Methods for identification of isolated carbonate buildups from seismic reflection data

Peter M. Burgess, Peter Winefield, Marcello Minzoni, and Chris Elders

ABSTRACT

Isolated carbonate buildups (ICBs) are commonly attractive exploration targets. However, identifying ICBs based only on seismic data can be difficult for a variety of reasons. These include poor-quality two-dimensional data and a basic similarity between ICBs and other features such as volcanoes, erosional remnants, and tilted fault blocks. To address these difficulties and develop reliable methods to identify ICBs, 234 seismic images were analyzed. The images included proven ICBs and other features, such as folds, volcanoes, and basement highs, which may appear similar to ICBs when imaged in seismic data. From this analysis, 18 identification criteria were derived to distinguish ICBs from non-ICB features. These criteria can be grouped into four categories: regional constraints, analysis of basic seismic geometries, analysis of geophysical details, and finer-scale seismic geometries. Systematically assessing the criteria is useful because it requires critical evaluation of the evidence present in the available data, working from the large-scale regional geology to the fine details of seismic response. It is also useful to summarize the criteria as a numerical score to facilitate comparison between different examples and different classes of ICBs and non-ICBs. Our analysis of scores of different classes of features suggests that the criteria do have some discriminatory power, but significant challenges remain.

INTRODUCTION

Isolated carbonate buildups (ICBs) are well-known targets for hydrocarbon exploration in both frontier and mature basins. They commonly contain significant accumulations of hydrocarbons.

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Various past assessments have estimated as much as 50 billion bbl of oil equivalent reserves stored within these types of features globally (e.g., Greenlee and Lehmann, 1993). Several super-giant fields are found in ICB strata (e.g., Tengiz and Kashaghan in the Precaspian Basin; Kuznetsov, 1997). The ICB play is also attractive because it can contain several favorable petroleum system elements in one relatively easily identifiable seismic feature. For example, many ICBs have enhanced reservoir properties compared to other occurrences of carbonate strata (e.g., Handford, 1998; Groetsch and Mercadier, 1999). Isolated carbonate buildup plays commonly have favorable trap and seal properties because the geomorphic shape of an isolated carbonate platform forms a four-way dip closure, commonly well sealed by fine-grained marine strata or evaporates (e.g., Handford, 1998). Laterally adjacent or underlying strata can form good source rocks, with a clear migration pathway and migration focus into the ICB trap (e.g., Todd et al., 1997). Consequently, reliable identification of ICBs on seismic data can be a key element in a successful exploration campaign, particularly in frontier basins where data are sparse.

Tools exist for the detailed description of carbonate reservoirs on three-dimensional (3-D) seismic data (e.g., Eberli et al., 2004a), but despite their historic significance as hydrocarbon plays (Greenlee and Lehmann, 1993), no clear set of diagnostic criteria for the identification of ICBs exists, especially in frontier regions or areas with sparse seismic data. Exploration for this type of carbonate play is therefore more difficult than might be expected. This article describes the work done for Shell International Exploration and Production in 2004 and 2005. The purpose of the work was to define and test a systematic method and set of diagnostic criteria for reliable identification and at least partial de-risking of ICB features. The main focus was to analyze possible ICBs imaged on two-dimensional (2-D) seismic data for frontier regions because this is the most challenging scenario encountered in global exploration. However, all the criteria can also be applied to 3-D data. More detailed work could be conducted, following the application of these criteria, to further de-risk features taking advantage of the extra information available in 3-D.

METHODS

Definitions: Buildups, Reefs, and Isolated Carbonate Platforms?

The term "buildup" can mean any geologic feature that results from accumulated material deposited in such a way as to construct

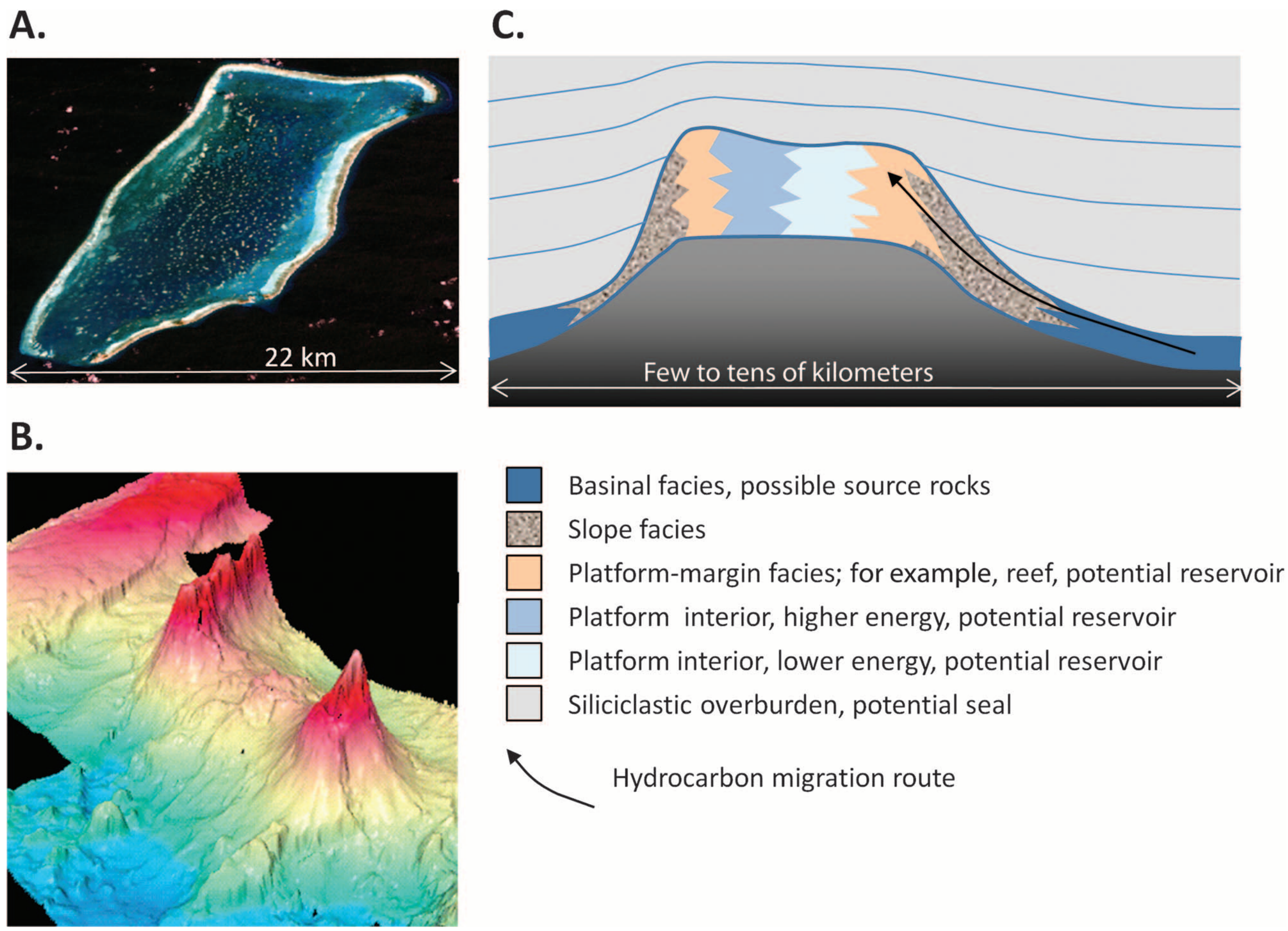


Figure 1. (A) A satellite image view of an isolated carbonate buildup (ICB) illustrating how such features are composed of multiple carbonate facies, ranging from a reef rim to a back reef sediment apron to a relatively deep-water lagoon interior with patch reefs. (B) ICB seismic morphology imaged in a three-dimensional seismic data set based on mapping of the top carbonate reflection. (C) An idealized representation of an ICB showing how such features can be a favorable combination of several petroleum system elements. Used with permission from Shell Philippines.

positive relief relative to the surrounding depositional surface. From this definition, the term "carbonate buildup" could include pinnacle reefs, carbonate mud mounds, attached carbonate platforms, and volcanoes. For the purpose of this work, we are most interested in isolated carbonate platform strata as an exploration target. Consequently, we use the term "isolated carbonate buildup" mostly to refer to carbonate platform strata deposited as a geomorphic feature with significant depositional relief relative to adjacent, time-equivalent, deeper-water strata, lacking any significant attachment to a continental landmass and including several depositional environments such as reefs, lagoons, tidal flats, and flanking slopes (e.g., Wright et al., 1996; Bosence, 2005) (Figure 1). The reference to the several depositional elements highlights the important distinction between an isolated carbonate platform, a pinnacle reef, and a mud mound. An isolated carbonate platform contains a series of different depositional elements (Figure 1A, C), may be several kilometers in length, and commonly contains strata with good reservoir properties. A pinnacle reef is an ICB composed of just one reef and probably has a very small areal extent and, therefore, a small volume and so is of less interest to an explorer. A mud mound is another type of ICB with quite different depositional elements that probably does not develop in shallow water and has potentially very different reservoir properties.

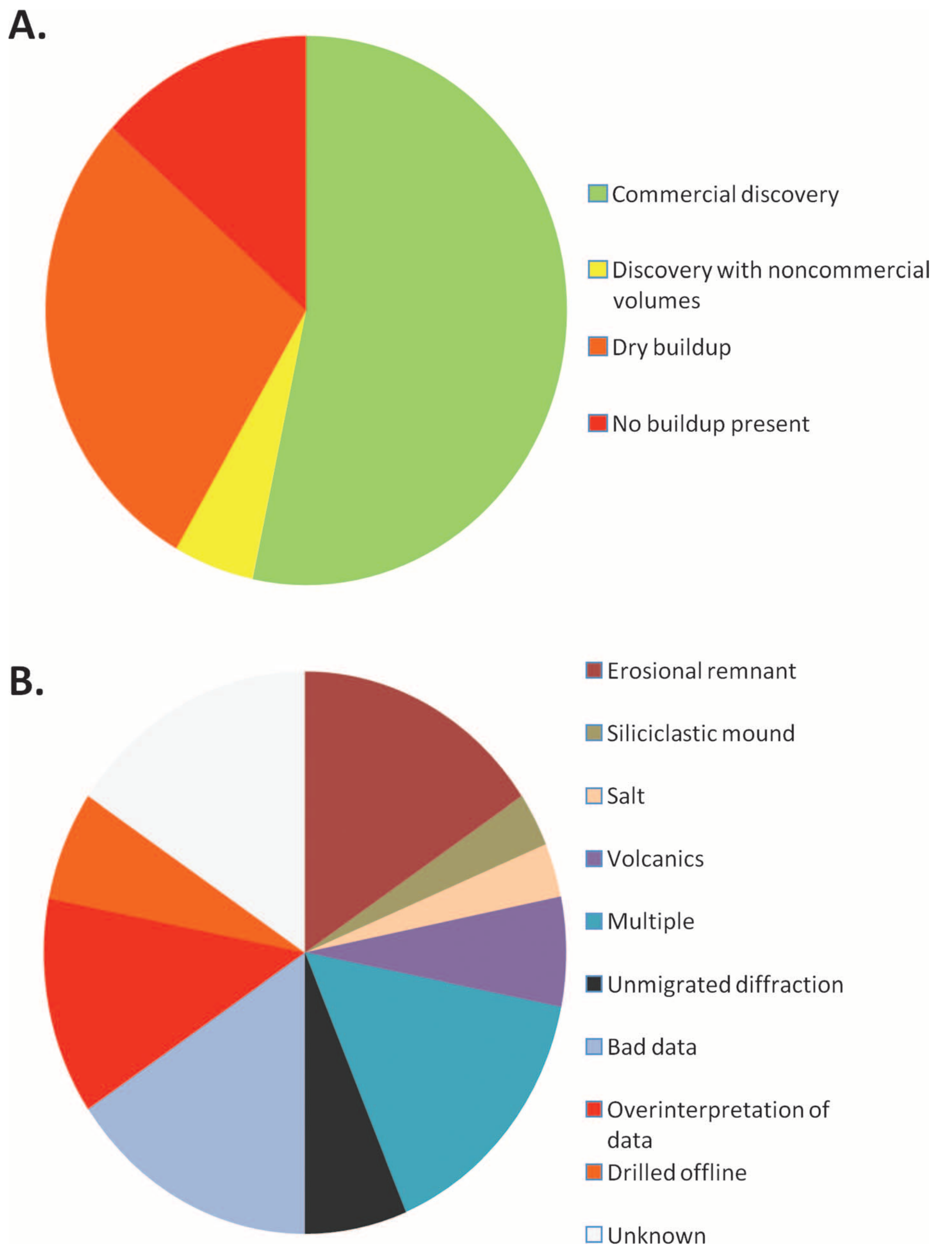


Figure 2. Results of approximately 60 wells drilled for isolated carbonate buildup plays by Exxon from 1975 to 1987 (Greenlee and Lehmann, 1993), used with permission of AAPG. (A) Pie chart showing general outcomes of these exploration tests. (B) Postulated reason for failure for those wells that failed to encounter carbonate buildups. The most common known reasons for failure to penetrate an isolated carbonate buildup are the misinterpretation of erosional remnants as buildups, bad seismic data, and nonrecognition of a seismic multiple. Although commonly invoked as a risk, misinterpretation of volcanics has been less significant than might be expected.

The Problem of Identification, Characterization, and De-risking of Isolated Carbonate Buildups

Reliable identification of ICBs is a significant challenge, despite many Neogene examples that are well imaged on 2-D and 3-D seismic data (e.g., Groetsch and Mercadier, 1999; Posamentier et al., 2010). It can be difficult to distinguish an ICB from other features that show similar evidence of an original positive relief, such as volcanoes, tilted fault blocks, and buried erosional topographic features. Examples that are less well imaged present additional challenges, commonly caused by depth of overburden, problematic overburden lithologies such as salt, or low seismic resolution. In these cases, even basic features like depositional relief may be difficult to reliably identify.

Greenlee and Lehmann (1993) reviewed 60 wildcat wells in which Exxon participated between 1975 and 1987, which targeted ICBs (Figure 2). Results showed that approximately 54% did not encounter an ICB. Of these, 15.6% were erosional remnants, 12.5% were noncarbonate lithologies (e.g., siliciclastics, volcanics, salt), and 27.5% failed because of poor-quality data. The remainder was flagged either as caused by simple overinterpretation of

Table 1. Seismic Data Sets Interpreted in This Study*

Geographical Area	Seismic Data Set**
Northwestern Palawan	2-D and 3-D
Northeastern Palawan	2-D
Makassar Strait and surrounding area	2-D
Bali-Flores Basin	2-D
North Madura	2-D and 3-D
Central Luconia	3-D
East Natuna	2-D
Papua New Guinea	2-D
Maldives	2-D
Mid–North Sea High	2-D
North Caspian Basin	2-D
Onshore Netherlands	3-D

*Note that seismic images were also included from other areas, but these were typically bitmap images and were not worked on as extensively as the data sets listed in the table.
**2-D = two-dimensional; 3-D = three-dimensional.

the data or as having an uncertain failure mechanism. Of those wells that actually penetrated ICBs, 28.6% were commercial discoveries, 21.4% failed because of poor reservoir development, 25% failed because of inadequate seal, and 10.7% failed because of lack of charge. Importantly, Greenlee and Lehmann (1993) also noted that, even when encountered, ICBs were not always good reservoirs (e.g., because of extensive meteoric diagenesis and or burial compaction). Reliable identification of an ICB is clearly an important but not conclusive step in exploration success. For example, further evaluation is typically required to work out where it is best to drill to provide the most diagnostic first test of an ICB structure.

Data Used in This Study

The data set used in this study is a diverse compilation of 234 seismic images of proven ICBs, features that may be ICBs, and features that share some common features with ICBs but are known not to be. The data set includes 106 examples of identified ICBs, penetrated by wells or directly tied to nearby well calibration. These examples range in size from 1 km^2 (0.39 mi^2) to several tens of square kilometers. An additional 107 examples of probable or possible ICBs were also studied, along with 21 non-ICB features such as tilted fault blocks and volcanoes. Seismic data sets used for this project came mainly from Southeast Asia, with a smaller number of images from other areas (e.g., North Caspian, onshore Netherlands). Most examples used in this study are Miocene or Oligocene-Miocene in age, with the remainder spread between the Devonian, Mississippian, Cretaceous, and Paleogene (Table 1). Examples were chosen to span a wide range of tectonic settings (e.g., Bosence, 2005), ages, and carbonate factory types (Lehrmann and Goldhammer, 1999; Wright and Burgess, 2005).

Southeast Asia provides an excellent seismic laboratory for developing methods of ICB identification because of (1) a large number of ICBs (e.g., Palawan, central Luconia) with different morphology and within different basin types; (2) availability of a variety of 2-D and 3-D seismic images with good-to-excellent well calibration; (3) presence of well-studied Miocene examples, including both fields and unpenetrated ICBs; and (4) a reasonably well-known regional geologic history (Sarg et al., 1995; Groetsch and Mercadier, 1999; Eberli et al., 2004b; Doust and Sumner, 2005). Non–Southeast Asian examples were added to the database from a variety of sources including literature (e.g., Belopolsky and Droxler, 2004; Eberli et al., 2004a), third-party proprietary databases, and Shell internal technical reports.

Data Interpretation and Classification

Each of the 234 seismic images was interpreted at least to the level of identifying top and base carbonate reflections or, in noncarbonate cases, identifying that such reflections were not present. Each image was then assigned to one of the three categories: proven, possible, and not an ICB. A proven feature has well penetrations proving the presence of carbonate strata and demonstrated (or very likely) depositional thickening relative to adjacent carbonate strata. A feature classed as "possible" has some seismic evidence indicating that an ICB may be present. Seismic evidence may be weak or strong. No well penetrations directly on the features classed as possible are observed, but nearby well penetrations demonstrate the occurrence of carbonates in the vicinity and in the same stratigraphic interval. Features classed as "not an ICB" are proven (with a well penetration), or strongly

Table 2. A Summary of the Identification Criteria Showing the Four Main Categories, the Criteria in Each Category, and the Suggested Action Associated with Each Criterion

Category	Criteria	Actions
Regional and stratigraphic constraints	1.1 Timing relative to paleolatitude, regional flooding, and framework builder types	Determine approximate age of candidate carbonate strata. Identify if this was a time of, for example, appropriate carbonate producers and favorable carbonate mineralogy (Figure 3). Determine if paleolatitude was tropical to subtropical. Identify from the regional geology and available chronostratigraphic syntheses the potential existence of long-term (e.g., 1–10 m.y.) transgressive trends.
	1.2 Spatial distribution relative to regional tectonic processes	Is candidate ICB located on a high structural trend, for example, tilted fault block crests or distal foreland basin margin (see Bosence, 2005, for examples)?
	1.3 Location relative to coeval siliciclastic input	Identify persistent paleodrainage trends from available paleogeographic reconstructions. Determine how paleodrainage trends may have changed through time using multiple paleogeographic time slices. Rank areas where siliciclastic input was consistently absent as higher potential for isolated carbonate buildup development.
Large-scale seismic morphology and basin geometries	2.1 Positive antecedent topography (paleohighs)	Look for onlap terminations in the basal part of the carbonate succession indicating the presence of a topographic high. Look for relatively thin regions on regional isochores between the candidate base carbonate event and a younger, relatively flat, regional marker.
	2.2 Significant localized thickening	Search for thick regions surrounded by thin regions on isochore maps of the candidate carbonate interval, or look for localized divergence of top and base carbonate reflections on available seismic lines.
	2.3 Onlap of overburden or presence of depositional wings	Identify onlapping stratal terminations against candidate isolated carbonate buildup margins. If absent or unclear, check strata adjacent to the candidate isolated carbonate buildup for wing features.
	2.4 Appropriate areal extent of isolated carbonate buildup planform top	Measure (on three-dimensional seismic data) or estimate (on two-dimensional data) the area of the isolated carbonate buildup planform near the midpoint between base and top carbonate. Compare against the exceedance probabilities (Figure 7) calculated from known isolated carbonate buildup examples.
	2.5 Absence of equivalent structure in the overburden	Determine if the generally convex-up structure of the candidate isolated carbonate buildup has a restricted depth or two-way time range. Look for continuation of convex-up reflections to surface or truncation beneath an angular unconformity.
	2.6 High-angle isolated carbonate buildup margins	Interpret the top carbonate reflection, and compute the angle of dip on the margins of the candidate isolated carbonate buildup.
Geophysical characteristics	3.1 Continuous high-amplitude capping reflection	In three-dimensional data, generate amplitude map of top carbonate reflection. On two-dimensional data, determine the lateral extent of high amplitudes at top carbonate. Compare distribution of high amplitudes with distribution of other features, for example, significant localized thickening and onlapping overburden.
	3.2 Velocity pull-up	Look for high seismic interval velocities in candidate isolated carbonate buildups. Look for high areas occurring in a restricted area beneath significant localized thickening. Check that the high does not show indications of topographic relief, for example, no onlap by younger strata.

Table 2. Continued

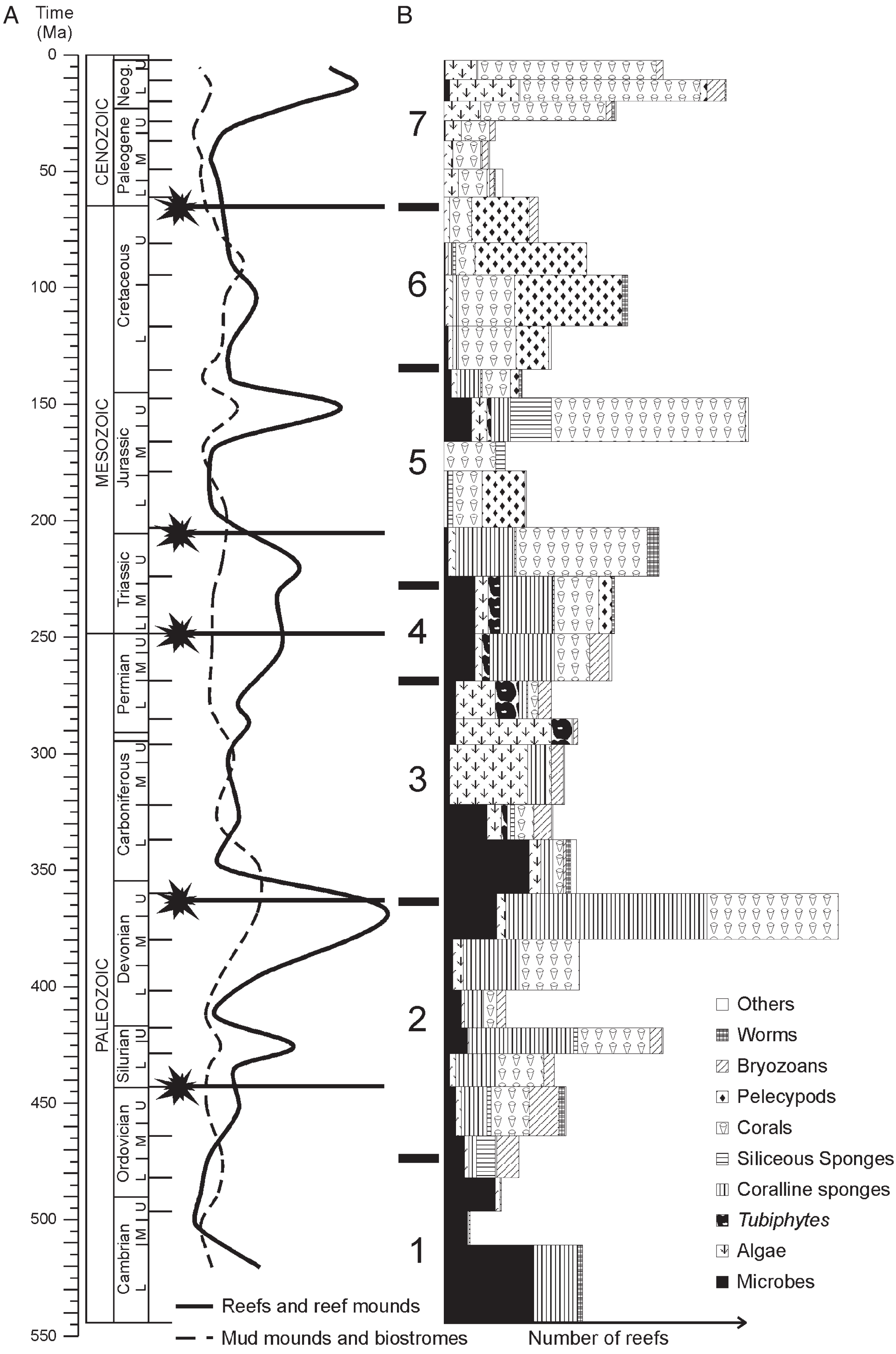
Category	Criteria	Actions
	3.3 Absence of gravity and magnetic anomalies	Examine potential field data for positive magnetic and gravity anomalies beneath the candidate isolated carbonate buildup. Model potential fields to understand the anomalies likely to be generated by the different possible features.
Finer-scale seismic geometries	4.1 Isolated carbonate buildup margin–related faulting and folding	Look for higher incidence of overburden faulting over isolated carbonate buildup margins compared to the surrounding strata. Check for fold structures, such as monoclines, developed locally in the overburden over candidate isolated carbonate buildup margins. Assess the impact of margin-related faulting on other diagnostic features such as stratal onlap.
	4.2 Systematic isolated carbonate buildup margin stacking patterns	Identify the platform margin on seismic using break-of-slope or seismic facies features (e.g., Figure 11). Trace the trajectory of the margin between base and top carbonate reflection and label intervals of aggradation, progradation, and retrogradation. Do the retrogradational intervals show backstepping geometries?
	4.3 Appropriate interior seismic character	Examine seismic data for appropriate distribution of seismic facies, for example, the presence of convex-up mounded features in the isolated carbonate buildup margin and continuous, flat, possibly high-amplitude reflections in the interior. Are the reflection characteristics within the potential isolated carbonate buildup notably different in character from the reflection characteristics in the surrounding strata?
	4.4 Thick-thin-thick depositional pattern	Trace top and base carbonate reflections laterally away from the candidate isolated carbonate buildup, checking for convergence into a single reflection, followed by expanding into multiple reflections in an adjacent lower elevation area.
	4.5 Coalescing growth reflection patterns	Examine reflection patterns between top and base carbonate, looking for evidence of clinoform development. If present, map progradational clinoform units to determine relative ages and reconstruct basic history of platform progradation and, if appropriate, coalescence. Check for evidence of aggradational stacking above.
	4.6 Potential karst-related features	Examine platform interior for chaotic, high-amplitude reflection patterns occurring at specific restricted intervals (e.g., Figure 15). On three-dimensional data, generate amplitude or attribute maps from top carbonate and older carbonate strata, and check for patterns (e.g., Figure 15). If present, determine if the chaotic unit is restricted to the platform top area or if it extends laterally into areas away from the platform top.

suggested (from nearby wells), to consist of non-carbonate lithologies, or carbonate strata formed in depositional settings other than an isolated platform.

Each image was also classified according to the apparent data quality by assigning a value from 1 to 4, where 1 represents excellent quality data providing clear imaging of the stratal architectures and 4 represents very poor data that do not allow reliable identification of stratal features. These classifications are useful for determining if the identification (ID) criteria described below generate appropriate results for cases known to be ICBs and cases known to be non-ICBs across a range of different data qualities.

Definition of Identification Criteria and Workflow

A key aim of this work was to define criteria that can be used to reliably determine how likely it is that an ICB is present in a seismic image and to distinguish between ICBs and other features such as volcanoes and tilted fault blocks that can look similar. These


A
Time (Ma)
B
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100
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200
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300
350
400
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CENOZOIC
MESOZOIC
PALEOZOIC
Neog.
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
7
6
5
4
3
2
1
Others
Worms
Bryozoans
Pelecypods
Corals
Siliceous Sponges
Coralline sponges
Tubiphytes
Algae
Microbes
Reefs and reef mounds
Mud mounds and biostromes
Number of reefs

criteria are summarized in Table 2. They can be grouped into four categories: (1) regional and stratigraphic constraints, (2) large-scale seismic morphology and basin geometries, (3) geophysical characteristics, and (4) smaller-scale seismic geometries. Generally, the four categories represent a progression in detail of interpretation, from an initial regional overview, through basic interpretation of large-scale seismic features, to analysis of some basic geophysical properties and, finally, to consideration of more detailed aspects of the seismic image. Each criterion is assessed for each candidate features imaged as either a clear positive response of "yes"; a weaker positive response of "maybe yes," where some uncertainty exists; a response of "unknown," where the criterion cannot be assessed, perhaps because of lack of sufficiently clear data; or a definitive negative response of "no," where the criterion is definitely not met. Working through and assessing these criteria in this way should provide a practical framework, or guide, for the identification and initial de-risking of ICBs. Each criterion is defined and explained below, along with methods for application and appropriate caveats.

Regional and Stratigraphic Constraints

Understanding the geologic development of a region or basin allows the identification of areas where and times when conditions were favorable for depositing significant volumes of carbonates. The three criteria below can be applied, in the absence of more detailed subsurface information, as a first-pass check on the likelihood of finding ICBs in a particular location. They can also provide context to enhance confidence in interpreting imaged features in situations where seismic data are available.

Timing Relative to Paleolatitude, Regional Flooding, and Framework Builder Types

Initiation of ICB development is dependent on various controls, some of which vary through time in a somewhat predictable manner (Mazzullo et al., 2007). For example, dominant carbonate framework-building organisms have changed through time (Figure 3). Hence, an area of exploration can be screened according to paleolatitude, extent of regional marine flooding, and age of strata present to determine the probability of encountering ICBs.

Paleolatitude is important because prolific carbonate production tends to occur, according to conventional models, at least, in warm-water low-latitude settings (James and Kendall, 1992). If plate-tectonic and paleogeographic reconstructions indicate an appropriate low paleolatitude, this is a favorable indicator. Although high paleolatitudes and associated lower water temperatures and light levels do not necessarily preclude carbonate growth (e.g., cool-water carbonate systems; James, 1997), they do make occurrence of large ICBs less likely (e.g., Schlager, 2005).

Initial ICB development and subsequent aggradation to form significant geomorphic features tend to occur during times of rapid subsidence, which lead to increased rates of accommodation creation and regional transgression, when any remnant relief suitable for carbonate nucleation is rapidly flooded and siliciclastic sediments are more likely confined to basin margins (e.g., the early postrift marine petroleum system type of Doust and Sumner, 2005). Major transgressions over continental deposits or onto a faulted substrate are particularly favorable in this respect because siliciclastic input is commonly low and carbonate accumulation can occur because topographic highs are flooded. The age of the base carbonate interval would be expected to correspond to such regional flooding events. For example, in central Luconia, base carbonates correspond to regional flooding on slowly subsiding basement during a sag phase of basin development (Epting, 1980; Doust and Sumner, 2005). If regional geology indicates the existence of such regional flooding events, these should be

Figure 3. Dominant Phanerozoic reef types and reef builders from Kiessling et al. (1999) used with permission from AAPG. (A) Cumulative number of reefs and reef mounds and the number of mud mounds and biostromes through time. (B) Cumulative number of reefs in which a particular reef builder is dominant. "Others" refers to brachiopods, pelmatozoans, and foraminifera. Several cycles of reef building are indicated by the peaks on both plots. Major mass extinctions are demarcated by starred lines. L = Lower; M = Middle; U = Upper; Neog. = Neogene.

examined as intervals of potential ICB development. Because tectonostratigraphic sequences depend on relative (not eustatic) sea level, single basins or subbasins probably exhibit a sea level history distinct from any global trend (e.g., Miall, 2010), so each basin probably needs to be considered individually.

The nature of carbonate production has changed through time because, for example, carbonate-producing organisms have evolved and ocean geochemistry has changed. Globally, it has been observed that certain geologic intervals (e.g., Devonian and Miocene; Figure 3) were times of exceptional production and accumulation of carbonates, with dominance of particular types of framework-building organisms. Probability of generating isolated platform geometries is increased during these periods (e.g., Tucker and Wright, 1990; Greenlee and Lehmann, 1993; Kiessling et al., 1999). As such, this criterion might be useful for targeting potentially carbonate-rich stratigraphic intervals and for potentially increasing confidence levels for particular leads or plays. Note, however, that this is also not a universal rule, so exceptions must also be considered.

The following actions can be conducted to assess this criterion: determine the approximate age of the candidate carbonate strata (e.g., Late Jurassic) and identify if this was a time of, for example, appropriate carbonate producers and favorable carbonate mineralogy (Figure 3); determine if the paleolatitude at the time of deposition was tropical to subtropical; and identify from the regional geology and available chronostratigraphic syntheses the potential existence of long-term (e.g., 1–10 m.y.) transgressive trends, particularly those that flood irregular tectonic or erosional topography (e.g., tilted fault blocks).

Spatial Distribution Relative to Regional Tectonic Processes

The tectonic or basement fabric of a basin exerts prime control on the regional distribution of ICBs (Bosellini, 1989; Tucker and Wright, 1990; Wilson et al., 2000; Bosence, 2005; Dorobek, 2008). Basement or other tectonic highs such as tilted fault blocks and thrust-top anticlines are typical nucleation sites for euphotic carbonate production. Euphotic producers, dependent on penetrating light to fuel photosynthesis, are the dominant components of framework-building carbonate sediment in modern environments. It is commonly assumed that ancient platform-building carbonate deposits are likely to be dominated by strata produced in shallow water by euphotic processes (e.g., Bosscher and Schlager, 1992). Moreover, elevated areas within a basin are more likely to be devoid of excessive siliciclastic sediment that normally accumulates first within depressed areas or lows by gravity-driven transport mechanisms.

The modern distribution of the Bahamas provides excellent examples of this relationship; the Bahamas island chain parallels an underlying Jurassic faulted margin. In general, the initial distribution of warm-water ICBs typically mimics the underlying basement fault pattern by concentrating carbonate growth on the upthrown margins of fault blocks where euphotic carbonate production is optimum (e.g., Bosscher and Schlager, 1992). Local differences in subsidence rates, commonly driven by reactivation of basement faults, may be responsible for confining carbonate accumulations to isolated areas, preventing lateral expansion to form coalesced platforms and, instead, generating a collection of closely spaced isolated platforms (e.g., the Maldives; Belopolsky and Droxler, 2004).

This criterion can be applied by examining candidate ICBs in the context of any information on the underlying tectonic structure of the area and determining if they are located on any structural trend that could provide favorable bathymetric and subsidence conditions, for example, tilted fault-block crests or distal foreland basin margins (e.g., Bosence, 2005). Note that a general regional alignment with underlying tectonic fabric might also be expected from volcanic sequences, although volcanoes are not necessarily expected to be associated consistently with upthrown blocks.

The following action can be conducted to assess this criterion: examine the position of the candidate isolated buildup to determine if it is located on a structural trend that may have provided favorable bathymetric and subsidence conditions, for example, tilted fault-block crests or distal foreland basin margin. Note that igneous features such as

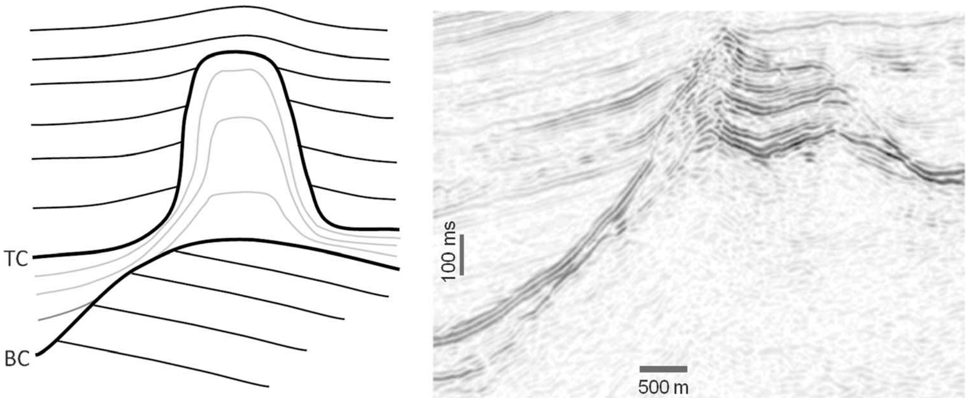


Figure 4. A schematic cross section and an example seismic image showing an antecedent topographic high beneath an isolated carbonate buildup. TC stands for top carbonate, referring to the reflection that marks the top of the carbonate succession, and BC refers to base carbonate, referring to the reflection that marks the base of the carbonate succession. Note onlap of the antecedent high by carbonate strata. See identification criterion 2.1 (Table 2) for discussion. Used with permission of Shell Philippines.

volcanoes may also show a general regional alignment with underlying tectonic fabric.

Location Relative to Coeval Siliciclastic Input

Carbonate production and accumulation rates can be greatly reduced by fine-grained, suspended siliciclastic sediment and the excess nutrient levels also commonly associated with terrestrial freshwater runoff (Hallock and Schlager, 1986; Erlich et al., 1990; McLaughlin et al., 2003), although the relationship is not always straightforward (Camoin et al., 1999; Hallock, 2001; Mutti and Hallock, 2003; Gautret et al., 2004). Consequently, ICBs might be expected to develop distal from siliciclastic sources, in areas of relative sediment starvation. For example, the regional distribution of modern reefs shows a clear inverse relationship between carbonate development and major sources of fine siliciclastic sediment input (McLaughlin et al., 2003). However, the magnitude of siliciclastic sediment supply varies through time, and sediment input points shift, shutdown, or start up, making mapping of sediment input points somewhat complicated. Carbonate accumulation can also occur in areas of high siliciclastic influx, for example, in front of deltas (Bosence, 2005; Wilson, 2005; Saller et al., 2010). Such delta-front carbonate accumulations tend to be relatively small and, therefore, are less likely to be of interest in hydrocarbon exploration.

The following actions can be conducted to assess this criterion: try to identify persistent paleodrainage trends from available paleogeographic reconstructions; try to determine how paleodrainage trends may have changed through time using multiple paleogeographic time slices; and rank areas where siliciclastic input was consistently absent as higher potential for ICB development.

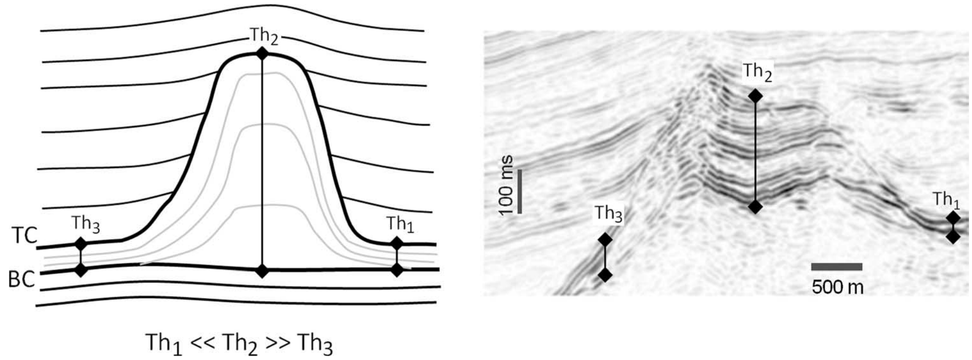
Large-Scale Seismic Morphology and Basin Geometries

These six criteria relate to the basic elements of the gross morphology of candidate ICBs, as imaged on typical 2-D seismic data. Identification of these elements, particularly when several are present in combination, should form the core of a reliable identification of an ICB. The challenge, as discussed below, is that many of these criteria may also be consistent with noncarbonate features such as volcanoes and tilted fault blocks, at least, when applied in isolation. Application of most of the general morphology criteria is dependent on the prior identification and interpretation of base and top carbonate reflections. Depending on requirements and the nature of the basin fill, base and top reflections can be picked to encompass the whole carbonate succession or just a particular interval of interest within a thicker carbonate succession.

Positive Antecedent Topography (Paleohighs)

As discussed in criterion 1.2 (Table 2), typical nucleation sites for carbonate production include shallow-water positive-topographic tectonic features such as tilted fault blocks and thrust-top anticlines. Other examples of positive antecedent topography that can nucleate carbonate growth are

Figure 5. A schematic cross section and an example seismic image showing the principle of significant localized thickening within an isolated carbonate buildup. See identification criterion 2.2 (Table 2) for discussion. TC is top carbonate; BC is base carbonate; and Th_1, Th_2, and Th_3 are thicknesses of carbonate strata at the locations indicated. Used with permission from Shell Philippines.



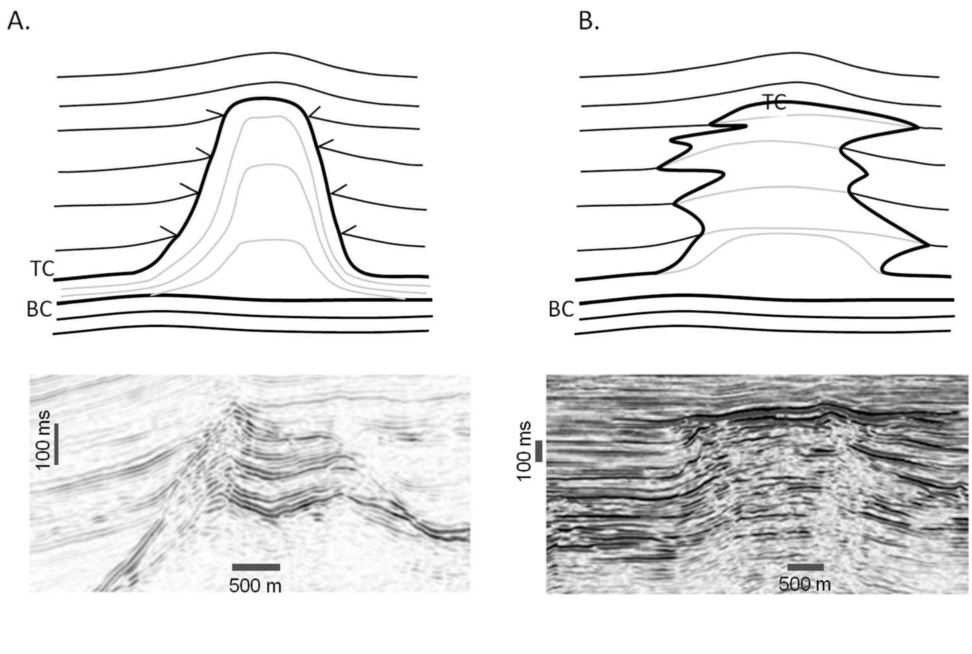
complete or partly eroded volcanic edifices, remnants of antecedent carbonate buildups or elevated platform margins, and shelf breaks (Figure 4). Thus, the presence of identifiable antecedent positive topography, or paleohighs, beneath a candidate ICB does tend to increase confidence in an ICB interpretation. Care should be applied when dealing with 2-D seismic data where line spacing could exceed the width of any antecedent topographic features because, in these cases, topographic highs might be missed.

The following actions can be conducted to assess this criterion: look for onlap terminations in the basal part of the carbonate succession, which might indicate the presence of an underlying topographic high; and look for relatively thin regions on regional isochores between the candidate base carbonate event and a younger, relatively flat, regional marker. These may be very subtle, but where they are present, they will indicate paleohighs that may have promoted ICB formation.

Significant Localized Thickening

Isolated Carbonate Buildups commonly develop a predominantly aggradational pattern forming a geomorphic feature with syndepositional relief on the order of tens to hundreds of meters. This reflects focused accumulation in a restricted area with a background of relative sea level rise probably driven primarily by tectonic subsidence (e.g., Pomar et al., 1996). Relatively thin contemporaneous strata adjacent to the ICB and relatively thick strata within the ICB indicate significant localized thickening (Figure 5). This key criterion demonstrates

Figure 6. Schematic cross sections and seismic images showing onlap of overburden onto the margins of an isolated carbonate buildup (A), contrasted with a situation where depositional relief on the margins of the isolated carbonate buildup was lower because of contemporaneous infill of the adjacent basin (B). In this case, carbonate material from the platform top was transported away from the platform margin to produce depositional wings that interfinger with the basin-fill strata. TC is top carbonate, BC is base carbonate. See identification criterion 2.3 (Table 2) for discussion. Used with permission of Shell Philippines and Petronas Malaysia.



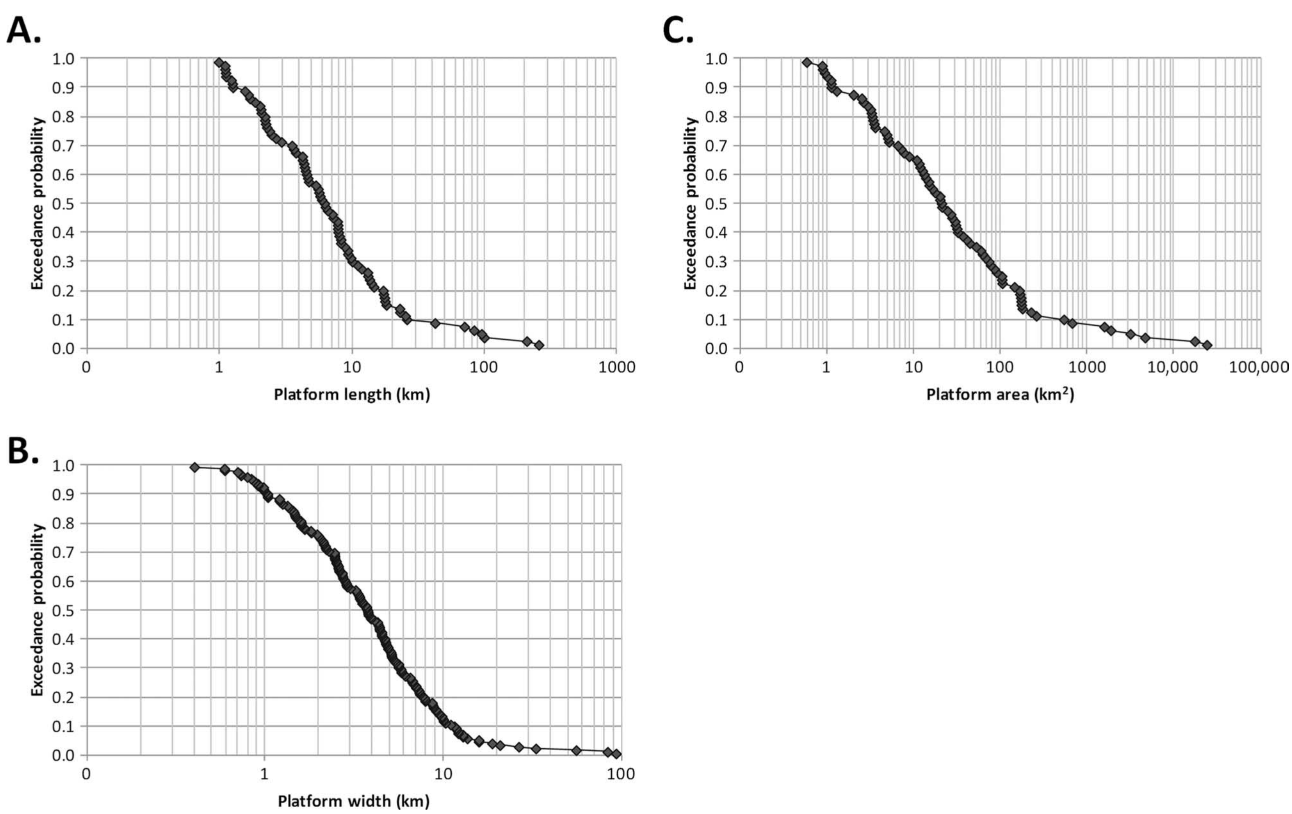


Figure 7. Exceedance probability plots for three different aspects of isolated carbonate buildup size: (A) length in kilometers, (B) width in kilometers, and (C) area in square kilometers. Note the log scale on the *x* axis in each case. For any particular value of length, width, and area, the plots show the probability of that value being met or exceeded based on more than 200 examples included in the database. These plots can be used to assess the probability that a feature of a given size observed on seismic data is not too big or too small to be an isolated carbonate buildup. See identification criterion 2.4 (Table 2) for discussion.

aggradational syndepositional relief. It is best demonstrated on 2-D or 3-D seismic by divergence of base and top carbonate reflections (Figures 1 and 5).

The following action can be conducted to assess this criterion: search for thick regions surrounded by thin regions on isochore maps of the candidate carbonate interval or look for localized divergence of top and base carbonate reflections on available seismic lines. Both are potentially indicative of significant localized thickening.

Onlap of Overburden or Pesence of Depositional Wings

Onlap of overburden is another criterion related to the development of syndepositional relief representing subsequent (or, possibly, partly coeval) burial of an ICB by younger strata. Strata deposited after aggradational syndepositional relief has developed must show an onlapping relationship with termination of younger reflections against the margins of the positive-relief feature (Figure 6A). Identification of such onlap significantly raises confidence in an ICB interpretation, facilitating discrimination from other seismic bumps such as postdepositional folds and fault-related folds that do not show onlap. Application of this criterion can be complicated by syndepositional tectonics. Positive-relief tectonic structures may be buried and onlapped (e.g., thrust-top anticlines or faulted submarine escarpments). However, onlapped syndepositional tectonic features are unlikely to also show significant localized thickening beneath the onlapping strata.

Identification of onlap on ICBs can be complicated by significant platform shedding or other contemporaneous off-platform deposition (i.e., syndepositional wings or stringers) that suppresses the development of contemporaneous steep high-relief margins and prevents onlap. Depositional wings are wedge-shape, elongated, high-amplitude strata that extend and thin out from positive-relief features into

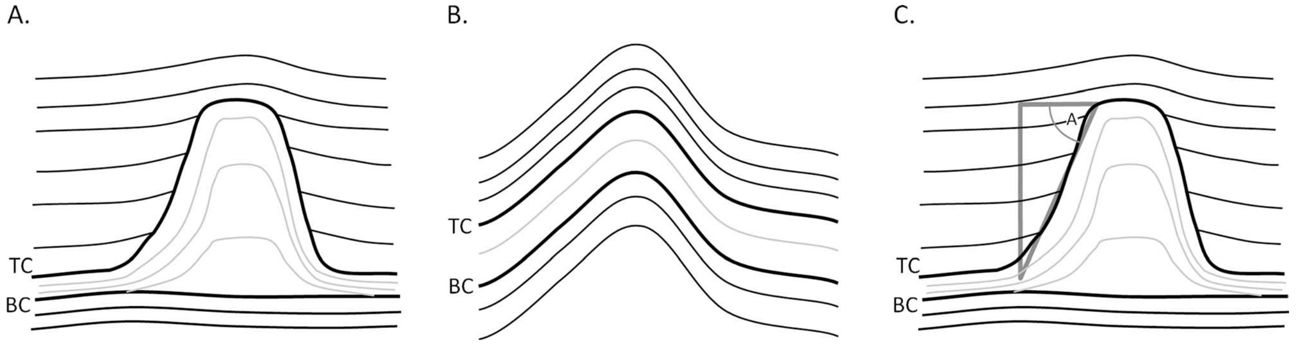


Figure 8. Schematic cross sections to demonstrate how an isolated carbonate buildup (ICB) is a concave-up structure not present in the overlying strata (A), allowing the ICB to be distinguished from a folded carbonate interval (B) where the concave structure would also be present in overlying strata. See identification criterion 2.5 (Table 2) for discussion. (C) Schematic cross section to show a high-angle ICB margin. A is the dip angle of the margin, either measurable from seismic data, assuming a reasonable depth conversion is possible, or just useful for comparison with the dip of surrounding strata. TC is top carbonate; BC is base carbonate. See identification criterion 2.6 (Table 2) for discussion.

the adjacent basin (Figure 6B). Examples have been drilled and described from ICBs in central Luconia (e.g., Bracco Gartner and Schlager, 1999). They represent redeposited material eroded from the ICB and redeposited as slides, slumps, turbidites, and debrites. In theory, similar features formed by pyroclastic flows might be expected to occur around volcanic edifices, although further work is required to establish if these would exhibit a similar seismic signature.

The following actions can be conducted to assess this criterion: identify onlapping stratal terminations against the margins of candidate ICB features; if absent or unclear, check strata adjacent to the candidate ICB for wing features.

Appropriate Areal Extent of Isolated Carbonate Buildup Platform Top

By definition, ICBs are geomorphic features separated from other adjacent or nearby carbonate platforms by deep water. This identification criterion is met if isolation of carbonate platform strata can be established from seismic data and if the area (on 3-D data) or length and/or width (on 2-D data) falls within the range of observed spatial dimensions of proven ICBs (Figure 7). Mapping of onlap termination of younger reflections on all imaged flanks of the candidate ICB and examination of top-carbonate minus base-carbonate isochore maps to determine the extent of significant thickening will establish the size of the feature. This length or area can then be compared with the size distribution of proven buildups (Figure 7). If the observed width, length, and area have a high exceedance probability based on the observed sample of known ICBs, this would increase the probability of the feature being an ICB. However, large outliers do exist, for example, the Bahamas Platform and the giant ICBs in the sub-Caspian Basin.

The following actions can be conducted to assess this criterion: measure the area (on 3-D seismic data) or estimate the width or length (on 2-D data) of the ICB near the midpoint between base and top carbonates and compare against the exceedance probabilities calculated from known ICB examples (Figure 7) to estimate the probability of occurrence of an ICB of the size observed.

Absence of Equivalent Structure in the Overburden

Isolated Carbonate Buildups are commonly marked by the presence of convex-up (mounded) top carbonate reflection geometries (Figures 1, 8A). However, similar convex-up geometries can be produced by postdepositional folding (Figure 8B). A general distinction between ICBs and tectonic folds is the vertical extent of the convex-up geometry through the imaged strata. Convex-up reflections associated with an ICB should occur only within the ICB and, allowing for minor deformation caused by differential compaction, in the immediately overlying strata. Above this, reflections should not show the same amplitude of convex-up structure (Figure 8A).

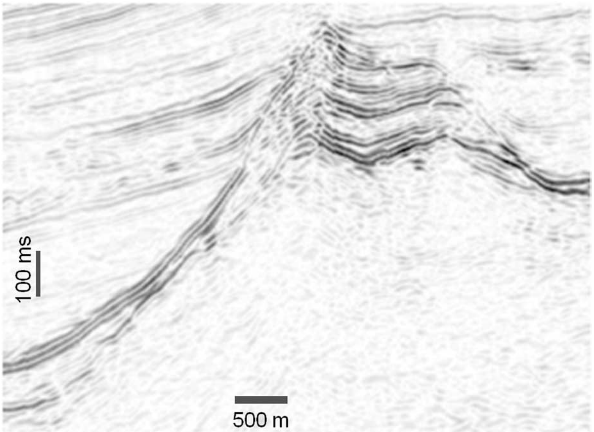


Figure 9. A seismic image showing a proven isolated carbonate buildup with a bright top reflection especially well developed on the flanks of the isolated carbonate buildup. See identification criterion 3.1 (Table 2) for discussion. Used with permission from Shell Philippines.

Conversely, a tectonic fold structure will extend vertically through more strata (Figure 8B), either to the surface or until truncated beneath an erosional unconformity, or be cut by faults.

The following actions can be conducted to assess this criterion: determine if the generally convex-up structure of the candidate ICB has a restricted depth or two-way time range and look for a continuation of convex-up reflections to the surface or the truncation beneath an angular unconformity or a truncation by faults.

High-Angle Isolated Carbonate Buildup Margins

Isolated carbonate buildups typically have a steep margin slope, with significant depositional relief from platform top to the adjacent basin floor. For various reasons, including early lithification and development of coarse-grained marginal aprons, platform-margin slopes can commonly support steeper dips than equivalent siliciclastic or volcanic structures (e.g., Schlager, 2005). Reflections situated on the edge of a candidate ICB structure (Figure 8B) with an estimated dip of more than 10° to 20° (in depth-converted data) or a dip significantly greater than other reflections in the area (in non–depth-converted data), increase the probability that a feature is an ICB.

The following actions can be conducted to assess this criterion: identify areas on the top carbonate reflection at the edge of areas of significant localized thickening (i.e., on the edge of the candidate ICB) with high estimated dips relative to other reflections in the area (Figure 8C) and calculate the angle of dip on the margins of the candidate ICB as accurately as possible with the available data.

Geophysical Characteristics

Although the seismic characteristics of carbonate strata are highly variable (e.g., Eberli et al., 2004a), the presence of the following three geophysical properties can be simple but useful ID criteria. Potential field data can also provide important evidence independent of the seismic response.

Continuous High-Amplitude Capping Reflection

Many of the ICBs in this study show a distinctive high-amplitude hard top reflection that results from relatively high acoustic impedance contrast at a shale-carbonate interface (Figure 9). Although very common throughout the data set, a hard top reflection might also be expected to occur at the top of several other geologic features (e.g., volcanoes) and may be diminished or absent because of hydrocarbons within the carbonates (e.g., Luconia buildups) or because of the presence of high-porosity carbonate layers. Conversely, this criterion may indicate carbonate strata deposited in a non-ICB setting, so it is suggested that the criterion be best used in conjunction with others (e.g., criterion 2.2, significant localized thickening).

The following actions can be conducted to assess this criterion: in 3-D or higher-density 2-D data, generate amplitude map of top carbonate reflection; on sparse 2-D data, determine the lateral extent of high amplitudes at top carbonate; compare distribution of high amplitudes with distribution of other features, for example, significant localized thickening and onlapping overburden.

Velocity Pull-Up

A velocity pull-up is an effect in seismic images where particular reflections appear higher in the section than they would otherwise be because the overlying strata have higher seismic velocities relative to laterally adjacent strata. Carbonate strata typically have higher seismic velocities than siliciclastic

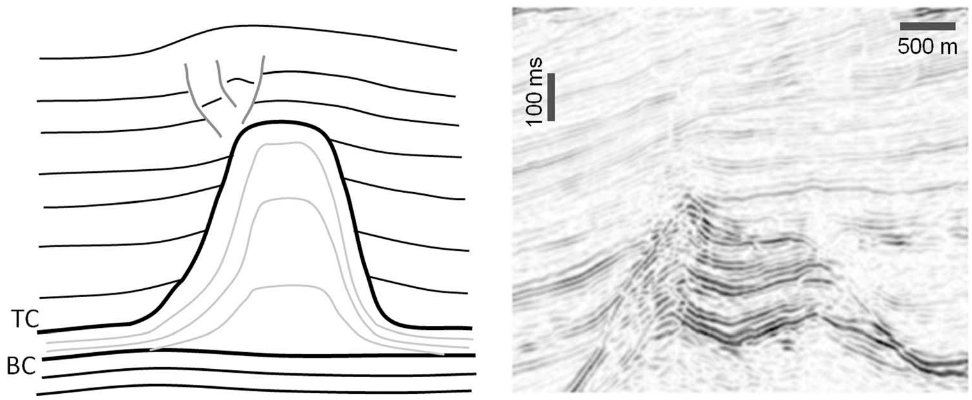


Figure 10. A schematic cross section and an example seismic image showing faulting and folding related to an isolated carbonate buildup margin. TC is top carbonate; BC is base carbonate. See identification criterion 4.1 (Table 2) for discussion. Used with permission from Shell Philippines.

strata. These high velocities, combined with significant localized thickening of carbonate strata in ICBs, may generate an identifiable velocity pull-up effect beneath an ICB. However, other geologic features with similar high velocities and thickening, for example, salt domes and, possibly, igneous bodies, may also exhibit velocity pull-up effects. Note also that positive antecedent topography beneath a candidate ICB may be difficult to distinguish from a velocity pull-up effect.

The following actions can be conducted to assess this criterion: look for coincidence of high seismic interval velocities with candidate ICBs; look for high areas below carbonate intervals, especially those occurring in a restricted area beneath significant localized thickening; and check that the high does not show indications of topographic relief, for example, it is not onlapped by younger strata. If such evidence is present, the high might be an antecedent high (see criterion 2.1; Table 2) instead of a velocity pull-up.

Absence of Gravity and Magnetic Anomalies

Igneous rocks forming volcanoes or intrusive bodies in faulted basement blocks may have a distinctive magnetic and gravity signature depending on their composition. A positive magnetic anomaly, and/or a positive gravity anomaly, could be indicative of an igneous body instead of a carbonate body. However, many ICBs are generated on bathymetric highs formed by tilted basement fault blocks or volcanoes. Consequently, the presence of a magnetic anomaly or a positive gravity anomaly does not preclude the presence of an ICB, but the absence of such strong positive anomalies may increase the probability of the feature being an ICB.

The following actions can be conducted to assess this criterion: examine any available potential field data around candidate ICBs and check for associated positive magnetic and gravity anomalies and model potential fields to understand the anomalies likely to be generated by the different possible features (e.g., volcano vs. ICB atop tilted basement fault block) developed at the depths indicated by the seismic data.

Finer-Scale Seismic Geometries

Compared with criteria in the general morphology and basic geometries category, this final set of six criteria is based on important seismic features and facies that occur commonly in well-imaged examples of known ICBs (Fontaine et al., 1987; Bachtel et al., 2004) but that are generally harder to detect on seismic images.

Isolated Carbonate Buildup Margin-Related Faulting and Folding

As a consequence of early cementation, ICB strata are commonly more rigid and are therefore more resistant to burial compaction than adjacent and overlying siliciclastic strata. Differential compaction across the platform margin may produce fold and fault structures in overburden strata (Figure 10). Where the siliciclastic overburden is deformed in a compressional stress regime, well-cemented brittle carbonate strata may also form structural buttresses, concentrating strain and leading to increased deformation of overlying strata around ICB margins. Margin-related faulting may act to hide other diagnostic features. For example, platform slope strata can act as preferential loci for the development of reverse faults or ramps in flat-ramp overthrusts

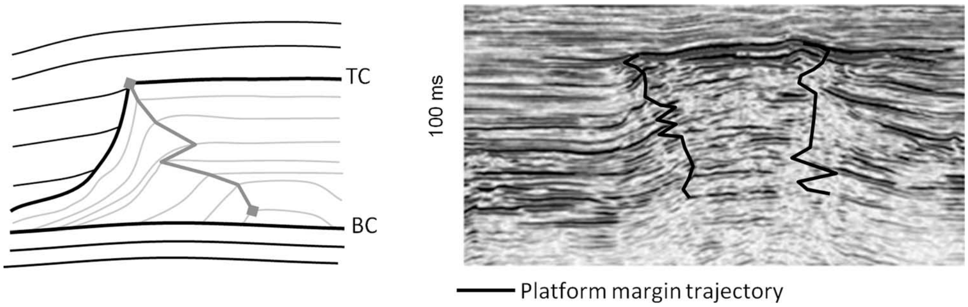


Figure 11. A schematic cross section and an example seismic image showing platform margin trajectories with phases of progradation, aggradation, and retrogradation, which can be indicative of an isolated carbonate buildup. TC is top carbonate; BC is base carbonate. See identification criterion 4.2 (Table 2) for discussion. Used with permission from Petronas Malaysia.

(Doglioni, 1984). In such cases, the original onlap of overburden may be partially or totally obscured.

The following actions can be conducted to assess this criterion: examine the margins of a candidate ICB and check for higher incidence of faulted overburden close to the ICB margin; check for fold structures, such as monoclines, developed locally in the overburden over candidate ICB margins; and assess the impact of margin-related faulting on other diagnostic features such as stratal onlap.

Systematic Isolated Carbonate Buildup-Margin Stacking Patterns

Isolated carbonate buildup margins can show progradational, aggradational, and retrogradational stacking patterns, depending on the balance between carbonate production and accumulation rates, rates of accommodation creation, off-platform transport processes, and the physiography and bathymetry of the platform margins. The ICB margin is commonly marked by a distinct break of slope from near-horizontal platform-top strata to relatively steeply dipping, adjacent platform-flank strata. Hence, the ICB-margin trajectory can commonly be mapped by identifying and tracing this break-of-slope feature (Figure 11). Tracing the ICB-margin trajectory can help with the identification if systematic trends of progradation, aggradation, and retrogradation can be related to other aspects of the observed seismic geometry, such as stratal downlap, truncation, or onlap. Many ICBs are dominated by aggradation (see criterion 2.2; Table 2). This effect can be mitigated by sediment transport off the platform top (shedding) or basinal siliciclastic infill at the toe of slope, generating flanking slope deposits that can form the substrate for in-situ production or reduce the accommodation that must be filled to allow progradation.

Retrogradation of ICB margins typically occurs as backstepping (e.g., Kusumastuti et al., 2002; Schlager, 2005). This differs significantly from the more steady retrogradational trends commonly observed in siliciclastic systems. Identification of platform-margin stacking trends is a useful identification criterion because other positive-relief features such as volcanoes or fault blocks are less likely to show systematic trends of this type. This criterion is most useful when similar backstepping trends can be observed through several potential ICBs in the studied region.

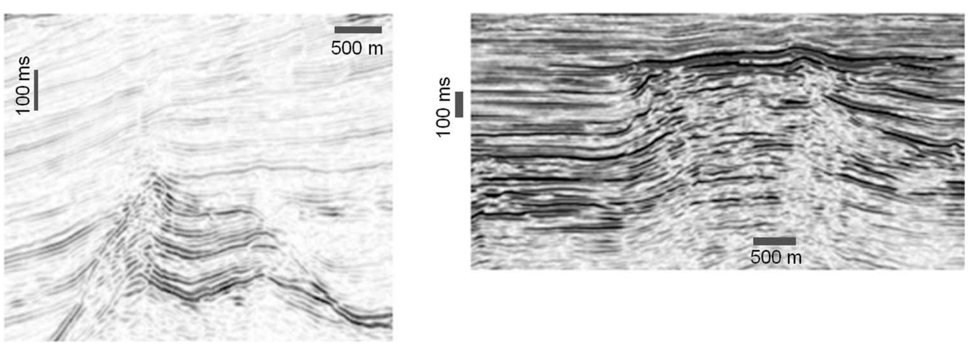


Figure 12. Two seismic images showing examples of well-imaged platform interior strata. See identification criterion 4.3 (Table 2) for discussion. Used with permission from Petronas Malaysia.

The following actions can be conducted to assess this criterion: identify the platform margin on seismic using break-of-slope or seismic facies features (e.g., Figure 11); trace the trajectory of the margin between base and top carbonate reflection and label intervals of aggradation, progradation, and retrogradation; and determine if the retrogradational intervals show backstepping geometries.

Appropriate interior seismic character: Depositional and sequence-stratigraphic models (e.g., Schlager, 2005) suggest that modern and ancient ICBs should have a well-stratified internal character, representing development of distinct depositional elements generated by interaction of various relative sea level, climatic, and diagenetic controls. Basic depositional models (e.g., Harris and Vlaswinkel, 2008) suggest that ICBs consist of high-energy deposits (reefs or sand shoals) at margins and protected interior lower-energy (but not necessarily low-energy) lagoonal deposits, possibly containing small patch-reef bodies. These features are expressed on 2-D or 3-D seismic data as mounded discontinuous reflections (reef) on the platform edges, enclosing more continuous, flat, potentially high-amplitude reflections (platform interior or lagoon; Figure 1) in the platform interior (Figure 12). Layering of platform-interior reflections can also be enhanced by periodic subaerial exposure of carbonate strata and related early diagenesis and cementation effects (e.g., Groetsch and Mercadier, 1999; Lehrmann and Goldhammer, 1999).

Consequently, identification of well-stratified internal reflections and a relatively chaotic seismic facies at the margin is an important diagnostic criterion in discriminating against other positive-relief features such as volcanoes and tilted fault blocks, which significantly increases confidence in identification. However, the absence of well-layered reflections or the absence of appropriately distributed seismic facies is not equivalently significant in a negative sense because, for both platform-interior and platform-margin strata, seismic facies related to primary depositional geometries can be easily overprinted and masked by later-stage diagenesis, fracturing, and faulting. Also, stratification and details of seismic facies may not be as evident on relatively poor-quality seismic data or at greater depths where high-frequency content in the seismic data is less.

The following actions can be conducted to assess this criterion: identify likely positions of platform margin and platform interior in the interval between top and base carbonate horizons; examine seismic data for an appropriate distribution of seismic facies, for example, the presence of convex-up mounded features in the ICB margin and continuous, flat, possibly high-amplitude reflections in the interior; and determine if the reflection characteristics within the potential ICB are notably different in character from the reflection characteristics in the surrounding strata. If they are, this would suggest a relatively ordered, well-stratified ICB interior and perhaps different velocity properties relative to surrounding strata.

Thick-Thin-Thick Depositional Pattern

Rapidly aggrading ICBs in sediment-starved basins may develop steep, erosional, or nondepositional bypass slopes with associated downdip correlative depocenters (e.g., Schlager, 1989). These features would be expressed on seismic data as a concave-up reflection representing the platform slope, extending from the edge of the platform and bifurcating into several correlative high-amplitude reflections in an adjacent basin (Figure 13). These correlative reflections could represent mass flow strata shed off the platform top or collapsed from the platform margin. Observing thick platform-interior strata, a thin bypass slope, and thick downdip correlative strata adds confidence to the identification of a positive-relief feature as an ICB. However, the absence of a thick-thin-thick geometry does not exclude an ICB interpretation because many ICBs do not develop bypass slopes.

The following action can be conducted to assess this criterion: tracing top and base carbonate reflections laterally away from the interior of the candidate ICB, checking for convergence into a single reflection, followed by expanding into multiple reflections in an adjacent lower elevation area.

Coalescing Growth Reflection Patterns

Internal reflections within a candidate ICB that suggest coalescence of originally smaller individual carbonate buildups into a single larger composite

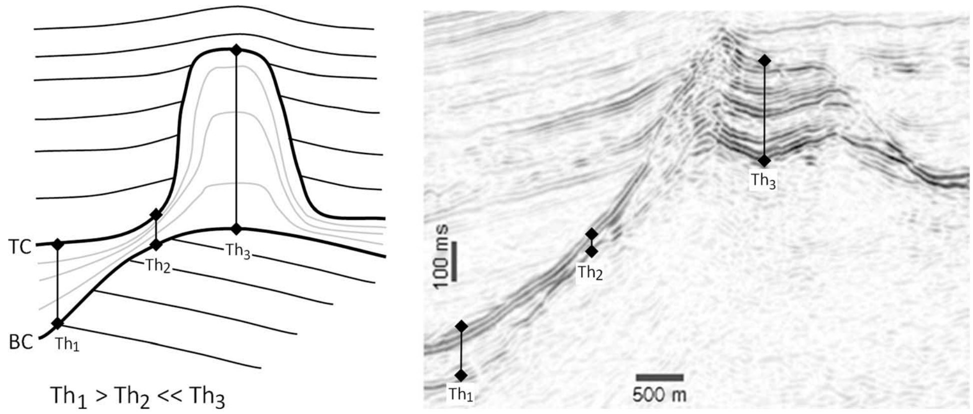


Figure 13. A schematic cross section and an example seismic image showing the thin-thick-thin pattern commonly developed on isolated carbonate buildups that are shedding material from the platform top through a bypass zone to be redeposited in deeper water adjacent to the platform. See identification criterion 4.4 (Table 2) for discussion. Used with permission of Shell Philippines. TC is top carbonate; BC is base carbonate; and Th_1, Th_2, and Th_3 are thicknesses of carbonate strata at the locations indicated.

feature may be significant diagnostic evidence that the imaged feature is an ICB. Coalescing growth occurs in the initial stages of platform growth when small ICBs form; prograde into adjacent open water to fill narrow seaways, straits, or channels; and merge into a single larger ICB. Seismic evidence for coalescence might consist of numerous internal clinoforms building out from areas of initial aggradation and merging (Figure 14). A subsequent change from progradational to aggradational stacking above the clinoform reflections may be observed (Figure 14). Examples of coalescence are described from the Bahamas (Eberli and Ginsburg, 1987b), the East Natuna Basin (Bachtel et al., 2004) and offshore Madura, Indonesia (Posamentier et al., 2010). Although not common in the studied data set, when present, this criterion strongly supports an ICB interpretation because similar processes are unlikely in other settings. However, coalescence does not occur in all cases of ICB growth and also may occur at scales below seismic resolution, so the apparent absence of this criterion should not be considered strong evidence against the presence of an ICB.

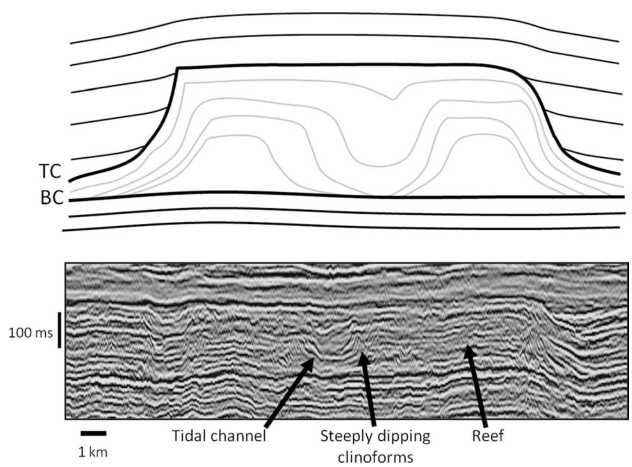


Figure 14. A schematic cross section and an example seismic image (from Posamentier et al., 2010), used with permission of SEPM, showing coalescing growth patterns toward the base of the carbonate interval. TC is top carbonate; BC is base carbonate. See identification criterion 4.5 (Table 2) for discussion.

The following actions can be conducted to assess this criterion: examine reflection patterns immediately above base carbonate, looking for evidence of smaller platforms with associated progradational clinoforms; and, if present, map progradational clinoform units and try to reconstruct basic history of early platform progradation and coalescence.

Potential Karst-Related Features

Dissolution of carbonate strata occurs during subaerial exposure and, sometimes, under specific conditions, in submarine settings with low accumulation rates. Dissolution can generate various geomorphic features, including large-scale cave systems, typically referred to as karst. On burial, karst features may be preserved, at least initially, as cavernous voids. Buried karst may also collapse, generating large disorganized breccia units within carbonate strata. If such large-scale caverns or breccia units can be

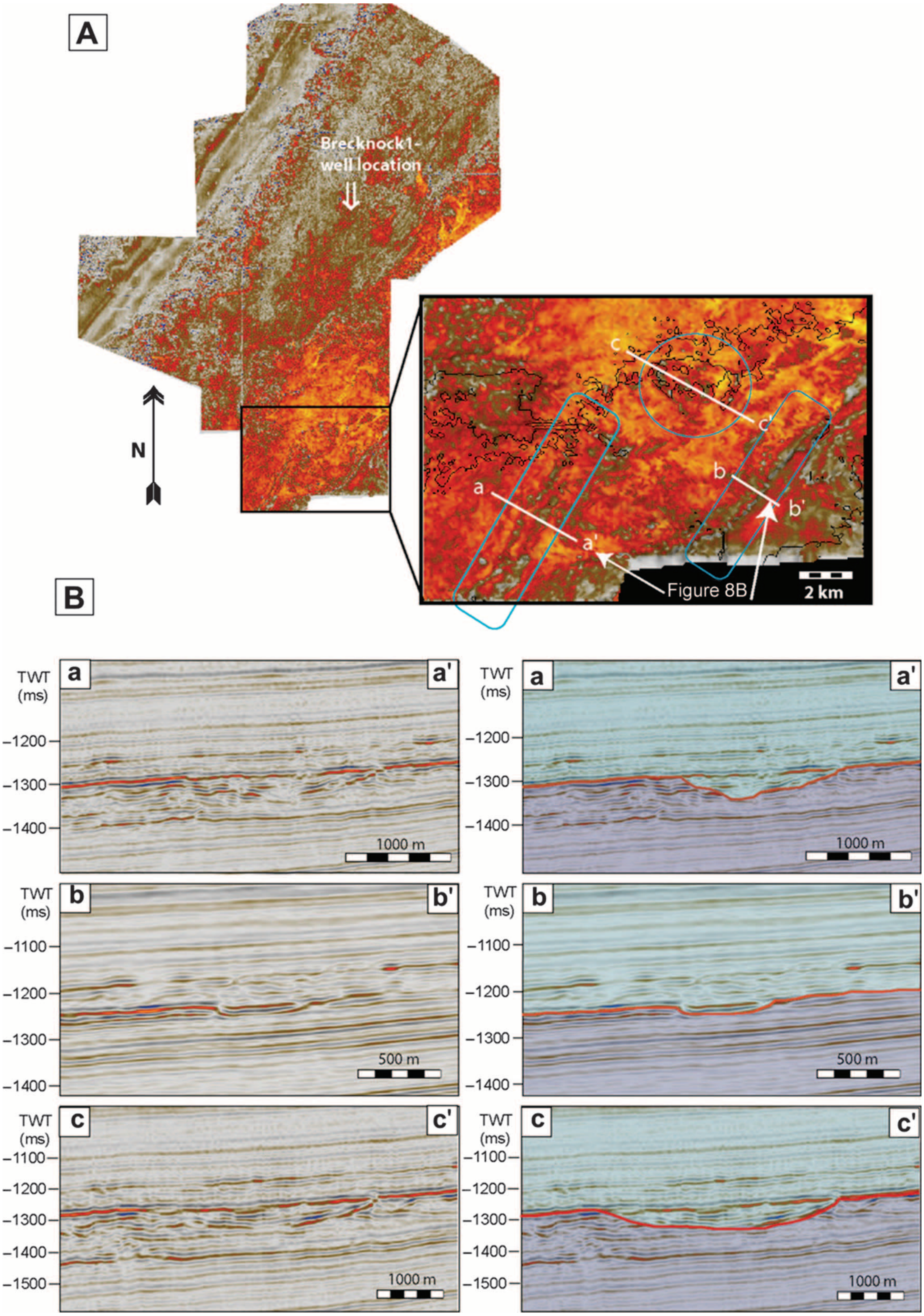


Figure 15. From Rosleff-Soerensen et al. (2012) used with permission of Elsevier. (A) An amplitude horizon slice from a carbonate interval. Red and yellow represent high amplitudes, probably caused by cementation of the reflector during subaerial exposure of the proximal part. Closeup shows karstification features and location of Figure 15B. Boxes represent karst troughs; circle, doline. (B) Seismic section with karst structures; for location, cf. Figure 15A. See identification criterion 4.6 (Table 2) for further discussion. TWT = two-way time.

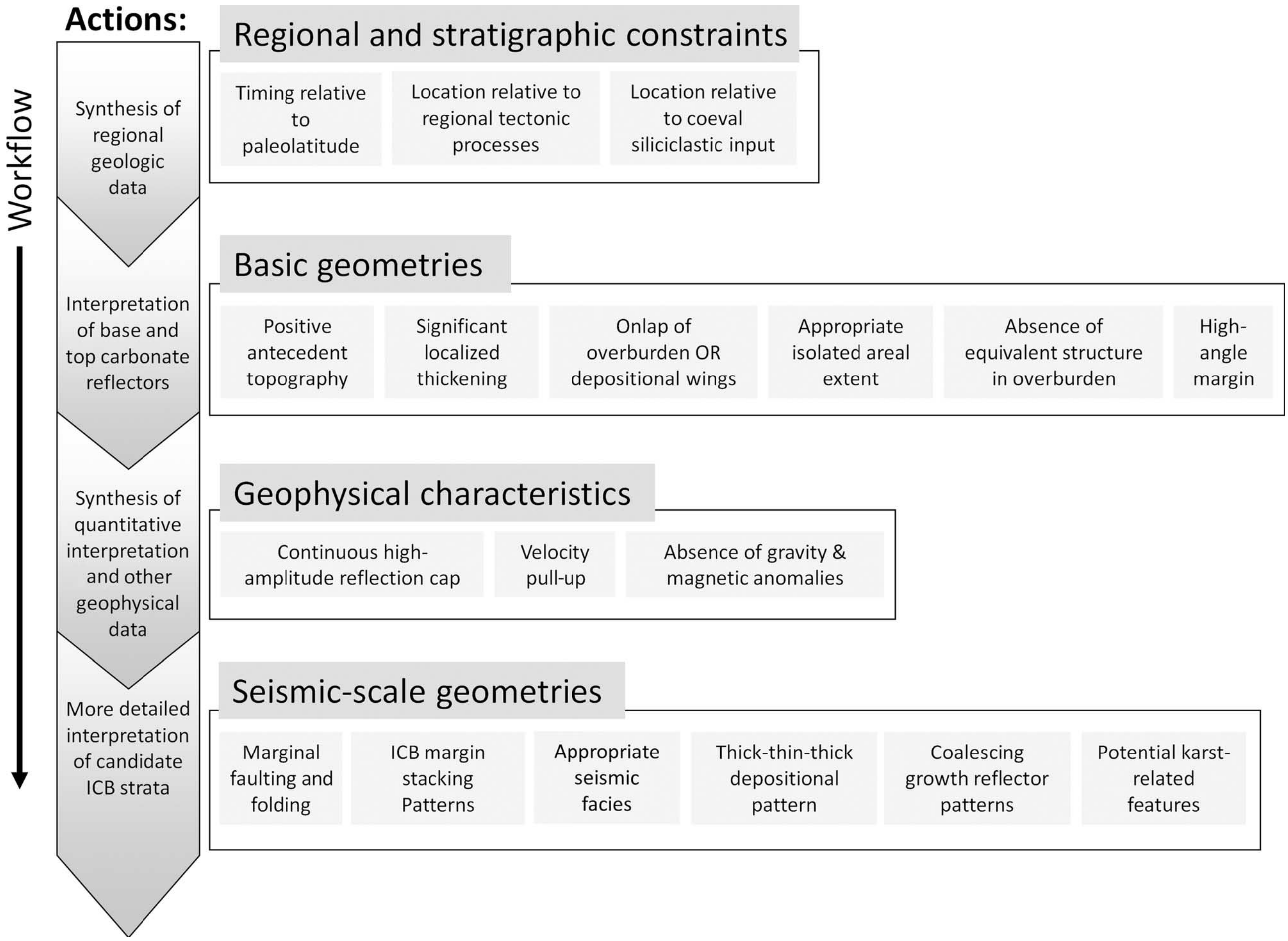


Figure 16. Flow chart indicating the sequence in which the identification criteria should be assessed. The arrow on the left indicates a progression of actions to be taken from synthesis of regional geologic data to analysis of fine-scale seismic geometries. For each scale of consideration, a series of criteria to assess working horizontally across the diagram from left to right exists. See text for description and discussion of individual criteria. ICB = isolated carbonate buildup.

identified on seismic data (e.g., Purdy and Waltham, 1999; Story et al., 2000; Rosleff-Soerensen et al., 2012) and, particularly, if they can be related to a suspected subaerial exposure surface, this can help identify a seismic feature as an ICB. For example, karst features in the top layers of a candidate ICB may help distinguish ICBs from noncarbonate positive-relief features such as volcanoes. However, seismic-scale karst does not always develop in carbonate systems, or it may be poorly imaged in less-than-optimal seismic data, so the absence of karst features should not preclude an ICB interpretation.

The following actions can be conducted to assess this criterion: examine platform interior for chaotic, high-amplitude reflection patterns occurring at specific restricted intervals (e.g., Figure 15); with 3-D data, generate amplitude or attribute maps for horizons between top and base carbonate and look for karst patterns in planform (e.g., Figure 15); and, if present, determine if the chaotic unit is restricted to the platform-top area or if it extends laterally into areas away from the platform top.

Scoring of Isolated Carbonate Buildups and Other Features Based on the Identification Criteria

The ICB ID criteria listed above and in Table 2 should be assessed following a particular sequence, working from large-scale to small-scale (Figure 16). Assessing all the criteria listed, starting at a regional level and ending with analysis of fine-scale seismic

	A	B	C	D	E
Timing relative to paleolatitude	+1	+1	+1	+1	+1
Timing relative to regional flooding	+1	+1	+1	+0.5	+1
Timing relative to framework builder types	+1	+1	+1	+1	+1
Location relative to regional tectonic processes	+1	+1	+0.5	+1	+1
Location relative to coeval siliciclastic input	+1	+1	+1	+0.5	+1
Positive antecedent topography	+1	+0.5	+0.5	−1	+1
Significant localized thickening	+1	+0.5	+1	−1	−1
Onlap of overburden OR depositional wings	+1	+1	+1	+1	−1
Appropriate isolated areal extent	+1	+0.5	+0.5	+1	0
Absence of equivalent structure in overburden	+1	+1	+1	0	−1
High-angle margin	+1	0	+1	+1	+0.5
Continuous high-amplitude reflector cap	+1	+1	+0.5	−1	+1
Velocity pull-up	+0.5	+0.5	+0.5	+0.5	−1
Absence of gravity-magnetic anomalies	0	0	0	−1	0
Margin related faulting and folding	+1	0	+0.5	−1	−1
Buildup margin stacking patterns	+1	+1	+0.5	−1	−1
Appropriate seismic facies	+1	+0.5	0	−1	−1
Thick-thin-thick depositional pattern	+1	0	0	−1	−1
Coalescing growth reflector patterns	+0.5	+0.5	0	−1	−1
Potential karst-related features	0	0	0	0	0
Score:	17	12	11.5	−1.5	−1.5

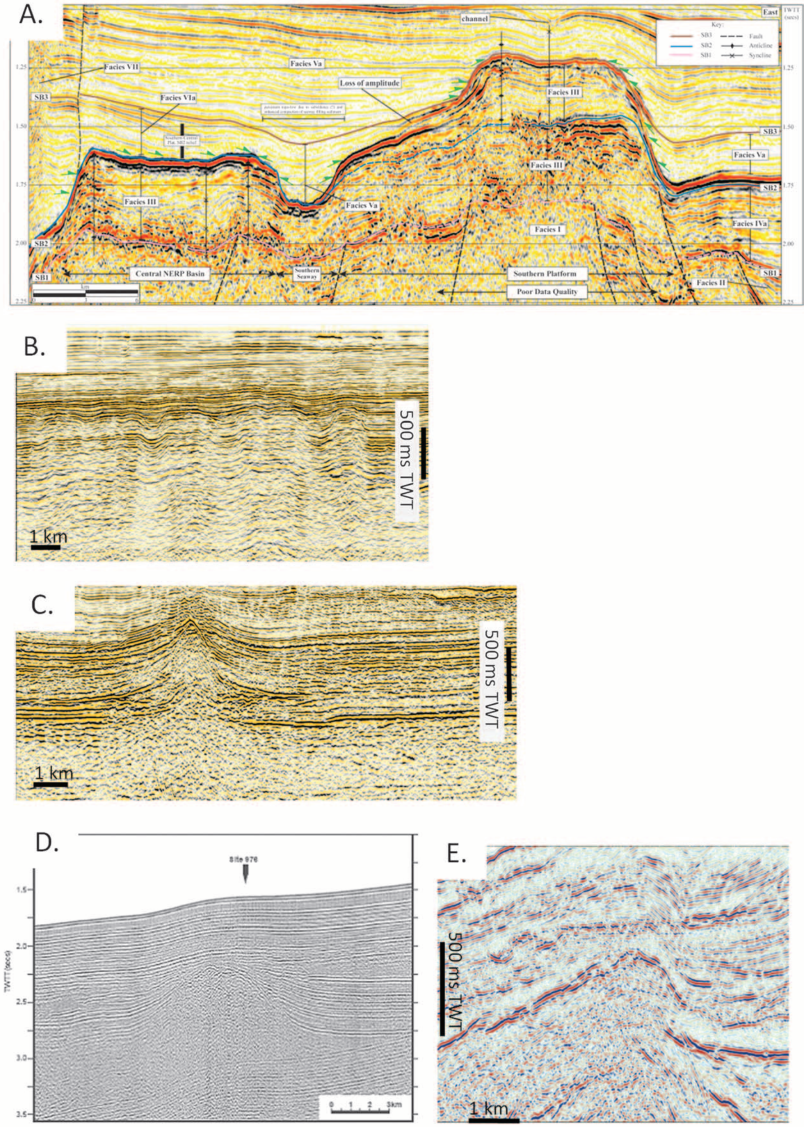


Figure 17. Examples of various geologic features imaged on seismic data (A–E) and assessed according to application of the identification criteria with quantitative scores applied for each criterion on a range +1 to −1. (A) The Da Nang isolated carbonate buildup (ICB), offshore Vietnam, is a proven ICB (Owens, 2001) and scores +17. (B) Feature classed as a probable ICB located offshore Madura, Indonesia, scores 12. (C) Located offshore Bali, Indonesia, and classed as a possible ICB, this feature scores 11.5. (D) This feature is tilted fault block. It scores −1.5. (E) This feature is a fold structure, not an ICB, and scores −1.5. TWT = two-way time.

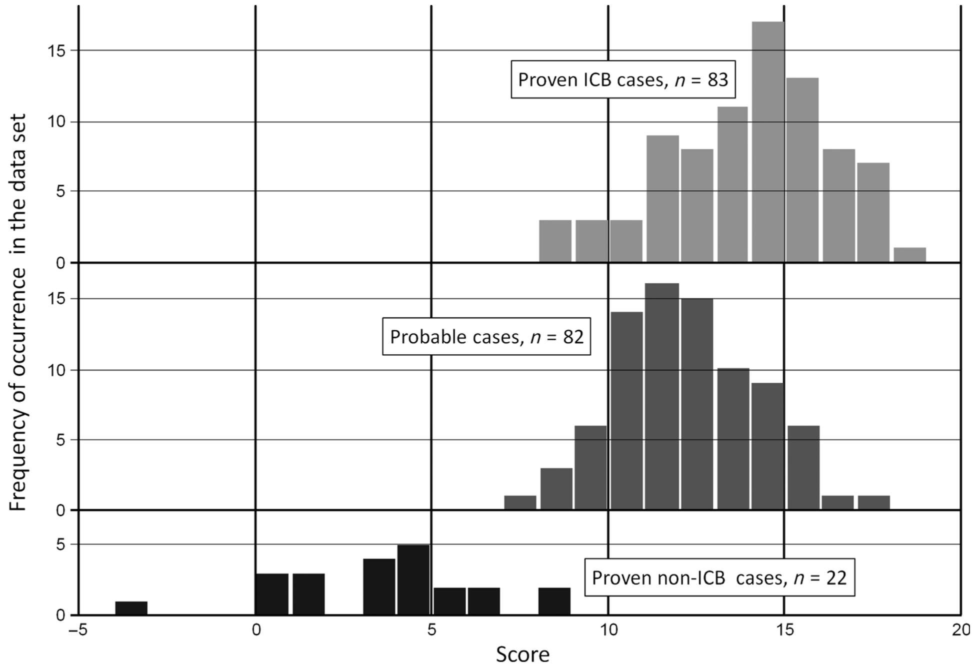


Figure 18. Three histograms showing the frequency of each score in the non–isolated carbonate buildup (ICB), probable ICB, and proven ICB categories. The modal score is highest for the proven category, and lowest for the non-ICB category. A large degree of overlap exists between the range of scores for the proven and probable categories but little overlap with scores for the proven non-ICB cases. This suggests that the scoring scheme does have discriminatory power, although with the caveat that the sample size is small (n = 22) for the proven non-ICB cases.

geometries, is intrinsically useful because it requires a systematic critical evaluation of the evidence present in the available data. However, it is also useful to have a simple summary of this process.

Numerical Scoring of Identification Criteria

One way to summarize the assessment of the ID criteria is to combine them into a numerical score (Table 2). To summarize the result while also incorporating uncertainty for each criterion, we assign a value of +1 for a clear positive response; +0.5 for a weak positive response, where some uncertainty exists; 0 for a case where the criterion cannot be assessed, perhaps because of lack of sufficiently clear data; and –1 for a definite negative. Possible score values range from 20 to –20. Note that scoring criterion 1.1 (Table 2) is separated into three components—timing relative to paleolatitude, timing relative to regional flooding, and timing relative to framework builder types—each of which is given an individual score (Figure 17).

Based on scores calculated for several ICB and non-ICB features (Figure 17), the scoring system does appear to have some discriminatory power between the different classes. Proven ICBs tend to get high scores. Features known not to be ICBs get low scores. The discriminatory power of the scoring scheme is further demonstrated with a larger data set that shows results from 187 examples classified as proven ICBs, possible ICBs, or not ICBs (Figure 18). Note that these 187 examples are the better data quality examples, excluding entries in the database with a data quality of 4 where poor data are an impediment to a reliable identification of stratal features and may lead to misleading low scores. Results from analysis of the 187 examples (Figure 18) tend to confirm the results from the smaller sample (Figure 17); the scoring scheme distinguishes between known ICB examples, which score between 7.5 and 17.0, and other seismic images known not to be ICBs, which score between –4.5 and 7.5. The lack of overlap in scores and the clear separation between modal scores (Figure 18) suggest that scoring according to the ID criteria should be useful in distinguishing between ICB features and non-ICB features in cases where the nature of the imaged feature is unknown.

Discriminatory Power of Individual Identification Criteria

As well as considering the discriminatory power of the whole scoring scheme, individual criteria can be analyzed and compared for their ability to

Table 3. Subtracting the Mean Score of Proven Isolated Carbonate Buildups from the Mean Score of Non–Isolated Carbonate Buildups for Each Criterion Gives Some Indication of Power of Each Criterion to Distinguish Isolated Carbonate Buildups from Non–Isolated Carbonate Buildups*

Criterion Number and Description		Mean Score of Proven ICBs**	Mean Score of Non-ICBs**	Discriminatory Power
4.2	ICB-margin stacking patterns**	0.988	−0.263	1.251
4.4	Thick-thin-thick depositional pattern	0.265	−0.921	1.186
2.2	Significant localized thickening	0.982	−0.053	1.035
4.1	Margin-related faulting and folding	0.048	−0.921	0.969
4.3	Appropriate interior seismic character	0.006	−0.921	0.927
3.2	Velocity pull-up	0.090	−0.763	0.854
3.1	Continuous high-amplitude reflector cap	0.843	0.053	0.791
2.1	Positive antecedent topography (paleohighs)	0.982	0.211	0.771
2.3	Onlap of overburden or presence of depositional wings	0.994	0.368	0.626
2.5	Absence of equivalent structure in overburden	0.988	0.421	0.567
2.6	High-angle margins	0.988	0.474	0.514
2.4	Appropriate isolated areal extent	0.946	0.500	0.446
1.3	Location relative to coeval siliciclastic input	1.000	0.737	0.263
1.2	Location relative to regional tectonic processes	1.000	0.789	0.211
4.6	Potential karst-related features	0.036	0.000	0.036
1.1	Timing relative to paleolatitude, regional flooding, and framework builder types	1.000	0.974	0.026
4.5	Coalescing growth reflector patterns	0.036	0.026	0.010
3.3	Absence of gravity and magnetic anomalies	0.000	0.000	0.000

*Criteria are sorted in order of decreasing discriminatory power.
**ICB = isolated carbonate buildup.

distinguish ICB from non-ICB. One simple way to do this is to find the mean of the scores for a particular criterion for both proven ICBs and non-ICBs, so

$$\mu_{\text{proven-ICB}} = \frac{\sum_{1}^{n_{\text{proven-ICB}}} S_{\text{i}}}{n_{\text{proven-ICB}}}$$

$$\mu_{\text{non-ICB}} = \frac{\sum_{1}^{n_{\text{non-ICB}}} S_{\text{i}}}{n_{\text{non-ICB}}}$$

and then calculate the difference, D, so

$$D = \mu_{\text{proven-ICB}} - \mu_{\text{non-ICB}}$$

where $\mu_{\text{proven-ICB}}$ is the mean score for a criterion applied to proven ICB cases, $\mu_{\text{non-ICB}}$ is the mean score for the criterion applied to non-ICB cases, S_{i} is a score for an individual feature in either case, and $n_{\text{proven-ICB}}$ and $n_{\text{non-ICB}}$ are the numbers of features analyzed in each class. The difference, *D*, between these mean scores is a statistic that gives some indication of the power of the criterion to distinguish between ICB and non-ICB. Values of *D* calculated for the 83 proven cases and 22 non-ICB good data quality cases in the database are shown in Table 3. Because possible scores per criteria range from +1 to –1, the maximum difference in score between a proven ICB and a non-ICB should be 2. However, because the example of scoring in Figure 17 and the range of scores in Figure 18 show that it is commonly difficult to assign values of +1 or –1 to criteria, even the highest values of *D* are all less than 2, reflecting individual image scores of +0.5 and 0 within the sample. Criteria are listed in Table 3 in the order of the decreasing value of *D*.

Based on this analysis, criterion 4.2, systematic ICB-margin stacking patterns, gives the greatest range of scores between proven ICBs and non-ICBs, with criterion 4.4, thick-thin-thick depositional pattern, and 2.2, significant localized thickening, also giving a D value greater than 1 (see Table 2 for criteria descriptions). The regional criteria 1.1 to 1.3 have low values of D, suggesting that, for this data set, at least, they are not strong discriminators. Criteria 4.5, coalescing growth reflector patterns; 4.6, potential karst-related features; and 3.3, absence of gravity and magnetic anomalies, also have low values of D, but this is caused by several scores of 0 reflecting a response of "unknown," where the criterion cannot be assessed, perhaps because of lack of sufficiently clear data. These criteria might be more powerful discriminators in cases where better data are available.

Impact of Variable Data Quality

Data quality and orientation of the seismic image can also influence scoring. Poorly imaged ICBs will likely score lower than better imaged ICBs simply because more criteria will be assessed as "unknown" because of poor data quality and associated imaging problems. Similarly, certain orientations of seismic lines through potential ICB features may make identification of the diagnostic criteria more difficult. However, analysis of four different variable-quality images of a proven ICB feature, ranging from a 3-D poststack time migration line parallel to the short axis of the ICB to a 2-D line oriented at an oblique angle, showed a range of scores from 17 out of 20 to 14.5 out of 20. This suggests that, at least in the case of high-scoring examples, the variation caused by line orientation and data quality is small over the range of data likely to be used through a typical exploration-appraisal process. Nevertheless, care should always be taken to distinguish a low score caused by poor data quality and a low score caused by definite absence of some diagnostic features.

DISCUSSION

Application of these ICB ID criteria and scoring system in subsurface evaluation projects has been demonstrated as a useful exploration tool. The ID criteria and the associated scoring system are useful because they provide a guiding framework for a systematic thoughtful analysis and interpretation of the available data while incorporating issues of uncertainty and data quality. For example, assessing the evidence for significant localized thickening requires careful assessment of the top and base carbonate picks, which leads to various considerations of likely seismic response, the likely stratal architectures of carbonate features, consideration of how the geometry of the candidate feature might vary in three dimensions, and an evaluation of the quality of the seismic data. It also requires a decision, for example, between a score of +1 for a clear positive response and +0.5 for a weak positive response, which in turn requires a degree of synthesis of the uncertainty involved in the interpretation of all the evidence mentioned above. However, the method is not a silver bullet that provides a simple infallible solution to the problem of ICB identification. Variable quality of seismic data and the complexity of sedimentary systems preclude such a simple solution.

These ID criteria will likely evolve with further use. For example, it is sometimes still difficult to distinguish volcanic features from ICBs based on the scoring system presented. This could be addressed by expanding the number of known volcanic features included in the database and analyzing the differences between known volcanoes and ICBs. Another possible development would be to weight scores from the different criteria, so that, for example, criteria that have higher discriminatory power (see Table 3) have a higher weighting in the final score. Future development of the scheme could also add additional scores to specific combinations of criteria. For example, the combination of significant localized thickening, coalescing growth reflection patterns, and systematic margin stacking patterns could be assigned a high score. This may help distinguish a volcanic feature, which may have some, but probably not all, of these features, from an ICB, which could have all three, at least in well-imaged examples. All of these possible developments should be based on rigorous statistical analysis of the scores; the present method of determining discriminatory power is effective, but more sophisticated multivariate methods, for example, might yield much additional information.

CONCLUSIONS

Isolated carbonate buildups continue to be important targets for hydrocarbon exploration and seem likely to deliver further significant volumes of oil and gas in the future. Identification and de-risking of ICBs in an exploration setting, commonly with relatively sparse 2-D seismic data, is an ongoing challenge. Compilation and analysis of a seismic image database with 234 entries has allowed generation of a set of ID criteria that can be used as part of a systematic evaluation of seismic evidence for the presence of an ICB. When combined with simple scoring systems, results suggest that the criteria offer a useful method to help distinguish ICBs from other imaged features such as tilted fault blocks and volcanoes that exhibit similar geometries and features. However, the criteria and, particularly, the calculated scores, are not a silver bullet solution to the problem of ICB identification. The best way to apply the criteria and scoring is as a tool to promote careful and consistent observation and as a realistic appraisal of the uncertainty involved in identification of a particular seismic feature. Various research avenues remain to be explored using the image database. For example, it is possible to further develop the scoring schemes using weighting criteria and statistical analysis.

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