# Insights on Oligocene-Miocene Carbonate Mound Morphology and Evolution from 3D Seismic Data, East Java Basin, Indonesia*

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## Abstract

The High Density MC3D seismic survey, acquired by PGS in 2003 over the North Madura platform, is excellent data for quantitative interpretation of carbonate-mound evolution. Detailed imaging of the growth histories of Oligocene-Miocene carbonate buildups provides insight into geometric parameters characteristic of platform initiation, development, and demise. Mound initiation occurs with development of small (<100m to 500m diameter), closely spaced, domal buildups, which become the nuclei for the formation of intermediate mounds (2km to 3km diameter). Nucleation mounds build concentrically to form intermediate mounds, which selectively coalesce into amalgamated platforms (>5km diameter), become isolated platforms of varying size (<5km diameter), or die-off altogether.

The high resolution and quality of the seismic data enable visualization and quantitative analysis of geometry, orientation, and spatial distribution of nucleation and intermediate mounds, suggesting models for development of isolated vs. amalgamated platforms. Seismic Discontinuity time-slices datumed at the base of the carbonate section provide clear images of mound size, distribution, and morphology at discrete growth stages, which record a complex history of initiation, aggradation, coalescence or isolation, progradation, potential exposure, and demise. Additional seismic attributes (e.g., isochron) can be exploited by innovative-volume-interpretation techniques for identifying, isolating, and extracting mound features. Geometric attributes such as mound area, aspect ratio, orientation, etc. are calculated directly from extracted elements of the seismic data. The resulting data provide dimensional, spatial, and seismic facies characteristics of carbonate buildups for conditioning geologic models. Additional ties to well and outcrop data improve prediction of reservoir presence, quality, and distribution.

## Introduction

The East Java Basin of Indonesia is a proven prolific hydrocarbon province with oil and gas fields producing from a variety of Tertiary reservoirs. A number of the largest fields in the basin occur in Oligocene- to Miocene-age carbonate reservoirs, e.g., Cepu, Sukowati, Bukit Tua, and Jenggolo, (Satayana 2001). Total resources of prospects and leads in Oligo-Miocene carbonates in the East Java Basin are estimated to exceed 30 BBOE (Satayana 2003). Improving the understanding of the development, growth, and evolution of Oligo-Miocene carbonates can improve capabilities for predicting the size, shape, and distribution of potential reservoirs of this age, ultimately impacting the success in exploiting the existing and remaining hydrocarbon potential of the basin.

This study utilizes the PGS MC3D seismic survey to examine the evolution of Burdigalian (early Miocene) carbonate buildups on the North Madura platform in north-central East Java Basin. In addition to visualizing the features of carbonate mounds in the seismic data, the aim of this study was to derive and compile a comprehensive database of quantitative dimensional and geometric data for various growth stages of Burdigalian mounds directly from 3D seismic data. This database improves the understanding of the evolution of carbonate mounds of this age, the capabilities for predicting the size, shape, and distribution of Burdigalian mounds, and has the potential to be used for conditioning and populating geologic models in analogous areas where seismic data are limited.

The MC3D seismic survey is a high-quality, multi-client survey acquired by PGS in 2003. The survey is approximately 100 km from east to west and 60 km from north to south, covering a portion of the 200+ km-in-length North Madura carbonate platform (Figure 1). It is a high-resolution survey with 72 fold, tight-bin spacing, and a 2-ms sample rate (PGS, 2003). The result is spectacular imaging of the Tertiary carbonate section, as well as clastic intervals and structural features. Examples of the details imaged in the survey are shown on the lower half of Figure 1 in a discontinuity time slice (lower left) and a shaded relief map of the time surface for the Burdigalian interval (lower right). These images and those in Figure 2 illustrate the impacts of using a high-quality 3D seismic data set to visualize carbonate-mound characteristics and evolution. They also demonstrate the general workflow of directly extracting and quantifying geometric and dimensional attributes of these mounds at various growth stages, ultimately applying the quantitative information to analogous areas with limited seismic data coverage and as input for conditioning geologic models.

In the survey area and East Java, in general, there are 4 main episodes of Tertiary carbonate deposition, separated by mixed carbonate/clastic deposition. Carbonates accumulated in the Rupelian (which lies just above the Tertiary economic basement), the Chattian, the Burdigalian, and the Tortonian near the top of the section. Each of these carbonate units has unique geometric characteristics (Posamentier, 2005; Simo et al., 2006) and unique seismic-facies character (Figure 3).

The Rupelian section lies at between 5000- and 6000-ft depth in the North Madura area. It is the least well imaged of the Tertiary carbonate units and was not the focus of this study.

The Chattian carbonates lie between 4000 and 5000 ft depth. The seismic expression at the top of this unit is high-amplitude discontinuous or disrupted appearance, which in map view appears as a blanket of small, circular positive relief features across the entire survey area that are < 100 m diameter and 10s of meters in height.

The Burdigalian section, between 3000 and 4000 ft, is an interval characterized by large amalgamated and isolated platform growth, with multiple stages of growth evident in the seismic data. The seismic facies of the Burdigalian platforms varies from mounded on the platform highs and parallel, semi-continuous between the highs. Individual mounds range in size from several hundreds of meters to several km in diameter, and are between 300 m and 400 m thick. Some mounds amalgamate into a mega-platform, whereas others amalgamate into isolated platforms. The Burdigalian carbonates drown in the late early-Miocene, due to influx of clastic sediments from the north, and are buried by Serravallian siliciclastics (Hughes et al., 2009).

The Tortonian section overlies the top of the stack at between 1500 and 2500 ft. The gross geometry of the Tortonian platforms, as imaged in the seismic data, is very different from the older Tertiary platforms, with broad, elongate, flat-topped mounds that in map view can be 5 to 10 km across and 20 km in length. Evidence of multiple stages of aggradation, progradation, and exposure is seen in the seismic data for the Tortonian mounds, before they ultimately succumb to an influx of clastic sediments.

The Burdigalian buildups are the focus of the research presented in this study, and the remainder of the discussion focuses on the visualization, extraction, and dimensional quantification of the carbonate mounds in this section.

## Methodology

### 3D Visualization and Feature Extraction of Burdigalian Interval

3D visualization and volume interpretation techniques were used to interpret, isolate, and extract the features of interest in the Burdigalian section. To start, the top and base of the unit were interpreted with proprietary and commercial software. The volume was then flattened on the base of the Burdigalian section to remove pull-up artifacts and to datum the section on a depositional surface. Attribute volumes such as discontinuity, dip, and Burdigalian isochron were generated from the flattened cube. The attributes were evaluated for their effectiveness in imaging and isolating internal characteristics of the section. Isochron illuminates thickness trends in mounds and inter-mound platforms and highlights sediment shedding wedges off platform margins (Figure 4). The Discontinuity volume provides high definition images of structural features and mound margins, as well as internal mound characteristics. Time slices from the Discontinuity data were examined at discrete growth steps for visualizing and interpreting the evolution and growth histories of the individual platforms, from nucleation through stages of growth and amalgamation or isolation (Figure 2).

Ultimately Discontinuity and Isochron were used in combination for extracting features from the volume. Co-rendering these two attributes provides the most effective constraints on isolating individual mounds, with isochron revealing the location of thick platform mounds and discontinuity highlighting the margins of the mounds. Figure 5 illustrates the methodology for extracting the thickest mounds from the Burdigalian section. Once extracted, polygons are generated around the margins of the extracted features. These polygons are then available for statistical analysis and generation of quantitative dimensional and geometric data.

A subset of the 3D survey representing a variety of sub-environments for platform development (mega-platform, channel, and basin) was chosen to extract mound features at several growth stages within the Burdigalian interval. The location of the subset is shown in Figure 5. Mound features were extracted at three stages of growth within this sub-area; mound initiation, intermediate stage growth and amalgamation, and late stage amalgamation (Figure 6). Polygons were automatically generated around the extracted geobodies, from which a comprehensive database of quantitative dimensional and geometric properties was compiled.

### Tie-to-Rock Properties

No well data directly on the 3D survey were available for this study. Logs from a well approximately 20 km off the survey were tied to a 2D seismic line, which displays seismic facies similar to the mounded seismic facies observed in the MC3D. Porosities from the log on the order of 20% were observed at a depth consistent with the tie-to-mounded seismic facies in the 2D seismic data. To further tie observations seen in the seismic data to rock properties and facies, outcrop studies were relied upon for analogous age rocks with similar geometries. Field mapping done by Sharaf et al. (2005) in onshore Java identified mounded coral and red algal rhodolith boundstones that may be analogous to the mounded seismic facies observed in the 3D survey. Geometries observed in the field in adjacent platy coral and benthic foram packstones and grainstones may be an analog for the parallel, continuous seismic facies adjacent to the mounded seismic facies in the 3D survey (Sharaf et al., 2005) (Figure 7).

## Results

The results of the feature extraction from the early, intermediate, and late stages of mound development yield both observational and quantitative information about the evolution and growth of the Burdigalian carbonate interval (Figure 8). Observationally, carbonates in this interval initiate as circular to sub-elliptical individual mounds in each of three sub-environments; mega-platform, basin, and channel. Mounds in the mega-platform area are greater in abundance, more tightly clustered, and generally smaller than those developing in the basin and channel areas. By the intermediate stage, early amalgamation or isolation of the initiation mounds is observed. Oncoid-like concentric growth outward and upward from nucleation sites, results in the initial amalgamation of the tightly clustered initiation mounds in the mega-platform area. In the basin, continued growth of the larger nucleation mounds has organized this area into several distinct semi-amalgamated isolated platforms. Early amalgamation of mounds in the channel has led to development of distinct isolated platforms that are smaller than those in the basin and elongated parallel to the channel axis. By late-stage growth, continued amalgamation results in randomly oriented and irregular-shaped mounds in the mega-platform area. Sub-circular, large isolated platforms developed in the basin due to continued growth and amalgamation of intermediate-stage mounds. Isolated platforms in the channel area continued to aggrade vertically, while retaining areal size, shape, and orientation established in the intermediate stage.

A subset of the quantitative results of the dimensional and geometric properties extracted from the 3D survey is summarized in Figure 9. The database provides quantitative information, such as area, aspect ratio, azimuth, and nearest neighbor as well as ranges for these parameters, for each growth stage in the mega-platform, basin, and channel areas. These results support and quantify the visual observations that small (0.5 to 1 km diameter), circular to sub-elliptical initiation mounds increase in size over time and develop into amalgamated mounds with size, shape, orientation, and distribution characteristics unique to each of the three sub-environments.

# Discussion

Several generalizations related to the evolution of Burdigalian mounds in the North Madura platform can be inferred from the quantitative and visual data extracted from the 3D seismic survey. When mounds initiated in the early Miocene, nucleation sites grew concentrically outward and upward forming circular to sub-elliptical mounds with aspect ratios less than 1.25. Mounds that developed into amalgamated platforms on the mega-platform were initially more tightly clustered than those that developed into isolated platforms, suggesting accommodation differences on the mega-platform relative to the basin and channel. Less a accommodation space forced earlier amalgamation on the mega platform. The result is irregular-shaped, randomly oriented amalgamated mounded buildups with mounded seismic facies characteristics, separated by intraplatform, non-mounded carbonate deposits with parallel, continuous to semi-continuous seismic facies.

Abundant accommodation space in the basin enabled less restricted growth and led to development of large (> 30 $km^2$ map footprint) isolated platforms. These platforms have upwards of 400-m vertical relief and developed through semi-amalgamation of 2 to 7 initial mounds, again with mounded buildups characterized by mounded seismic facies and separated by intra-platform, non-mounded carbonate deposits with parallel continuous to semi-continuous seismic facies.

Isolated platforms also developed in the channel area, but their growth was limited by early development of steep-walled mounds parallel to the channel axis, likely created by strong currents along the axis of the channel. Unrestricted growth and amalgamation parallel to the channel axis and vertically resulted in channel platforms that are > 400m in height and elongated with and orientation parallel to the azimuth of the channel.

In most natural systems, as the size of features increases, their abundance decreases with a log-normal distribution. This relationship holds for the Burdigalian mounds in this study. An initially large number of relatively small mounds in each sub-environment evolved into a smaller number of relatively larger mounds. The quantitative database contains information on how many fewer mounds and how much larger (Figure 10).

Logarithmic trends for mound abundance versus size emerge for each sub-environment; however, the slope of the relationship varies from area to area.

The results of the study have an impact on conditioning and populating geologic models. The quantitative dimensional data combined with visual observations derived from the 3D seismic data provide a greater understanding of the initiation, growth, and distribution of Burdigalian-age carbonate mounds and facies in the East Java Basin. Ties-to-rock properties from outcrop analogs and well data further enable distribution of reservoir properties in a model (Figure 11).

## Conclusions

The insights gained from studying the high-quality 3D seismic data set are not only visual insights on the evolutionary and growth stages of mounds in the Tertiary section of the East Java Basin, but also quantitative insights on their dimensional and geometric characteristics and tie-to-rock properties. 3D visualization, volume interpretation, and quantitative analysis have enabled compilation of a quantitative database of geometric and dimensional properties of Oligocene-Miocene carbonates in the East Java Basin. Combining this database with depositional models for accumulation and growth of carbonates in this basin creates a powerful exploration tool for predicting buildup size, distribution, geometry, and facies, and a statistical basis for conditioning and populating geologic models in analogous areas (Figure 12).

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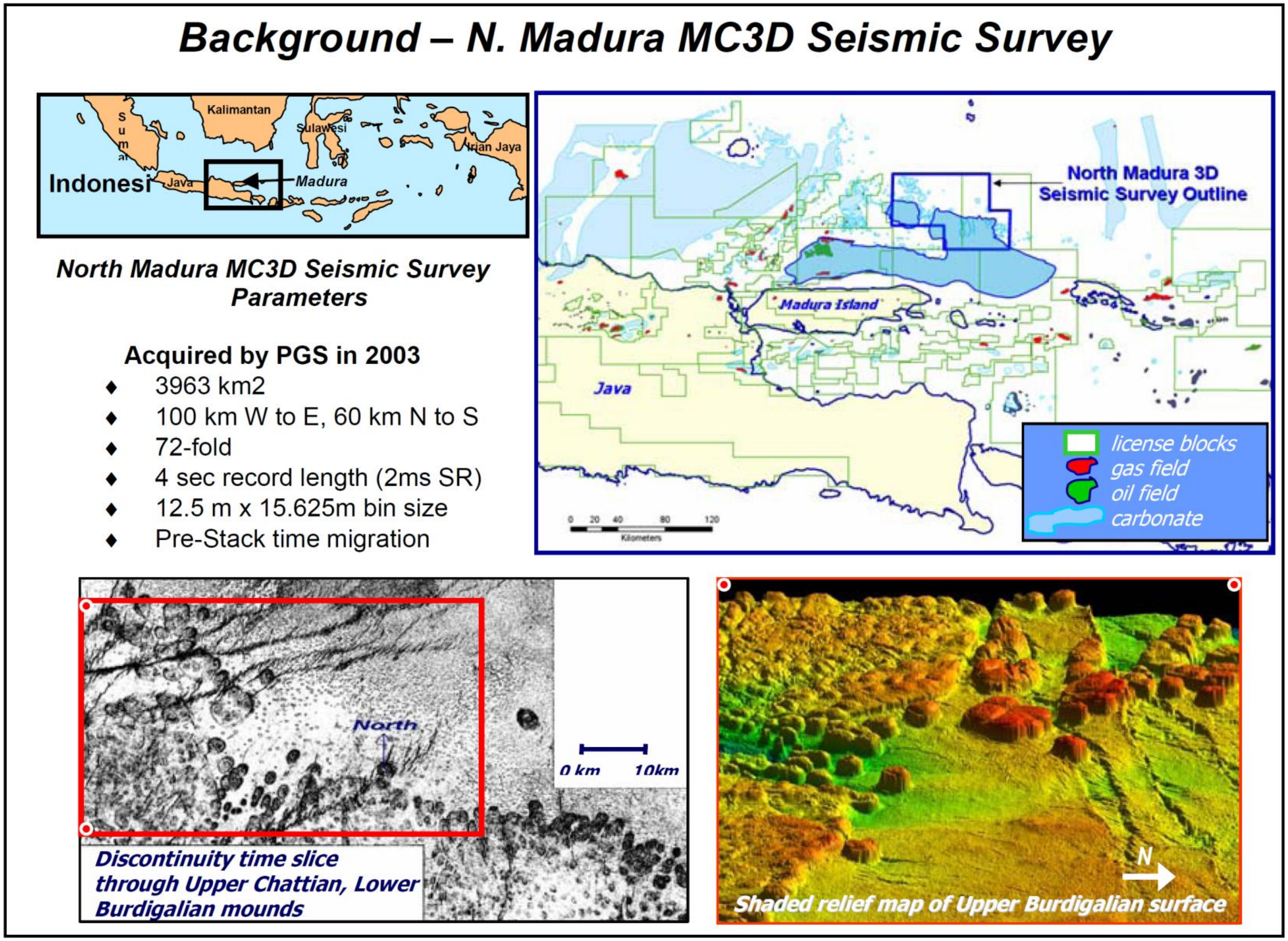


## Background – N. Madura MC3D Seismic Survey

**North Madura MC3D Seismic Survey Parameters**

**Acquired by PGS in 2003**

- 3963 km2
- 100 km W to E, 60 km N to S
- 72-fold
- 4 sec record length (2ms SR)
- 12.5 m x 15.625m bin size
- Pre-Stack time migration

Discontinuity time slice through Upper Chattian, Lower Burdigalian mounds

Shaded relief map of Upper Burdigalian surface

Figure 1. Location map of East Java Basin, Indonesia, highlighting the location and parameters of the North Madura MC3D seismic survey (PGS, 2003). Also shown is the location of Oligocene-Miocene carbonate platforms. Images in the lower half of the figure are derived from the 3D data set; discontinuity time slice illustrate internal platform morphology (left), and perspective map of the upper Burdigalian surface in time (right).

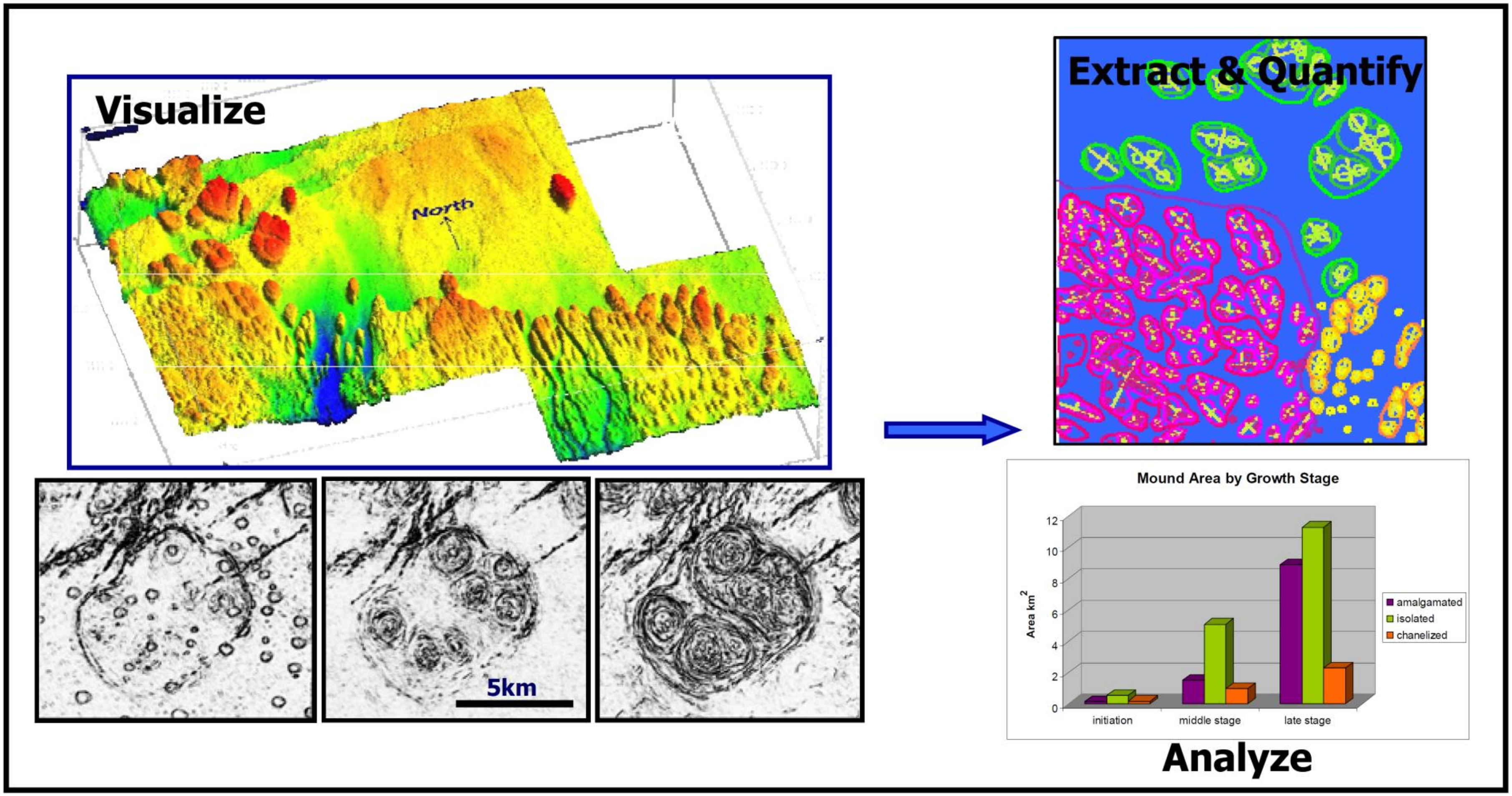
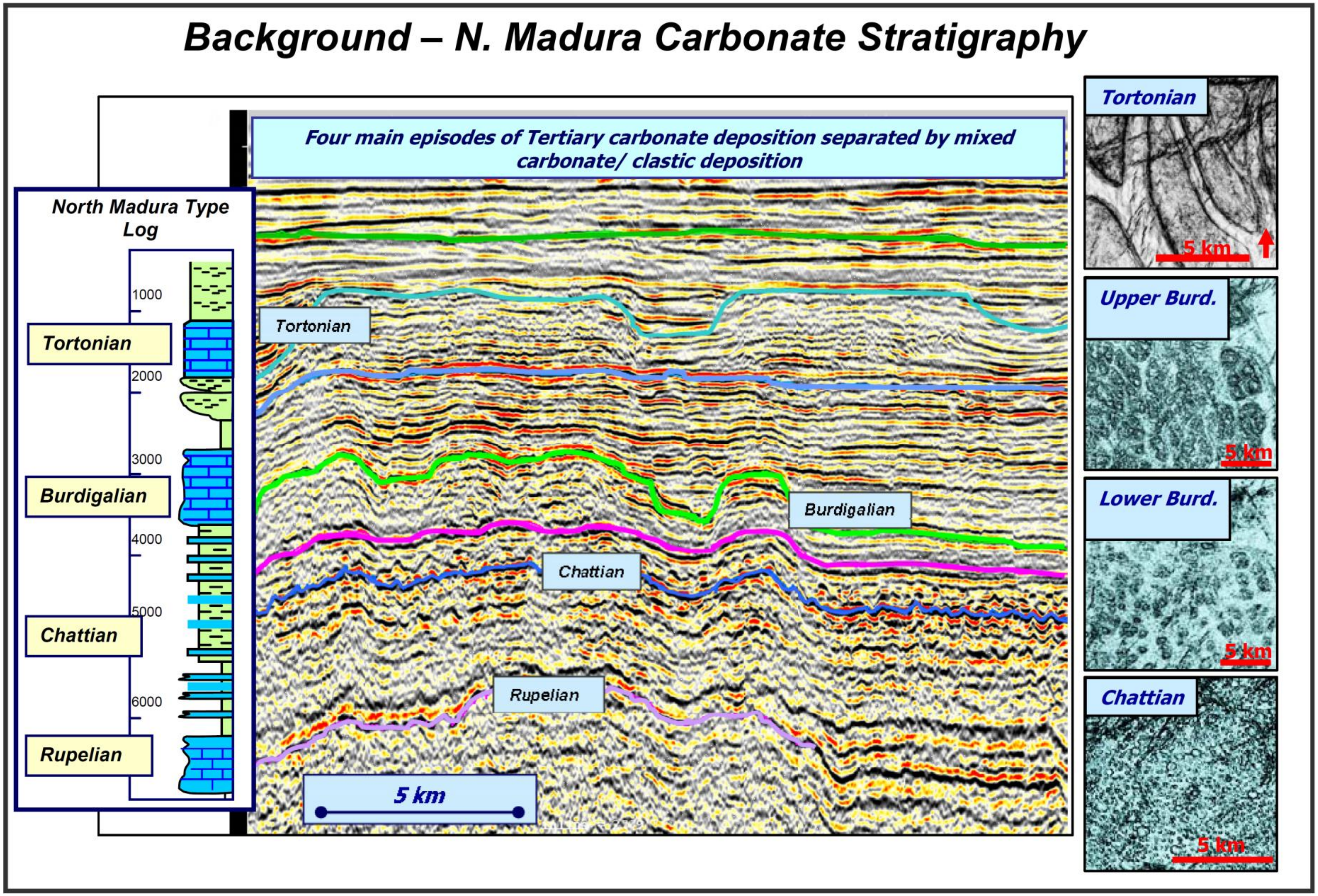


Figure 2. Images derived directly from the North Madura 3D seismic survey, illustrating the impact of visualization, extraction, quantification, and analysis of carbonate-mound characteristics and properties.


**Background – N. Madura Carbonate Stratigraphy**

*Four main episodes of Tertiary carbonate deposition separated by mixed carbonate/ clastic deposition*

Figure 3. Seismic inline from the MC3D survey illustrating the Tertiary carbonate intervals imaged in the seismic data. Corresponding map-view expressions of three of the intervals are displayed down the right hand side of the figure in discontinuity time slices. Type log of the Tertiary carbonates is displayed on the left side of the figure.

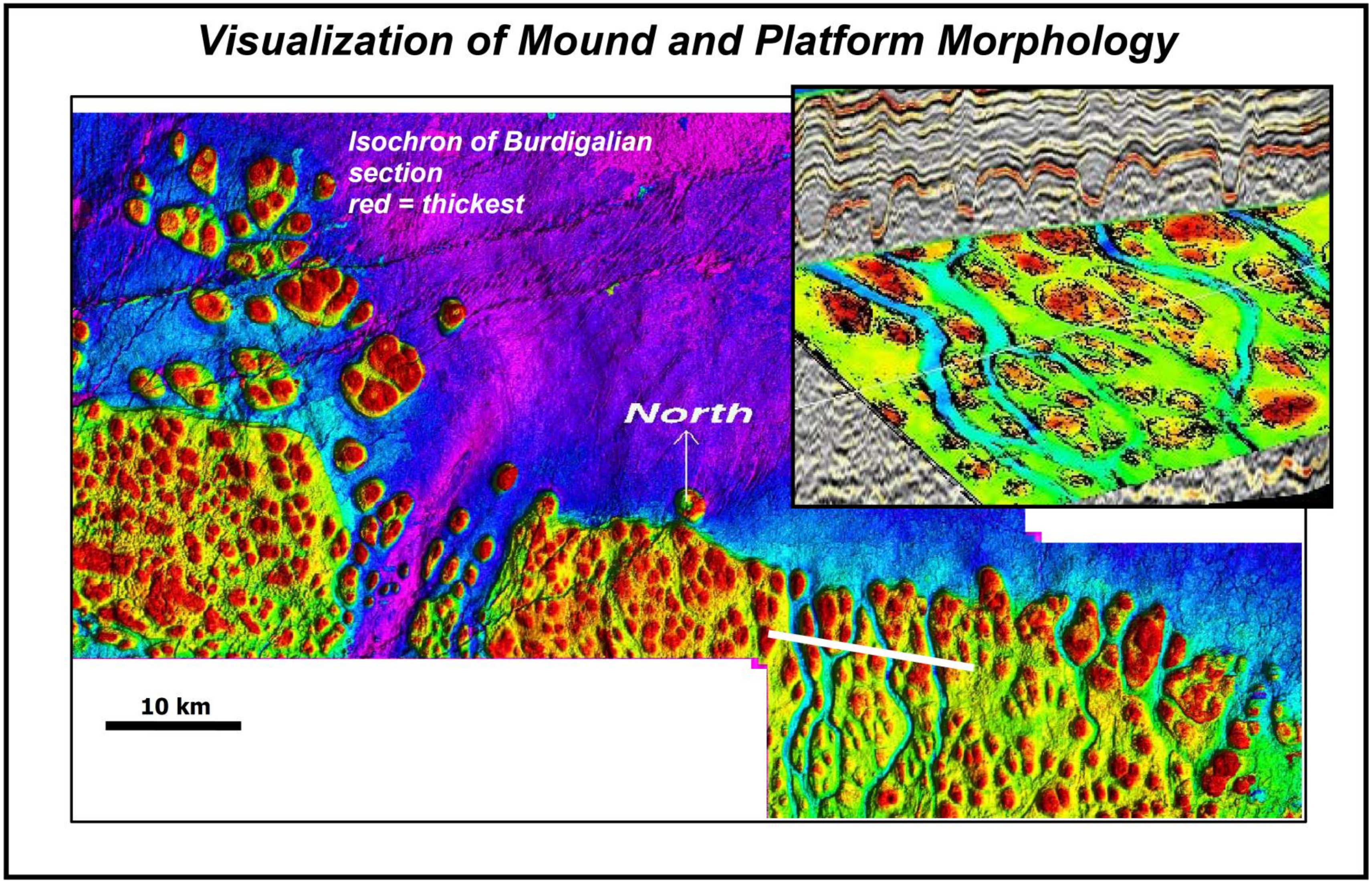


Figure 4. Top Burdigalian map with co-rendered Discontinuity and Isochron attributes. Red areas are isochron thicks, grading to thinnest in blue/purple areas. Platform highs (thicks) and margins are well defined by these two attributes, and faults zones stand-out in the NW corner of the map. Off-platform transport of platform sediments is evident in the northward thinning cyan to blue wedge on the north margins of the platform. The white section line in the lower right of the figure shows the location of the inset image, which is a time slice of co-rendered Discontinuity and Isochron attributes intersecting a profile section from the amplitude volume. Steepness, depth, and morphology of platform channels are well illustrated in this image.

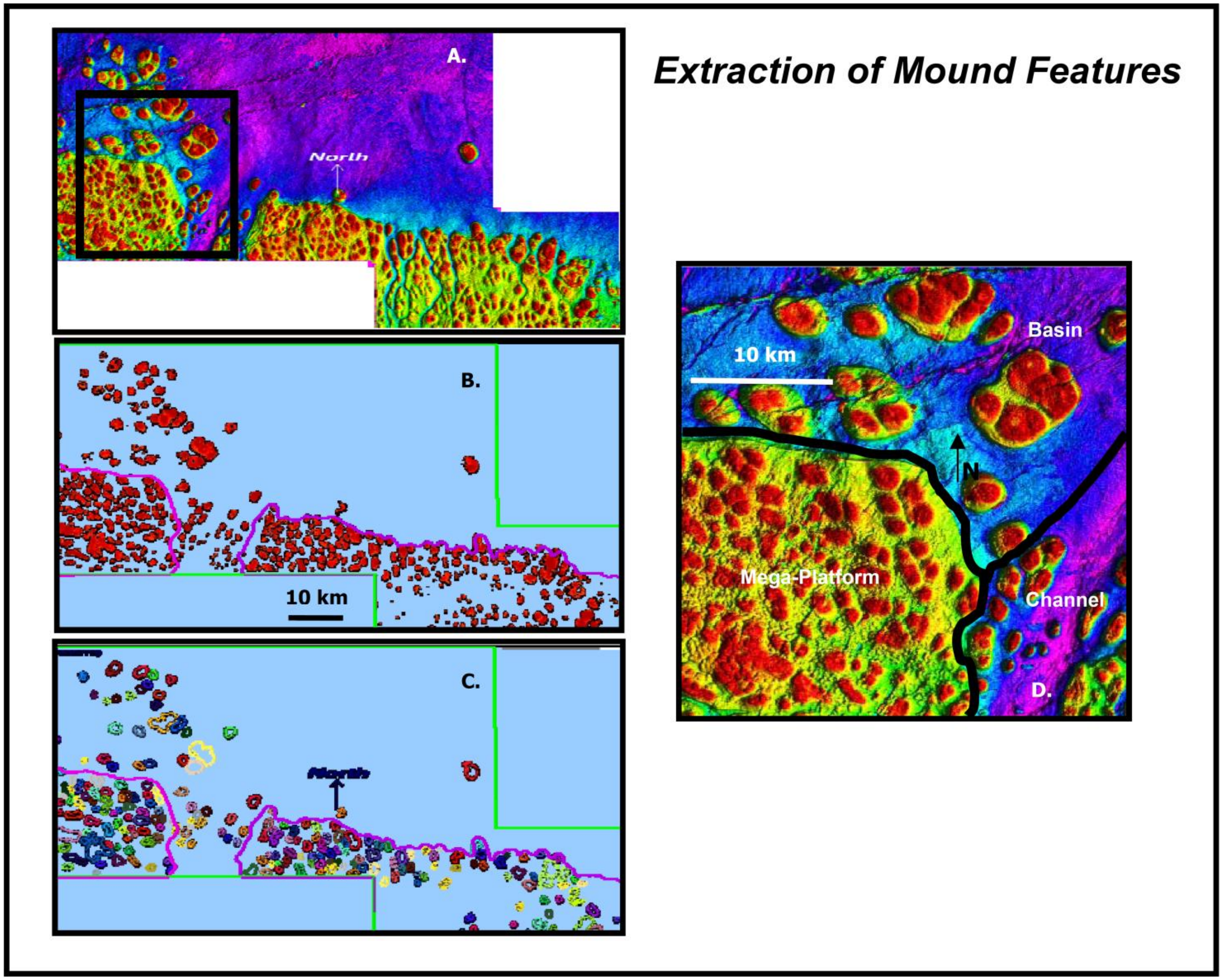
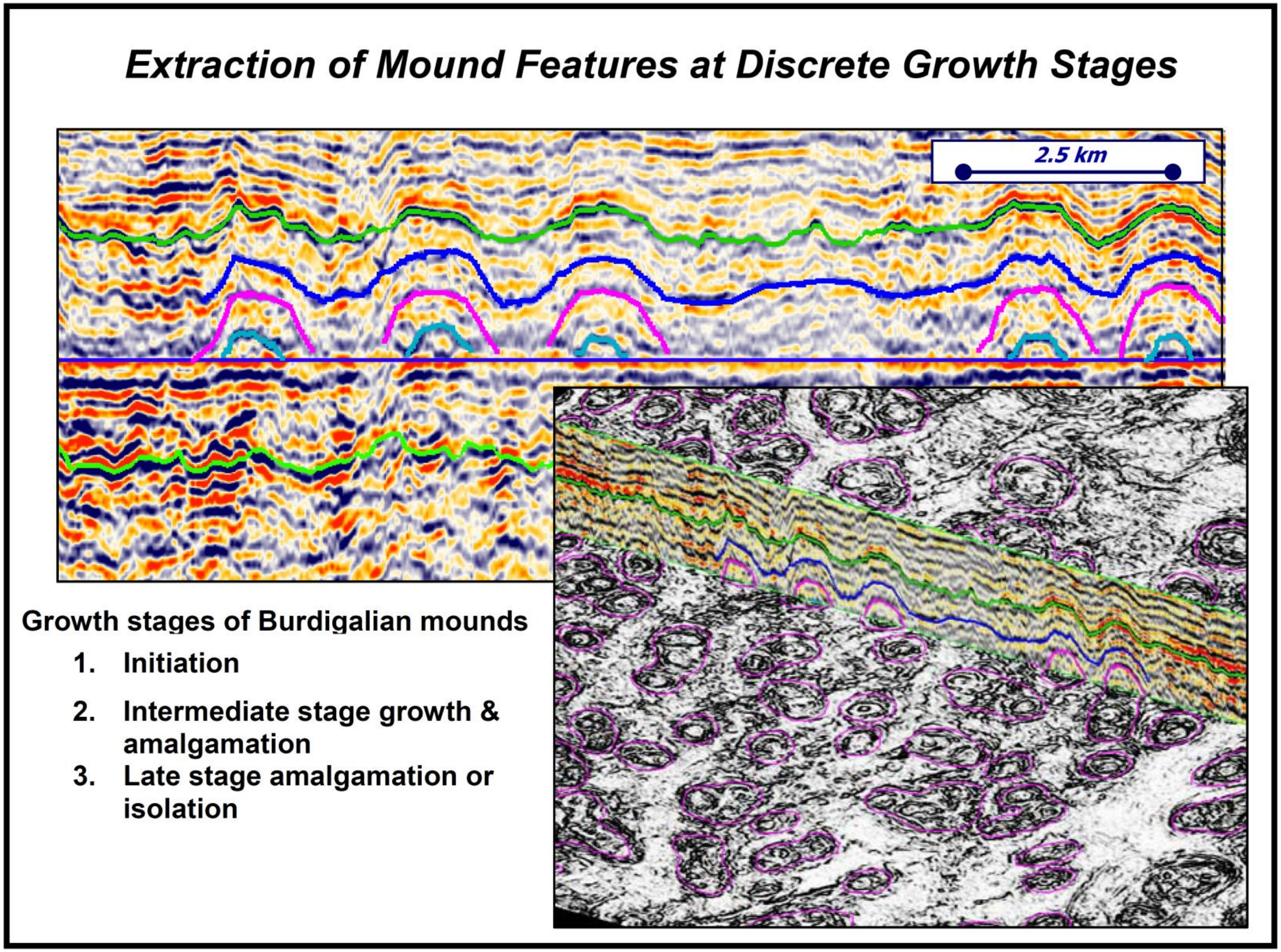


Figure 5. Illustration of the methodology and volumes used for extracting mound features from the seismic data. A) Burdigalian Isochron co-rendered with Discontinuity. B) Extraction of thickest mounds using seed detection constrained by Isochron and Discontinuity attributes. C) Polygons generated around extracted geobodies. D) Subset of volume selected for extracting mound features from three growth stages in the Burdigalian; initiation, intermediate stage growth and amalgamation, and late stage amalgamation. Location of subset is marked by black outline in Figure 5A. The subset volume covers three carbonate sub-environments: mega-platform, channel, and basin.



## Extraction of Mound Features at Discrete Growth Stages

**Growth stages of Burdigalian mounds**

1. **Initiation**
2. **Intermediate stage growth & amalgamation**
3. **Late stage amalgamation or isolation**

Figure 6. Flattened seismic amplitude profile showing interpretation of top Burdigalian (green), base of Burdigalian (datum – flat blue line), and three intermediate mound growth stages (cyan, pink, and blue). The top Chattian is also posted as the green surface below the datum. Discontinuity time slice inset provides a visual display of the mounds extracted in the intermediate stage platform growth and corresponding polygons.

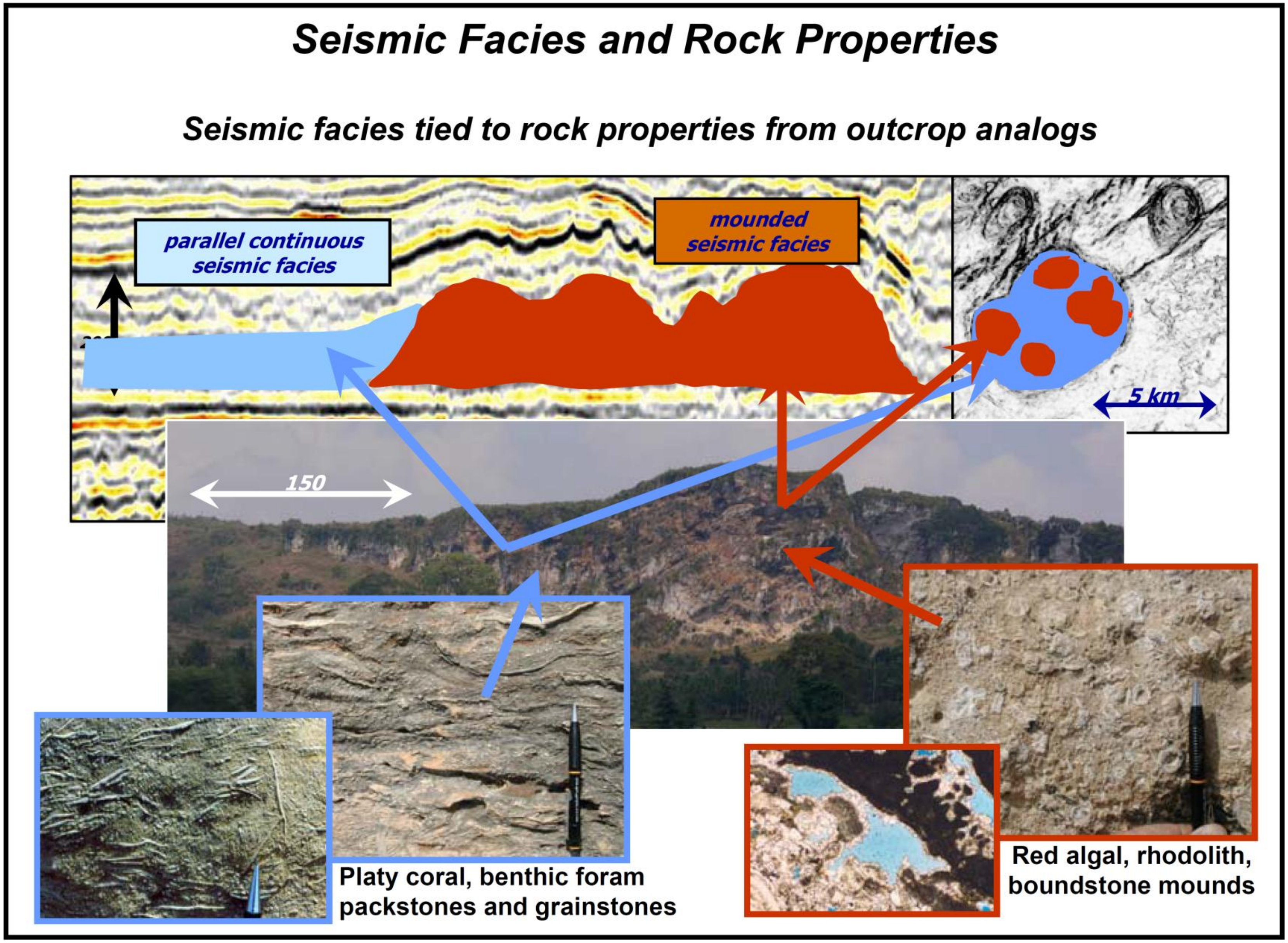
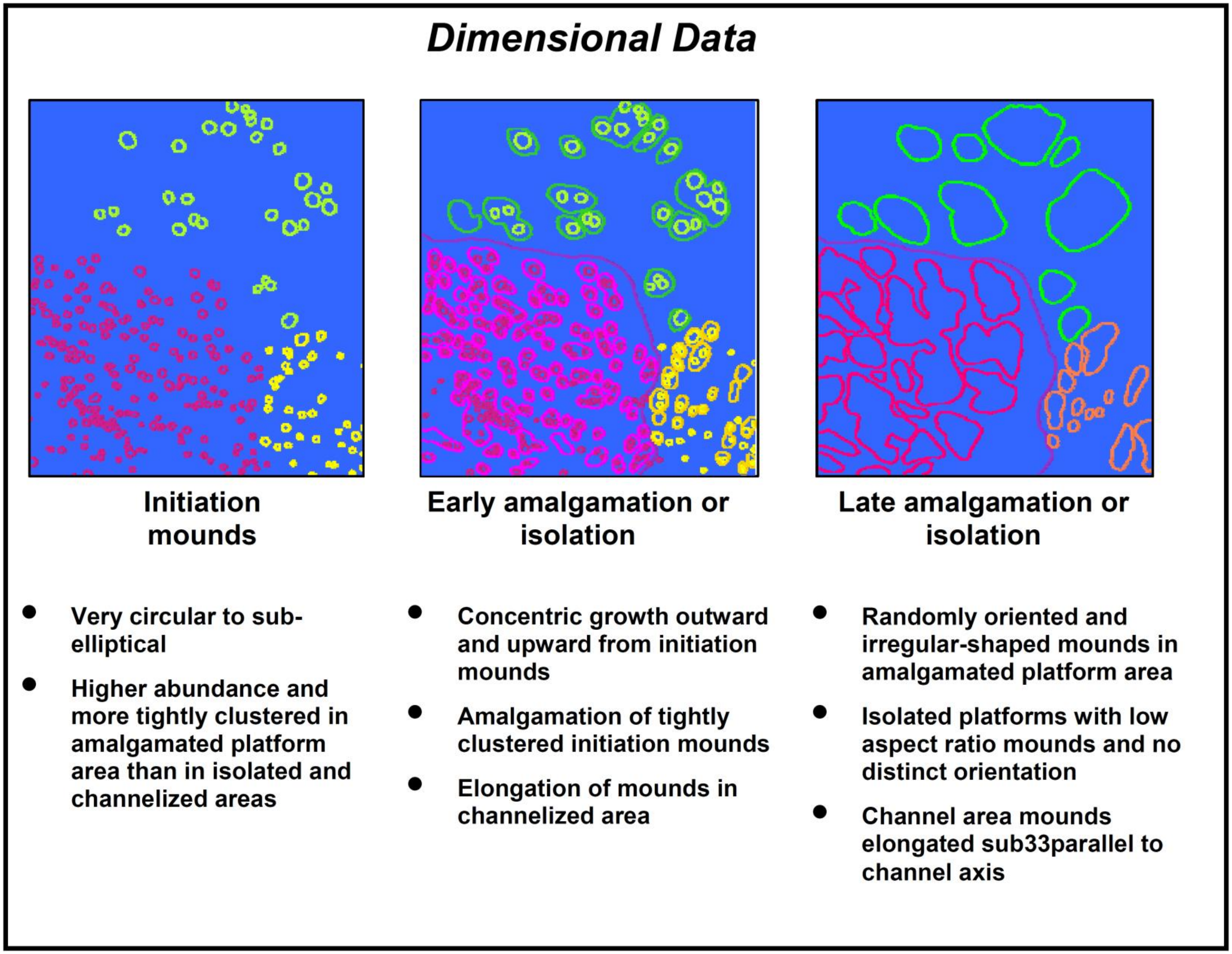


Figure 7. Seismic facies tied to outcrop observations of analogous age rocks. Field geometries of exposed coral and red algal rhodolith boundstone mounds are remarkably similar to the geometries observed in the mounded seismic facies in the 3D survey. Field geometries of platy coral and benthic foram packstones and grainstones are equated to the parallel continuous seismic facies.



**Initiation mounds**

- Very circular to sub-elliptical
- Higher abundance and more tightly clustered in amalgamated platform area than in isolated and channelized areas

**Early amalgamation or isolation**

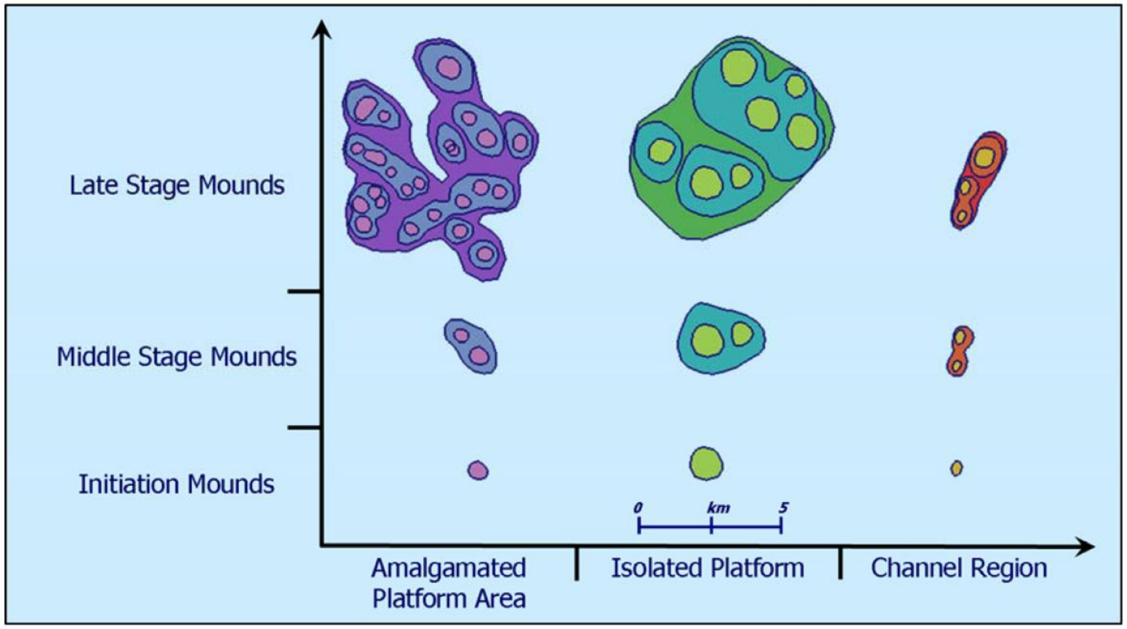
- Concentric growth outward and upward from initiation mounds
- Amalgamation of tightly clustered initiation mounds
- Elongation of mounds in channelized area

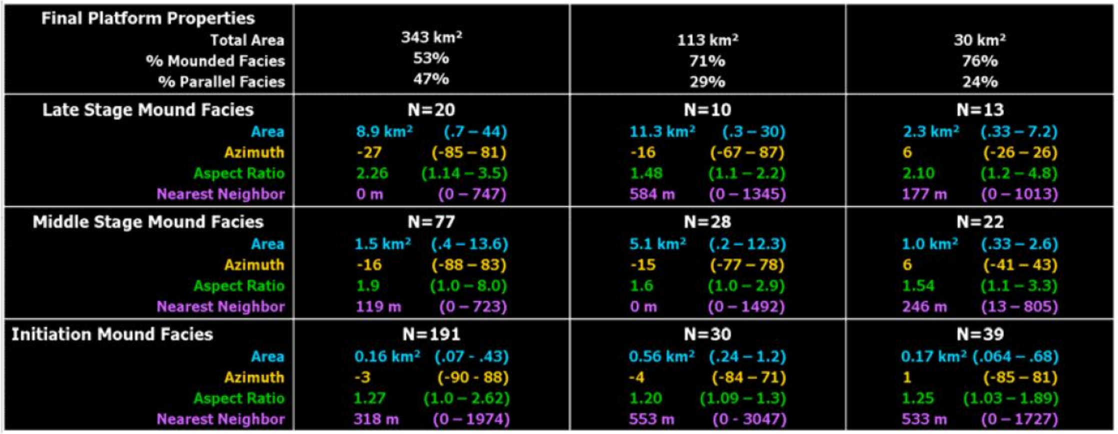
**Late amalgamation or isolation**

- Randomly oriented and irregular-shaped mounds in amalgamated platform area
- Isolated platforms with low aspect ratio mounds and no distinct orientation
- Channel area mounds elongated sub33parallel to channel axis

Figure 8. Qualitative and visual summary of the mound geometries extracted from the 3D seismic survey, in three sub-environments and in three stages of carbonate growth.

***Quantitative Database of Mound Properties***





| | | | |
|---|---|---|---|
| **Final Platform Properties** | | | |
| Total Area | 343 km$^2$ | 113 km$^2$ | 30 km$^2$ |
| % Mounded Facies | 53% | 71% | 76% |
| % Parallel Facies | 47% | 29% | 24% |
| **Late Stage Mound Facies** | N=20 | N=10 | N=13 |
| Area | 8.9 km$^2$ (.7 – 44) | 11.3 km$^2$ (.3 – 30) | 2.3 km$^2$ (.33 – 7.2) |
| Azimuth | -27 (-85 – 81) | -16 (-67 – 87) | 6 (-26 – 26) |
| Aspect Ratio | 2.26 (1.14 – 3.5) | 1.48 (1.1 – 2.2) | 2.10 (1.2 – 4.8) |
| Nearest Neighbor | 0 m (0 – 747) | 584 m (0 – 1345) | 177 m (0 – 1013) |
| **Middle Stage Mound Facies** | N=77 | N=28 | N=22 |
| Area | 1.5 km$^2$ (.4 – 13.6) | 5.1 km$^2$ (.2 – 12.3) | 1.0 km$^2$ (.33 – 2.6) |
| Azimuth | -16 (-88 – 83) | -15 (-77 – 78) | 6 (-41 – 43) |
| Aspect Ratio | 1.9 (1.0 – 8.0) | 1.6 (1.0 – 2.9) | 1.54 (1.1 – 3.3) |
| Nearest Neighbor | 119 m (0 – 723) | 0 m (0 – 1492) | 246 m (13 – 805) |
| **Initiation Mound Facies** | N=191 | N=30 | N=39 |
| Area | 0.16 km$^2$ (.07 - .43) | 0.56 km$^2$ (.24 – 1.2) | 0.17 km$^2$ (.064 – .68) |
| Azimuth | -3 (-90 - 88) | -4 (-84 – 71) | 1 (-85 – 81) |
| Aspect Ratio | 1.27 (1.0 – 2.62) | 1.20 (1.09 – 1.3) | 1.25 (1.03 – 1.89) |
| Nearest Neighbor | 318 m (0 – 1974) | 553 m (0 - 3047) | 533 m (0 – 1727) |

Figure 9. (Top) Schematic summary of visual observations of Burdigalian mound evolution over three growth stages and in three sub-environments. Observations suggest small initiation mounds coalesce over time to form larger amalgamated isolated and mega-platforms with unique size, shape, and orientation characteristics. (Bottom) A subset of the quantitative data extracted from the 3D seismic survey provides ranges on the dimensional and geometric characteristics of Burdigalian carbonate mounds.

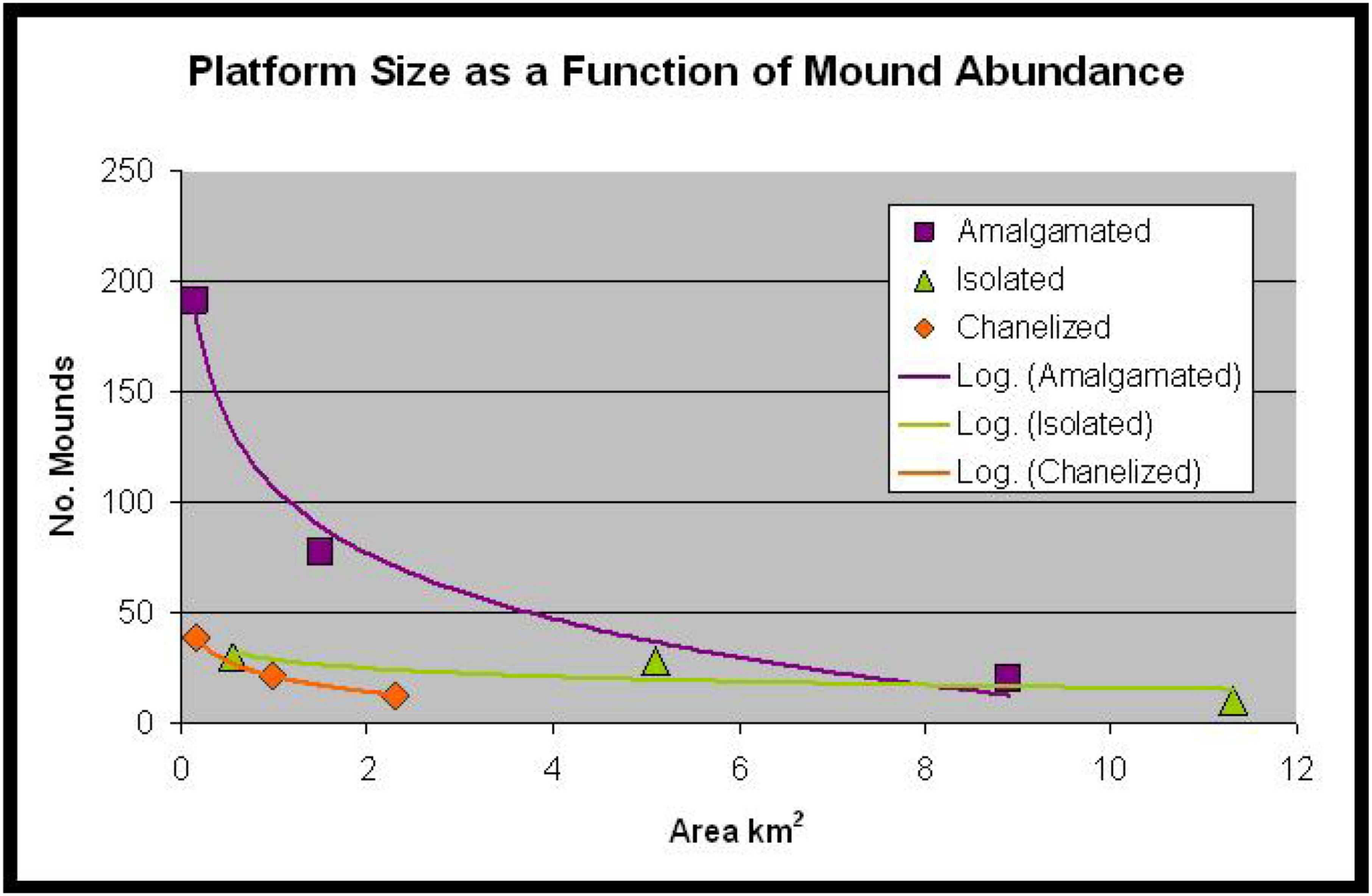


Figure 10. Trends in mound abundance versus size in each sub-environment analyzed. A logarithmic relationship exists for each area; however, the slope of the relationship varies one sub-environment to the next.

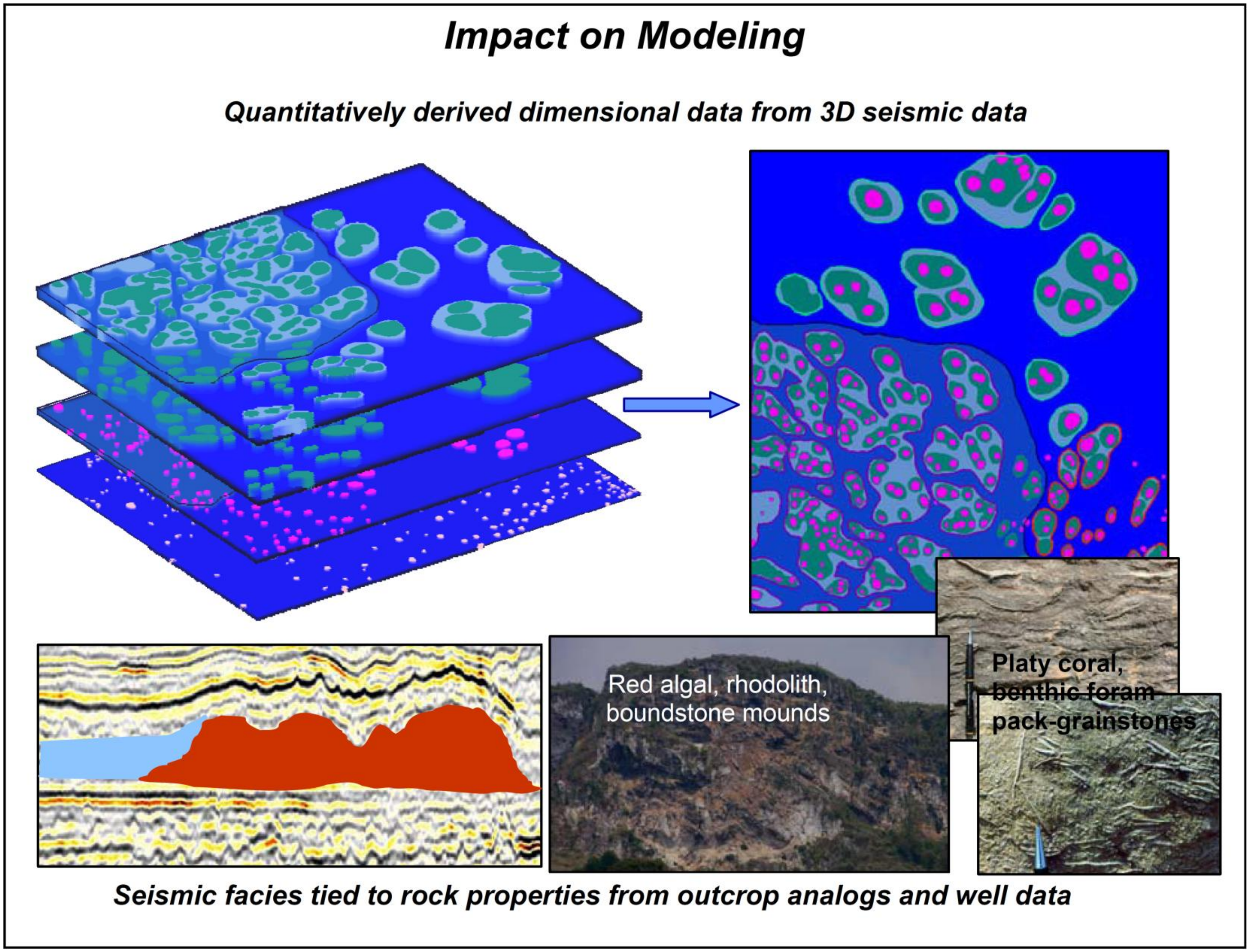


Figure 11. Impact on building and populating geologic models. Quantitatively derived information on mound size, geometry, and distribution is combined with seismic facies observations, which are tied to reservoir properties for conditioning geologic models.

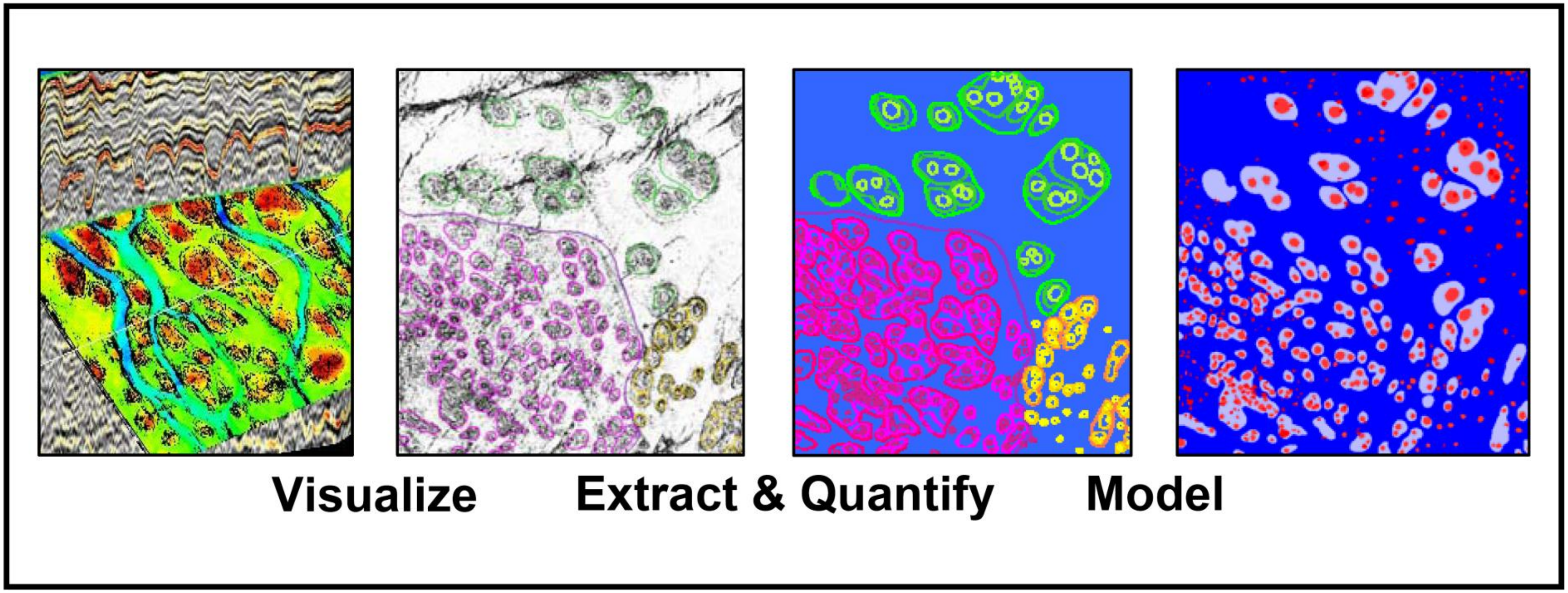


Figure 12. Impact of the integration of 3D seismic-data attributes and visualization and volume-interpretation techniques to first visualize and then extract and quantify features observed in seismic data.