aiba, they are associated with rudist build-ups. The lower Shu'aiba in Oman correlates well with the Dariyan Formation in the study area.

The upper prograding unit C (Fig.9) consists of miliolid-rich packstones that indicate a shallowing-upward trend (Hughes, 2000; Immenhauser *et al*., 2000; Pittet *et al*., 2002). The top of this unit corresponds to a hiatus and an exposure surface that can be correlated regionally (Koop and Stonely, 1982; Sharland *et al*., 2001). Scrolling throughout the generated seismic facies cube and interpretation of the prograding build-up geometries in 3D show this prograding unit to be laterally extensive (Fig. 10).

RESULTS

Neither conventional seismic data nor well data have provided a sequence stratigraphic model for the Dariyan Formation in the study area (Figs 9 and 10d).

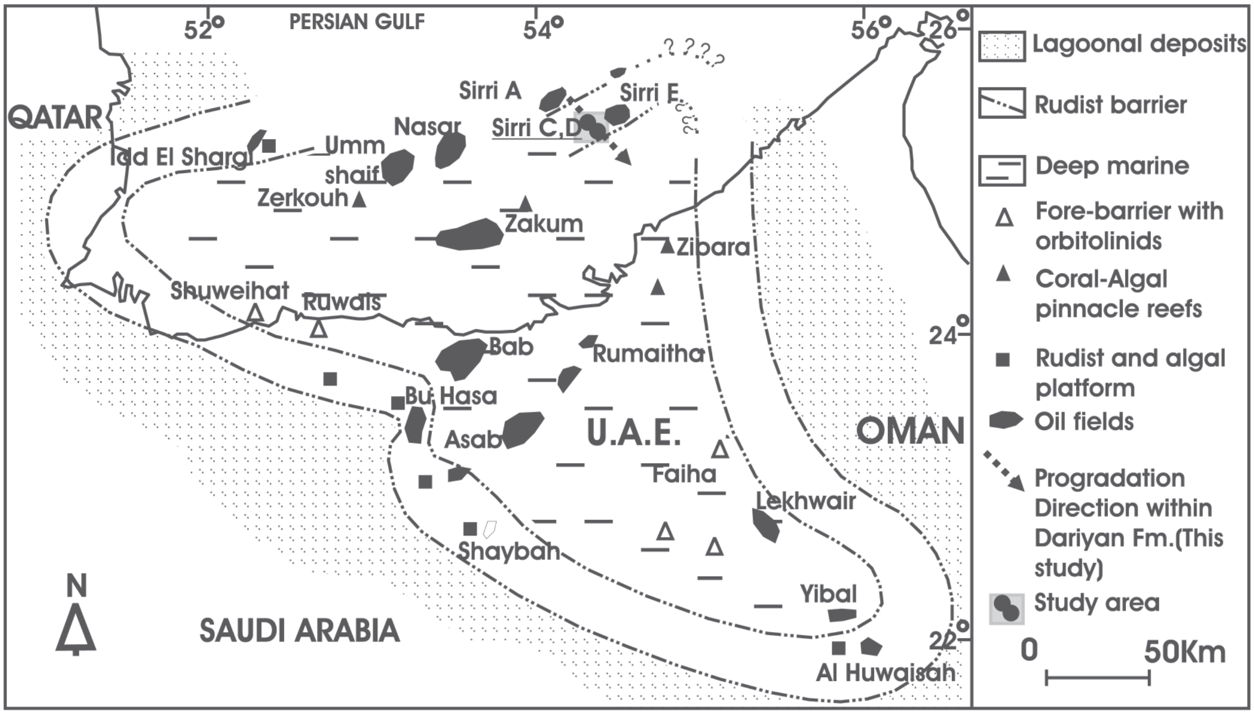


Fig. 11. Location map of the Aptian basin (see Fig.1 for regional location) present during the deposition of the Shu'aiba Formation. Note the progradation direction of the Dariyan Formation in the study area. (Adapted from Al Dabal and Alsharhan, 1989; Kendall *et al.*, 2000).

In this study, a combination of the seismic facies volume, wire line logs and core reports has allowed some improvement in the depositional model.

The classification extended through an interval of 70 ms making it possible to visualize the pattern of build-up distribution in 3D (Fig.10). Sub-parallel and discontinuous facies classes characterize progradation/aggradation of the lower part of the Dariyan Formation (unit A, dominated by seismic facies classes 1 and 2; Fig. 9). Seismic-scale build-ups are rare within the lower part, and lithologies are dominated by mudstones consisting of mixed, diverse biota (Figs 9 and 10). Facies class 1 (calcareous shale with rudist debris) may possibly be interpreted as a tempestite based on its geometry (possibly a transported sediment geometry, Fig 9). By contrast, the "middle" part of the Dariyan Formation (unit B, Fig. 9) is characterized by seismic-scale build-ups (the red and yellow facies class 6; Figs 9 and 10), with the red class dominant over their crests. Facies class 6 passes laterally and down-dip into the green (facies class 5) and the blue (facies classes 4 and 3) showing dipping discontinuous facies (Figs 9 and 10). This relationship suggests that facies class 6 represents the core of the build-ups. The observed association of rudist debris with *Bacinella* (Fig. 9) suggests very shallow, well-oxygenated depositional environments. Well *C1* penetrated a flank of one of the build-ups and core descriptions indicate a high-energy micro-breccia with reworked rudist material corresponding to facies class 6.

More structured flank deposits show a transition from grainstones to packstones and wackestones based on the core description. These can be correlated with facies classes 3, 4 and 5. The gamma-ray log -derived sequence B shown in Fig. 9 corresponds to an increase in vertical accommodation space and the stacking of carbonate build-ups. The third depositional phase (unit C, Fig. 9) is a progradational coarsening-upward succession with more clay influx into the system. This phase is interpreted as the late highstand during which accommodation space decreased. Sea-level fall resulted in a forced regression with the occurrence of miliolids and *Orbitolina* (Witt and Gokdag, 1994) in the top-most Dariyan Formation, ending with a regional unconformity (van Buchem *et al*., 2002b).

The relatively constant thickness of the Dariyan Formation (subtle differentiation in time thicknesses) suggests that tectonism and regional differential subsidence did not play a major role during deposition, and that the complex internal patterns are possibly the results of eustasy, clay influx and other environmental changes.

A rudist-dominated barrier in the Aptian basin formed during the deposition of the equivalent Shu'aiba Formation in the NE Arabian Plate (Al Dabal and Alsharhan, 1989; Kendall *et al.*, 2000) (Fig. 11). Evidence for the progradation direction of the build-up geometries that resulted from this study is shown in Fig. 11. In this study, stratal slicing (Zeng and Hentz, 2004) or proportional slicing (Posamentier *et al*., 1996) appeared to be the most useful of the available

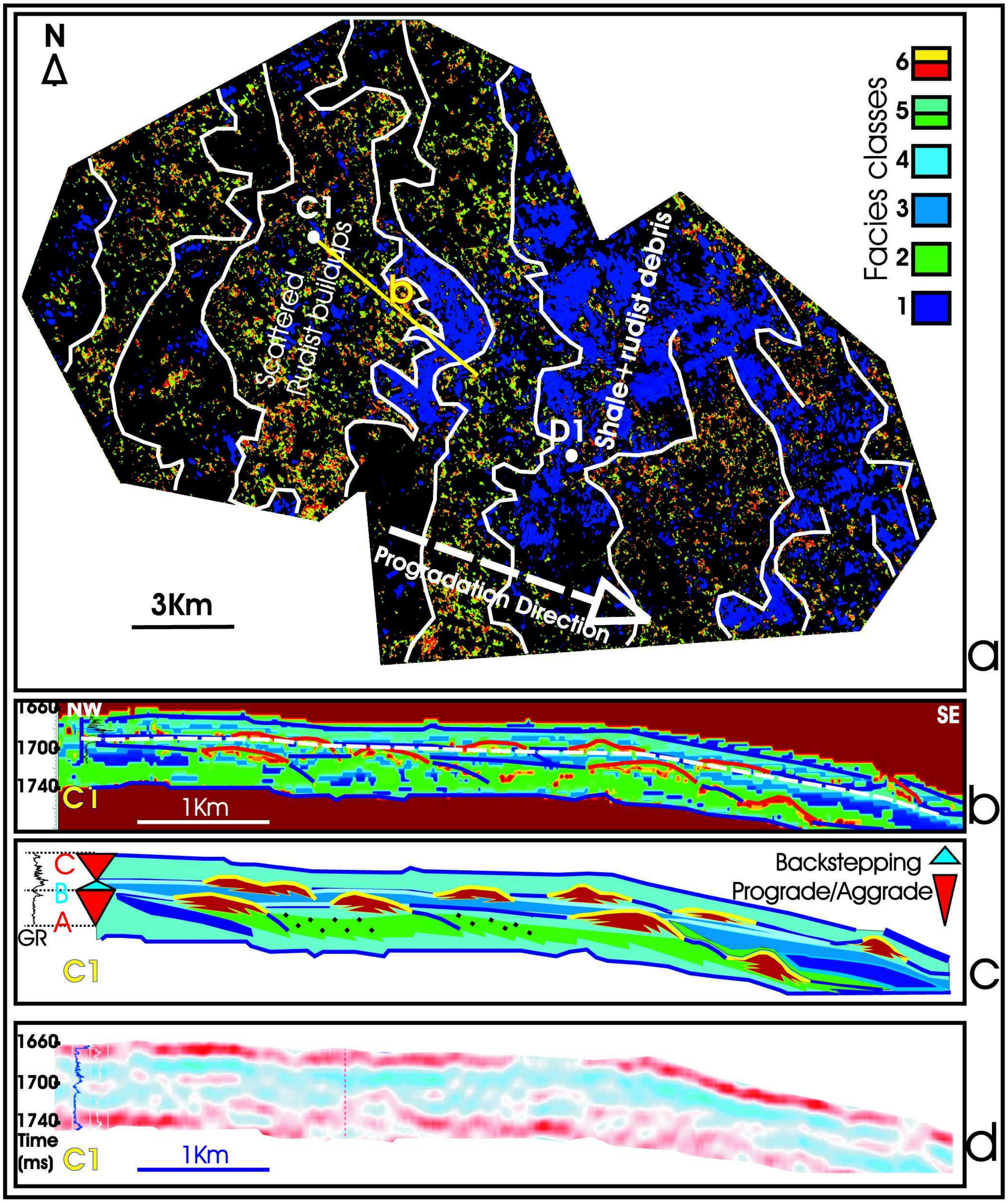


Fig. 12. A proportional slice (a) through the seismic facies classification volume showing the distribution of rudist build-ups (facies class 6, Fig. 9) and calcareous shales with scattered rudist debris (facies class 1, Fig. 9) throughout the study area. A random line (b) starting from Well *C1* shows the position of the proportional slice (white dashed line) and the internal geometry of the prograding build-ups. A geological model (c) illustrates the stacking pattern of the build-ups in relation to the fine vertical detail of the wells (see Fig. 9) showing that the generated seismic classification volume allows for a more confident sequence stratigraphic correlation. A conventional seismic section with the same orientation (d) is shown for comparison.

approaches. Computed proportional slices are proportionally distributed between the two reference time surfaces and are in conformity with both of the surfaces (applicable even with constant thicknesses). Successive proportional slices were computed between the tops of the Dariyan and Gadvan Formations. A proportional slice through the generated classification volume that conforms to both reference horizons confirms the trend and the progradation direction of the rudist-dominated barrier within the Dariyan Formation in the study area (Fig. 12). Interconnected build-ups are observed within the stratal slices throughout the 3D classification data in the study area. These build-up geometries differ significantly from generally isolated build-ups, which were interpreted from well and outcrop studies of the Lower Cretaceous carbonate systems in Oman and UAE (Calavan *et al*., 1992; Witt and Gokdag, 1994; Fischer *et al*., 1997;Borgomano *et al*., 2002; van Buchem *et al*., 2002b; Droste and van Steenwinkel, 2004). Build-ups are heterogeneous and mapping them in 3D without using proportional slicing is a challenge.

The complex prograding pattern within the Dariyan Formation resolved by seismic facies classification indicates lateral variations in depositional facies and thus lithology within the carbonate build-ups.

DISCUSSION

This study demonstrates how volume-based interpretation, integrating seismic attribute volumes, and reducing the redundant data have improved the identification of geometries and lithofacies variations within the Dariyan Formation, offshore southern Iran. A comparison between the single attributes illustrated in Figs 5, 10d and 12d shows that the seismic classification data is more diagnostic. However, simulations of the stratal geometry from seismic data are non-unique and depend on data resolution to establish the best interpretation. Wave-front propagation generates spreading of the information, causing lateral and vertical redundancy in the seismic data.

Noise often tends to inflate the data cloud and can link sub-clusters to remove their external isolation (Coleou *et al*., 2003). The N-dimensional cross-plots of seismic data employed in this study showed the organization of elongated subclouds, and made it possible to eliminate the components which did not contribute to the maximum spread of the subclouds. Noise was probably still a component, but its reduction resulted in recognition of some geologic features (rudist build-ups and possible transported sediment geometries) in isolation.

Inspection of the 3D classification data indicates the internal variability of the Dariyan Formation. Combining these data with vertical detail from wells permits a more confident correlation and sequence stratigraphic interpretation based on seismic facies stacking patterns. Well control is essential in order to evaluate all aspects of the seismic classification. Geologic knowledge of the reservoir and experience play a major role in relating the lateral variations of seismic facies to possible scenarios of reservoir modelling using well data. Classification results cannot be used directly for thickness nor for porosity calculations or deriving numerical models of well data. In the classification process, seismic data are only interpolated within the individual patterns (sub clusters) and there is no interpolability in the classification volume; therefore, only individual facies class or groups of classes should be calibrated to rock properties. For quantitative use of classification data, it is necessary to consider lateral continuity or restrict it to individual categorical variables. Without sufficient well control, however, seismic facies can still improve our understanding of the seismic response to geology.

A close relationship exists between the depositional facies of the carbonate build-ups and the reservoir properties of the time-equivalent Shu'aiba Formation in Oman and the UAE (Calavan *et al*., 1992; Fischer *et al*., 1997; Droste and van Steenwinkel, 2004). In this study, the classification has provided new information concerning the volume and connectivity of possible reservoir facies in the build-ups.

This 3D seismic facies analysis and seismic stratigraphic study of the Dariyan Formation improves our understanding of the internal characteristics of the formation in the study area. The generated facies patterns are more diagnostic and easier to interpret than the original seismic reflection data and single attribute volumes.

Three depositional units (two coarsening-up and one fining-upward) recognized from gamma-ray logs and core descriptions were resolved by the seismic facies classification. The aggrading unit in the lower and the prograding unit in the upper Dariyan Formation are separated by a fining-upward unit, corresponding to an increase in accommodation. This flooding event gave rise to the progradation and aggradation of rudist-rich carbonate build-ups, which are isolated and scattered throughout the study area.

In the study of discrete sedimentary geobodies such as carbonate build-ups, the 3D distribution of which is hard to predict, 3D hierarchical multi-attribute facies classification and data reduction by PCA can provide detailed 3D geometrical information. Mapping of the build-ups in the SE Persian Gulf clearly helps in the delineation of subtle stratigraphic traps.

CONCLUSIONS

A sequence-stratigraphic based seismic facies classification established for the Dariyan Formation at the *Sirri* fields, SE Persian Gulf, integrates geologic and geophysical data and provides a framework for 3D reservoir simulation studies.

By involving additional attribute volumes into the classification process and representing the large dataset in vector space, we expand the information content while reducing the redundant data. The data are cross-plotted (in N-dimensional space), and the main trends of the patterns (clouds) in the cross-plots are identified as principal directions that represent the heterogeneity of the multi-dimensional clouds. A rotation of the co-ordinate axes resulting in discrimination of maximum variance of the data clouds described the data more effectively, and separated those (redundant) data components with lesser contributions to the main elongation trends. Hierarchical classification of the input data volumes into population clouds and sub-clouds generated a single facies volume. Combination of the seismic facies volume with well data formed complementary information related to geologic features hidden within the seismic data.

The recognition of the prograding clinoforms, which were difficult to observe in the original seismic data, provided a coherent model explaining the facies distribution. Sequential stratal slicing throughout the classification volume provided plan views of important new geological information and detail, reflecting the true shape, connectivity and heterogeneity of the main features of interest. This resulted in new insights into the internal architecture of the Dariyan Formation which are consistent with the available well information.

This study provides an initial 3D realization of depositional systems of the Dariyan Formation, and will hopefully be of relevance to and assist future exploration in the SE Persian Gulf. Mapping the distribution of rudist build-ups which are possible potential reservoir units is a step towards seismic pattern recognition in this area.

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