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HRAM AS A TOOL FOR PETROLEUM SYSTEM ANALYSIS AND TREND EXPLORATION: A CASE STUDY OF THE MISSISSIPPI DELTA SURVEY, SOUTHEAST LOUISIANA

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ABSTRACT

The utility of high-resolution aeromagnetics (HRAM) as a tool for petroleum system analysis (Magoon and Dow, 1994) and trend exploration is evaluated for the Mississippi Delta Survey located in the Southeastern Louisiana transition zone. The results included here are intended to address some of the common exploration risk factors, and why HRAM integrated with well and seismic data was useful to address those risks. These data represent a non-exclusive survey acquired by World Geoscience Corporation. The total field data are reduced to the pole (RTP) and filtered with traditional techniques which include a 2nd vertical derivative, a suite of upward continuations, and 2nd horizontal gradient filters of the upward continued data. The origin, characteristics, and residual questions that concern the Gulf of Mexico Basin are documented in the literature (Ewing, 1991 and Salvador, 1991). More specific to the South Louisiana Gulf Coast, Schuster, 1995, discusses detailed interpretations of salt features and their evolution. These studies provide geologic background information to develop an interpretation of the salt evolution, timing, and charge history for this work. The resultant filter images of HRAM data from this work were integrated with local well data, 2-D and 3-D seismic data, regional gravity and magnetics data, temperature data, basin models, and historical production across the transition zone of the Mississippi River delta of South Louisiana. The key applications of HRAM data are illustrated in this paper. Included are interpreted basement features and intra-sedimentary features. The basement features identified are deep fault trends, intra-basement lithologic boundaries, igneous intrusive bodies, and early rift-basin geometry. This information is used to develop a geologic model for autochthonous salt distribution, early rift, syn-rift, and subsequent drift aged source rock distribution. The intra-sedimentary features identified are shallow fault trends, allochthonous salt features, and channel-like features. This information is used to develop a geologic model for sediment transport fairways, to help characterize the structural evolution, timing, and reservoir facies models and to bridge the regional to prospect scale understanding across this prolific petroleum province.

INTRODUCTION

The Mississippi Delta speculative HRAM survey was flown by World Geoscience Corporation in 1996, and includes 187 659 line kilometres (117,287 total line miles) of data with an inline spacing of 250 metres oriented north to south and a tie line spacing of 1250 metres oriented east to west. The data were flown across a 96 by 144 kilometres (60 by 90 miles) swath of the Southeastern Louisiana transition zone at an elevation of 150 metres (500 feet) above mean terrain. A cesium vapor total intensity magnetometer with active aircraft compensation was used. The data were leveled and processed by World Geoscience Corporation through total field corrections. The tight line spacing was intentional to mitigate cultural contamination with data density in this mature petroleum province.

Conoco initiated participation in the project area with three goals. They wanted to characterize the risk for plays in the mature south Louisiana petroleum province, to characterize the risk for prospects and leads in the area, and to develop new ideas. A key question was: "Can these goals be accomplished with HRAM in such a mature region which includes more than 47,000 wells and associated infrastructure?" This concern was well illustrated by a 2nd vertical derivative of the data that focused on the highest frequency features. Control points for those data, which did not pass statistical noise criteria, were flagged and removed from further processing steps (Fig. 1).

On a regional scale, essentially the survey map area, Conoco wanted to gain an integral geologic understanding of the present structural and stratigraphic framework from the crystalline basement to the seafloor. From this work, they could develop models for the burial history, the salt evolution, the time of salt movement, and facies distribution. With these models exploration risk factors such as reservoir potential, trap style, hydrocarbon charge events and pathways from source to reservoir could be assessed for potential exploratory prospects. Traditional data that included well control, 2D and 3D seismic data provided information on many parametres such as the development of the Middle Miocene and younger depositional framework. The traditional data provided a tool to extrapolate interpretations for deeper potential reservoir targets with notable limitations. The deep well control rarely penetrated beyond the primary Tertiary reservoir section. The marginal marine environment of the South Louisiana coast represents a costly and technically challenged province in which to acquire seismic data. The existing seismic data coverage was sparse. Significant

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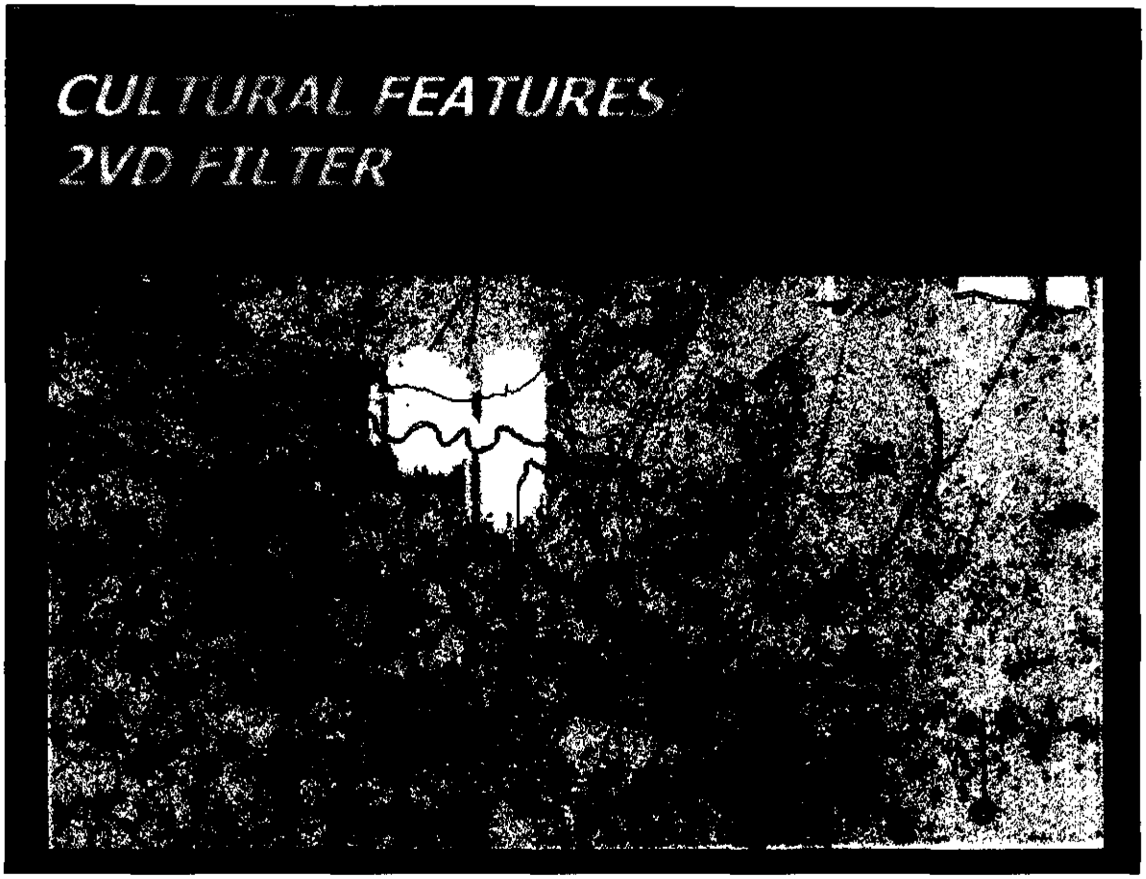

Fig 1. The 2nd vertical derivative filtered data shown in the background grayscale focuses on the highest frequencies in the data and illustrates the cultural features. Control points for these data that did not pass statistical noise criteria are over-posted in blue. These data were removed from any further processing. The blanked areas represent no-fly zones associated with the airport, city of New Orleans, and the National Park Islands of offshore Mississippi. The coast, major rivers and lakes of south Louisiana are overlain in black as a cultural reference. The area included in the map is approximately 96 by 144 kilometres (60 by 90 miles).

interpretive quality signal was usually limited to the first 4500 metres (15,000 feet). New exploratory reservoir targets included 4200 to 6000 metres (14,000 to 20,000 feet) target depths. Furthermore, of the five source systems proposed for the region from deep well control and basin model work, four were Mesozoic, rarely penetrated, and they were expected to occur at depths greater than 6000 metres (20,000 feet).

HRAM was chosen as a reconnaissance tool that was less expensive to acquire than additional seismic data. Second, the magnetics data could be used to extrapolate the regional petroleum system interpretations through and beneath the reflection seismic data window of investigation. The anticipated magnetic sources included the crystalline basement-to-sedimentary interface, lithologic variations within the basement, igneous intrusives, and the allochthonous salt-to-sediment interface. The initial expectation from these data was to define an autochthonous salt distribution model, an allochthonous salt distribution model, and from these models, infer Mesozoic source potential and distribution. These data were also expected to locate potential basement faults, igneous features, and varied basement provinces that occur within the crust. These expectations were all met with additional surprises such as high amplitude and high frequency anomalies that exhibit a channel-like geometry. Data filtered to enhance linear edges and high frequency yielded features that were compared to seismically defined sedimentary faults. Where seismic data control were more densely spaced, similarities were observed. Where seismic data were sparse, more differences were observed. One possible explanation for the differences is the lack of an adequate density of seismic control to link the faults. A second explanation could be the effect of residual cultural contamination. For the latter reason, straight linear features were disregarded. The HRAM data provided a tool to highlight these uncertainties. The revision of the interpretation, consistent with all the data, was recommended as a future work program. The broader implication was that HRAM could help interpreters link intra-sedimentary faults in the absence of other control. Examples of the filtered HRAM data that illustrate the basement configuration, intra-sedimentary linear features, cultural noise, allochthonous salt, and channel-like anomalies follow.

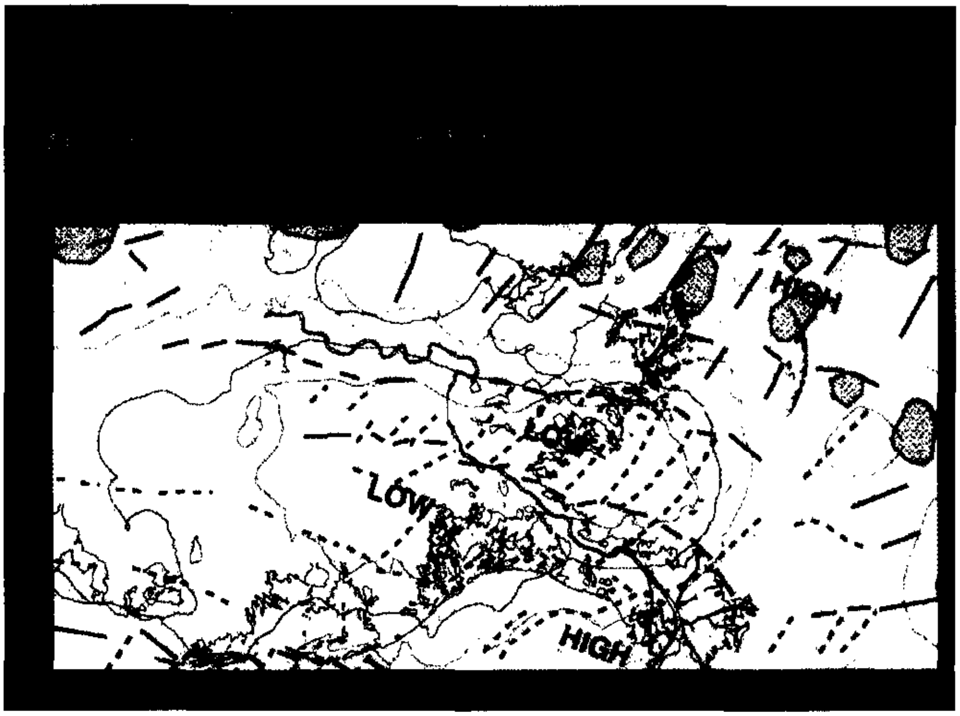

Fig. 2. Interpreted fault trends and basement boundaries are shown in brown. The depth to magnetic basement grid is colour contoured from purple 18 300 metres (60,000 feet) to orange 6100 metres (20,000 feet) with a 3050 metres (10,000 feet) contour interval. A first order NE-SW trend is dominant over the basement high region observed in the northeastern corner of the region studied. A second order WNW-ESE trend is also observed. This region corresponds to the offshore extension of the carbonate dominated and Mesozoic aged, Florida shelf geologic province. These shallow depths are consistent with deep Jurassic aged exploratory wells drilled in the region. The few depth solutions from this province that exceeded 9100 metres (30,000 feet) are interpreted as intra-basement features that may relate to lithologic variations in the continental and thick transitional crust that underlies this province. The interpreted possible and probable igneous intrusive bodies are shown as the pink pattern areas.

The green contour delineates the boundary between the shallow basement and more highly attenuated crust. A change in orientation and style characterizes this second province located in the central map area. The first order trend exhibited is WNW-ESE. Werner depth solutions as deep as 18 300 metres (60,000 feet) were consistently calculated, with a few solutions that exceeded 21 300 metres (70,000 feet). The lines are dashed where the trends are more subtle, and they define a second order grain oriented NE-SW. There is less confidence in this interpretation than the trends defined by the solid brown lines.

The exploration significance of the basement architecture has the potential for impact to multiple petroleum system risk factors. The deepest basin located in the central map region is interpreted to have had the thickest deposits of autochthonous Louann Salt. The model for the initial salt distribution and relative thickness was used to predict the regions with the greatest potential for accommodation space. Those regions were then interpreted as likely sediment transport fairways and accumulation sites. The paleotopographic influence from the major structural elements associated with the early Mesozoic-aged rift event may vary the source potential characteristics of the syn-rift and drift aged Mesozoic carbonates that include Oxfordian to Tithonian aged sediments. The opportunity for varied compaction, salt evacuation into allochthonous features, and differential subsidence that results from the underlying structural influence yield significantly different degrees of hydrocarbon maturation and critical moments of hydrocarbon expulsion events. The basement fault trends provided zones of weakness for the autochthonous salt to breakout into the sedimentary section as allochthonous features. These deep faults and salt evolutionary pathways also provided conduits and connectivity between younger potential reservoir systems and stratigraphically separated older source systems. Igneous intrusions may also have provided local paleotopographic elements that influence subsequent depositional facies.

Observations

The key applications of HRAM data included the interpretation of basement features and intra-sedimentary features.

1. The basement features identified were deep fault trends, intra-basement lithologic boundaries, igneous intrusive bodies, and early rift-basin geometry (Fig. 2). This information was used to develop a geologic model for autochthonous salt distribution and early rift, syn-rift, and subsequent drift aged source rock distribution as well as connectivity models between potential reservoir systems and source systems.
2. The intra-sedimentary features identified were shallow fault trends, allochthonous salt features, and channel features (Fig. 3). This information was used to develop a geologic model for sediment transport fairways, and to help characterize the structural evolution, timing, and reservoir facies models.

The basement interpretation was aided by HRAM data by the application of a 2400 metres (8,000 feet) upward continuation filter of the RTP data (Fig. 4). The 2nd horizontal gradient filter was then applied to this upward continued data. The 2nd horizontal gradient filter is defined as the square

Fig. 3. The dominant provenance for clastic sediments that enter the study area is shown with a large red arrow. Small red pointers depict additional minor clastic contribution from the N-NE. The depth to magnetic basement colour contours, from purple 18 300 metres (60,000 feet) to orange 6100 metres (20,000 feet) with a 3050 metres (10,000 feet) contour interval are included for deep basin orientation relative to the young Tertiary features. The bold blue dashed lines indicate the location of the shelf margin at 23.50 MYBP, 12.50 MYBP, and 10.50 MYBP as dominantly Micocene aged clastic sediments pro-graded across the area. Bold red dashed lines indicate the interpreted sediment distribution pathways along three first order fairways that originate from the northwest. The western fairway carries the heaviest coarse sediment load. These sediments fill a prominent sub-basin locally referred to as the Hourna Embayment. The central fairway system is relatively more starved for sediments, with a dominant NW-SE depositional dip. The eastern fairway is even more starved for coarse sediments, with a slightly WNW-ESE dispositional dip. Only very minor sediment contribution comes from the NNE. Smaller red dashed lines depict the second order distribution of syn-kinematic to post-kinematic sequences. These intervals fill local inter-salt sub-basins that are bounded by allochthonous salt features. Green pattern polygons depict probable salt features and green line polygons depict subtle or more deeply buried possible salt features. Light and dark aqua lines depict faults from 2-D seismic interpretations near the top and base of the Middle Miocene section.

The HRAM data gave the first evidence to suggest this sediment distribution model. The concept was tested for consistency with the observed sand distribution in Middle Miocene penetrations and with the seismic stratigraphic character. The reservoir isopach maps were re-contoured, biased with this depositional model to create a more refined prediction of reservoir facies and thickness. This predictive technique was favourably supported along the eastern fairway system by recent drilling activity just north of the Mississippi Delta, in the offshore areas known as Breton Sound and Main Pass.

root of the sum of the difference between adjacent grid nodes squared in both the north to south and east to west direction. To further image enhancement, intensity and azimuth filters were then applied. The results were displayed as a background grayscale image. Chuck Campbell with ACCEL Services completed a proprietary Werner depth to basement interpretation across the region. These data were gridded with minimum curvature techniques. In the example shown here, the depth to basement grid is shown colour-draped over the previously described gray scale surface (Figs. 5 and 6). Basin maximum solutions exceed 21 kilometres (70,000 feet). Basement is shallower than 6100 metres (20,000 feet) on the Florida platform area. These depths are consistent with known depths to the base of the Mesozoic basin-wide rift event as interpreted from deep Mobile Bay well data. Intra-basement solutions in the 10 500 to 12 200 metres (35,000 to 40,000 feet) depth range were also interpreted associated with the Florida platform area where a prominent NE-SW structural grain is observed. In contrast, the thick tertiary filled sub-basin exhibits a more subtle fabric with a distinctively different WNW-ESE orientation. The thickest salt that provided accommodation space for the clastic invasion of the Tertiary is associated with the deeper sub-basin areas. The regional sand fairways inferred from this work followed this same orientation. As the sub-basins filled, progradation drove continued salt evolution through time to the present day allochthonous position. Clastic invasion from the northwest across this dominantly carbonate starved platform area was first initiated in the Upper Cretaceous when course-grained slope deposits, interpreted from well control to be age equivalent to the Lower Tuscaloosa Formation, were deposited in the area (Figs. 3 and 6).

The intra-sedimentary fault interpretation was aided by HRAM as illustrated in Figure 7, with a 1200 metres (4,000

Fig. 4. This is an image of the RTP data that has been upward continued 2400 metres (8,000 feet). Positive anomalies are shaded red and negative anomalies are blue. The range of the data is 227 NT.

feet) upward continuation of the RTP data. The 2nd horizontal gradient filter was then applied to the upward continuation filtered data. To further image enhancement, intensity and azimuth filters were then applied. The results were displayed as the background grayscale image. A 2-D seismic data derived isopach of the Middle Miocene depositional package, defined as the sequence boundary of 10.50 to 15.50 MYBP, was colour-draped over the shaded surface (Fig. 8). On the filter image, straight linear features were interpreted as residual cultural noise, however there were also numerous curvilinear features that corresponded to seismically defined fault traces at the top and base of the Middle Miocene package (Fig. 9). Expanded scale examples of the correlation are also shown (Figs. 10 and 11). The location of paleo shelf margins, that bracket the Middle Miocene interval, along with the isopach geometry support the geologic model of the pro-gradation of a deltaic wedge that filled accommodation space along the proposed basement influenced sediment transport fairways. The thickest deposition locally exceeded 3600 metres (12,000 feet) and thins to 300 metres (1,000 feet) up-dip, down-dip, and laterally from the depositional locus.

The allochthonous salt was well imaged with a residual created by the subtraction of the 1200 metres (4,000 feet) upward continuation from the 2400 metres (8,000 feet) upward continuation of the RTP data (Figs. 12 and 13). A combination of amplitude and geometry were used to interpret the shallow salt. Both probable and possible salt features were identified. Features in the northeastern shallow basement area were excluded based on their larger size and their position over very shallow basement where salt was also known to be thin or absent. These features were interpreted as igneous intrusives. This residual was also used to interpret sediment distribution pathways for syn- to post-kinematic clastic deposition where shallow salt may have had a local paleotopographic influence. Close inspection showed a few distinct features that exhibit a channel-like geometry that coincides with shallow channels observed on 2-D seismic. A second, more deeply buried, less obvious feature observed on the HRAM data represents a channel system interpreted by subsurface well and seismic control (Figs. 14 and 15).

A final colour image was created from the first three principal components calculated as a statistical analysis of the relative relationship of the various residual filters used in the interpretation (Figs. 16 and 17). Included was the upward continuation difference, the 2nd horizontal gradient filter of the upward continuations, a second vertical derivative, and the depth to basement surface. This image was especially useful in the interpretation of the igneous intrusive bodies as well as salt evolution characterization. Several features within the map area were interpreted to be intrusive bodies. An age of emplacement of approximately 82 MYBP, as published by Braunstein and McMichael, 1976, was inferred. The overall basement influenced grain observed in the HRAM that underlies the thick Middle Miocene clastic fill was well illustrated in this image. When compared to historical production and hydrocarbon richness for the region, the WNW-ESE basement fabric was sub-parallel and coincident

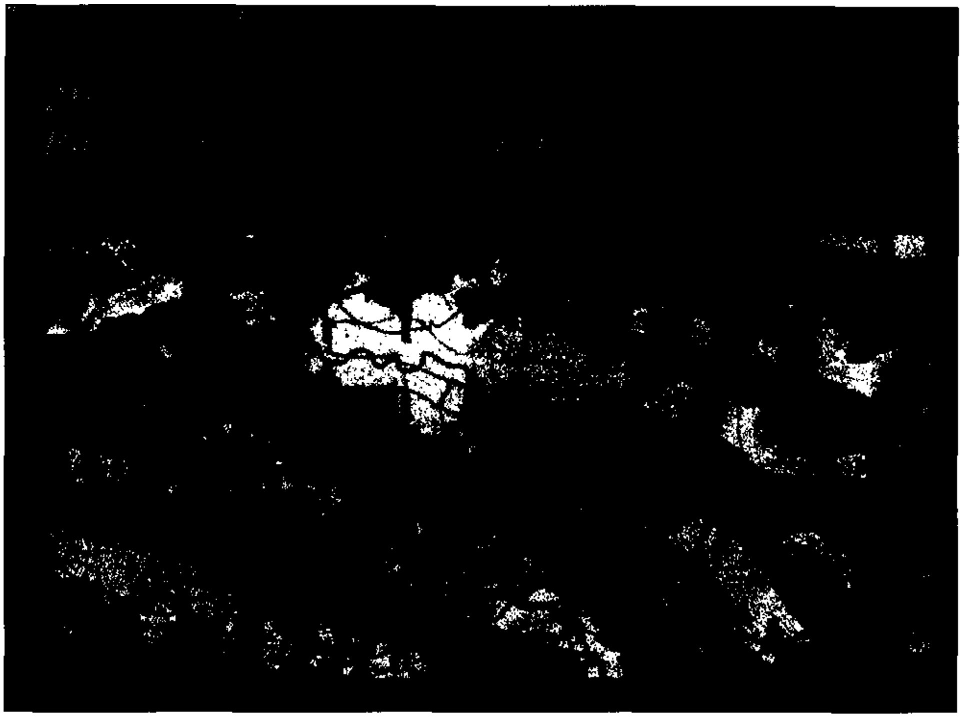

Fig. 5. The intensity shading comes from a 2nd horizontal gradient magnitude filter applied to a 2400 metres (8,000 feet) upward continuation of the RTP data. Werner derived depth basement solutions were gridded and colour-draped over the shaded surface. The depth to magnetic basement grid is colour contoured from purple 18 300 metres (60,000 feet) to orange 6100 metres (20,000 feet) with a 3050 metres (10,000 feet) contour interval. A first order NE-SW trend is dominant over the basement high region observed in the northeastern corner of the region studied. A second order WNW-ESE trend is also observed. This region corresponds to the offshore extension of the carbonate dominated and Mesozoic aged, Florida shelf geologic province. These shallow depths are consistent with deep Jurassic aged exploratory wells drilled in the region. The few depth solutions from this province that exceeded 9100 metres (30,000 feet) are interpreted as intra-basement features that may relate to lithologic variations in the thick transitional crust that underlies this province. The basin maximum solutions shown in blue exceed 21 kilometres (70,000 feet). The red shades seen across the upper right hand corner, associated with the Florida carbonate platform are less than 6100 metres (20,000 feet). These depths tie well with known depths to the base of the Mesozoic Gulf of Mexico rift event from deep well data in the Mobile Bay area. In this region, depth solutions for intra-basement features are in the 10 500 to 12 200 metres (35,000 to 40,000 feet) depth range. The mean depth across the map area is 12 200 metres (40,000 feet).

with the best production, yet oblique and compartmentalized relative to the general E-W reservoir facies fairway (Fig. 17). The industry has often continued exploration along reservoir system trends. In this region, hydrocarbon production that was posted by age, not size, followed an E-W orientation (Fig. 19). While this might have found a potential reservoir interval, it may not find the best reservoir, and clearly the rest of the petroleum system components were critical to find the most significant hydrocarbon accumulations. A comparison of the PC123 image (Figs. 16 and 17) with the historical production image (Fig. 18), illustrated that the WNW-ESE grains were prominent in both maps. The richest production was defined by five key elements. First, it was located adjacent to a "petroleum kitchen" with stacked mature source systems. Second, it was associated with moderately shallow basement. Third, deep basement fault systems provided access and connectivity between the stacked source systems and the potential reservoir system. Fourth, there was enough young overburden deposited to drive maturation as a diachronous front that linked the critical moment of expulsion and charge to the age and thickness of the overburden. Fifth, the allochthonous salt provided a significant structural trap type for hydrocarbon accumulation. The salt evolutionary path was linked to the duration, preservation and hydrocarbon trap integrity through time. The HRAM data provided key information on each of these elements of the petroleum system.

Conclusions

The results of this project were illustrated with a suite of map images of the filtered HRAM data. The deep features observed lead to an interpretation of autochthonous salt distribution associated with the early sub-basin architecture. The shallow features aided in the development of a geologic facies model for early source rock distribution, clastic syn- to post-kinematic sediment distribution pathways, and salt evolution models. The HRAM data also provided a useful tool for the regional interpretation of source access and plumbing systems as illustrated by qualitative correlation of the results with historical production from the region. An understanding of deep source rock distribution, plumbing and migration pathways, timing and salt evolution, in part interpreted from

Fig. 6. With the interpretation overlain, the prominent grains of the Mesozoic Carbonate Platform were well defined. In contrast, the deep basin exhibited a more subtle fabric and a distinctively different orientation. The thickest autochthonous salt that provided accommodation space for the clastic invasion of the Tertiary was associated with the deeper sub-basin areas. Regional scale sand fairways were inferred to follow this same orientation as the thickness of the sedimentary overburden drove the evacuation of autochthonous salt. As the new accommodation space was filled with clastic sediments, continued sedimentation drove pro-gradation. Salt with-drawl and sedimentation continued, influenced by the varied initial supply of autochthonous salt.

the filtered HRAM data helped identify play and trend scale regions for petroleum exploration. The project expectation was this approach and the application of these data would impact play and prospect risk. Those goals were met. Wells were budgeted in the area, in part based on the results of this work. The filtered images of HRAM data provided a tool to bridge regional to prospect scale petroleum system work when integrated with traditional data (Fig. 20).

Acknowledgments

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I thank World Geoscience for acquiring a high quality, high frequency speculative survey and for permission to present the filtered results.

I thank Chuck Campbell with Accel Services, for his interpretive contributions and consultation.

ERMAPPER software was used to enhance the filtered residual images.

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Fig. 7. This is an image of the RTP data that has been upward continued 1200 metres (4,000 feet). Positive anomalies are shaded red and negative anomalies are blue. The range of the data is 254 NT.

Fig. 8. This image shows the filtered data used for the intra-sedimentary fault grain interpretation. The intensity shading comes from a 2nd horizontal gradient magnitude filter applied to a 1200 metres (4,000 feet) upward continuation of the RTP data. The depth to magnetic basement colour contours from purple 18 300 metres (60,000 feet) to orange 6100 metres (20,000 feet) with a 3050 metres (10,000 feet) contour interval are included to illustrate the relationship of the shallow deposition to the deep basin configuration. A 2-D seismically derived isopach of the Middle Miocene depositional package that includes the interval from the sequence boundary of 10.50 to 15.50 MYBP is colour draped over the shaded surface. The thickest deposition, shades orange, locally exceeds 3650 metres (12,000 feet) and thins to 300 metres (1,000 feet) in the blue regions, and is centered above the deep sub-basin regions. Straight linear features likely represent residual culture. There are also numerous curvilinear features that may be interpreted as geologic information.

Fig. 9. The overlain interpretation shows the Middle Miocene aged deposition bracketed by the shelf margin positions through time. The prominent thick facies is inferred to be a deltaic shelf margin wedge. Inspection of local isopach thick areas shows the sub-basin architecture filled along the proposed sediment transport pathways as depicted with red arrows. Further inspection of the grayscale features and their correlation with interpreted fault trends suggests some of the curvilinear signal may correspond to intra-sedimentary fault systems. The straight black traces show the location of the interpreted 2-D seismic data.

Fig. 10. Two areas have been expanded for a more detailed inspection of the features. The blanked curvilinear features represent the missing section of the faulted interval from the seismic interpretation. Note how the dark NW-SE shading of the lower view is cross cut by the seismically defined faulted out region that trends more EW. The sparse 2-D seismic may have lead to an aliased fault interpretation. The HRAM data could be integrated with the seismic data to predict a fault linkage pattern. In contrast, the upper right view shows an excellent correlation of the faults located in the upper left corner. There are even subtle indications of a second synthetic system, and a second fault trend oriented oblique to the major trends along this feature. The sparse seismic data control missed these. Notice also the relationship of the isopach thick regions to these faults. Thickening of the hanging wall in map view is observed as well as some subtle thickening near the southeastern termination of the two synthetic faults.

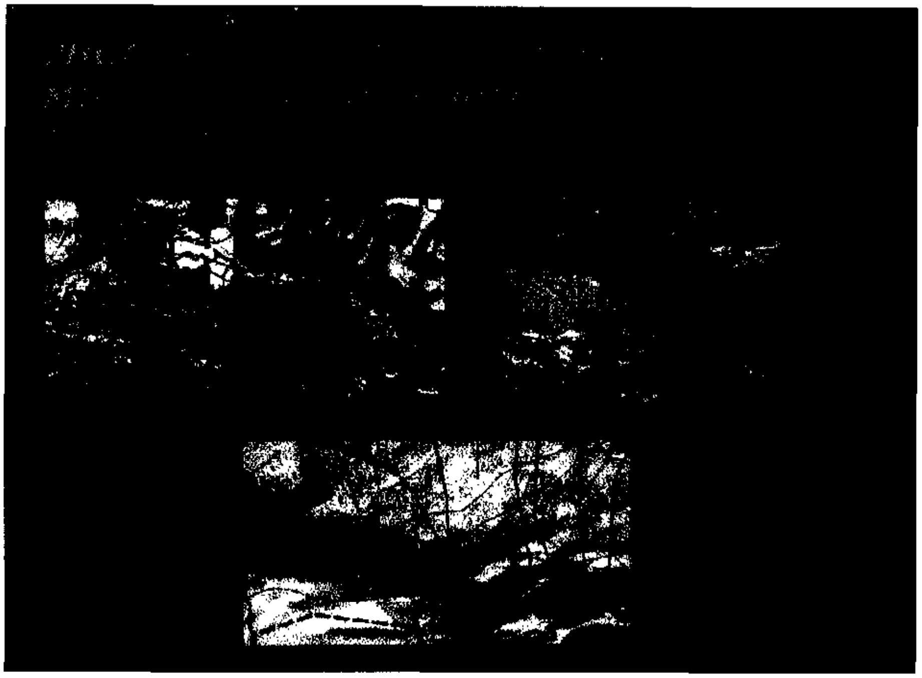

Fig. 11. The 2-D seismic and geologic interpretations are overlain. Light aqua lines are the fault traces from the seismic interpretation near the top of the Middle Miocene section. The dark aqua lines are the fault traces from the seismic interpretation near the base of the Middle Miocene section. The correlation is excellent for the upper right example of the major WNW feature although the magnetics data suggest there may be additional small faults. In the lower example, the correlation is poor. The magnetics data fabric suggests the seismic fault interpretation could be aliased due to sparse data. A re-interpretation of the fault linkage should be performed to develop an interpretation consistent with all data.

Fig. 12. Allochthonous salt is well imaged with a residual created by the difference of the 1200 metres (4,000 feet) upward continuation filter from the 2400 metres (8,000 feet) upward continuation filter of the RTP data. Blue regions depict relative negative contrasts. Yellow-to-smoke gray colours depict relative positive contrasts. Four patterns of blue features are apparent. They differ in scale, amplitude, and characteristic polarity signature. For example, the small intense blue features located in the lower left corner of the map correspond to shallow seated vertical salt piercment features confirmed by wells and seismic data. The small subtle amplitude blue to white features that are "non-linear" can be correlated with deep salt pillows and *residual features in the eastern central offshore region of the map. The subtle amplitude blue to white features that are "linear" such as seen in the* southwestern map region are residual cultural contamination in the data from pipelines and infrastructure. The large blue features with a positive core pattern located in the northeast are characteristic of the interpreted igneous intrusive features.

Fig. 13. The negative amplitude, geometry, size, and pattern attributes were used to interpret the allochthonous salt distribution. The possible salt bodies are depicted with green line polygons, and the probable salt bodies are depicted with green pattern filled ploygons. The red arrow, pointers, and dashed lines depict the clastic input locations and the inter-salt distribution system. The blue regions in the northeastern area are excluded based on their larger size, their dipolar pattern with a positive core, and their location over very shallow basement where salt is geologically known to be very thin or absent. This filter was useful in the interpretation of the igneous intrusive bodies as well as the allochthonous salt characterization. Shell drilled a well in the 1960s and published an age date of 82 MYBP or Middle Late Cretaceous for the "altered porphyritic basic rock" encountered in the well and named the "Doorpoint Buried Volcano" of southeast Louisiana. The approximate well location is marked by a teepee symbol with a red circle (Braunstein and McMicheal, 1976). The interpreted possible and probable igneous bodies are depicted by pink patterned polygons.

Fig. 14. Expanded examples of the inter-salt curvilinear features interpreted as channel-like zones are shown. The image on the bottom left exhibits very strong amplitude, high frequency, and a characteristic sinuous pattern in map view. A shallow channel system interval has been observed on a 2-D seismic data in this area. The feature occurs within the first second (2-way time), or from the surface to a depth of approximately 900 metres (3,000 feet). The feature is interpreted to correspond to a Pleistocene-to-Pliocene aged, abandoned feeder channel on the Mississippi delta system. *The image on the right corresponds to the location of a Middle Miocene buried channel system that has been identified from well penetrations and* seismic data character. The system is buried to depths of 2400 to 4000 metres (8,000 to 13,000 feet) below the surface. The channel-like geometry of the filtered HRAM data is lower in amplitude, broader in wavelength, and subtle in pattern.

Fig. 15. Expanded examples of the interpreted channel-like features are depicted with red dashed lines. The green line polygons depict the possible allochthonous salt. The green pattern polygons depict the probable salt features. Well locations are marked with an "x". Numbered black cultural boundaries denote the lease boundaries that measure approximately 4800 metres (3 miles) on a side for a reference scale. Recently drilled wells that tested concepts supported by these interpretations are shown with a red circle and star at their approximate locations. Devon Energy published a press release with preliminary test results of the MP-36 State Lease 14964 #2 well on August 12, 1998. The information was posted on their website (www.devonenergy. com). The release states the well flowed at a rate of 14 million cubic feet of gas and 900 barrels of condensate per day with a flowing tubing pressure of 10,400 psi over a 36 hour test from perforations at approximately 5000 metres (16,500 feet). The other two wells were plugged and abandoned in 1998.

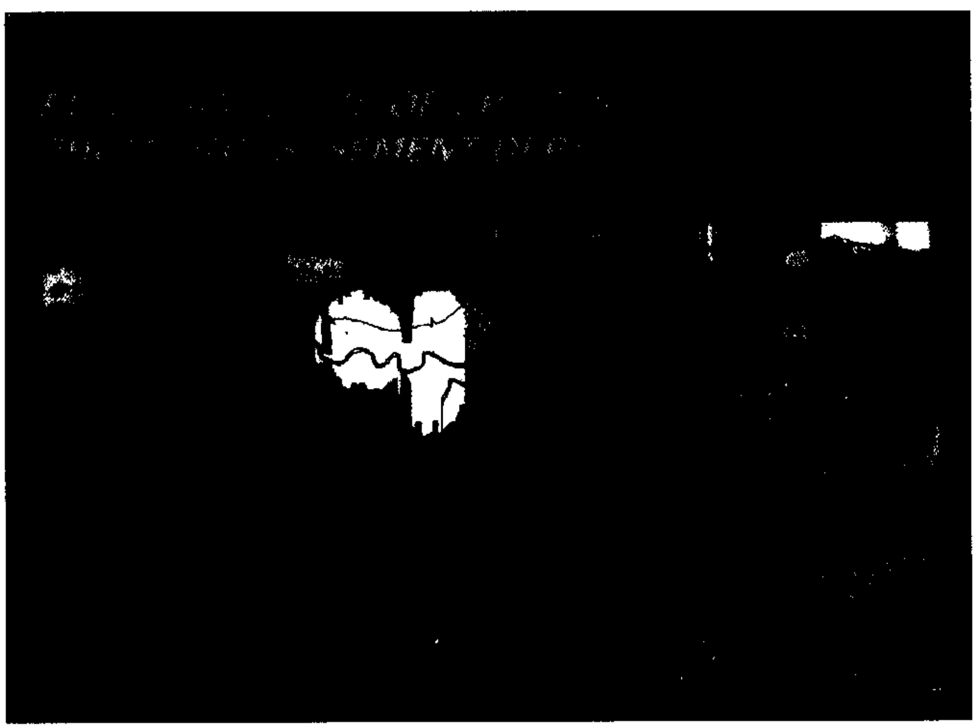

Fig. 16. This image is the result of a principal component analysis of the various filters used in this project. Included were the upward continuation residual differences, the 2nd horizontal gradient filter of the upward continuations, the basement depth surface, and a 2nd vertical derivative surface. This was useful for further interpretation of the igneous features as well as salt evolution characterization.

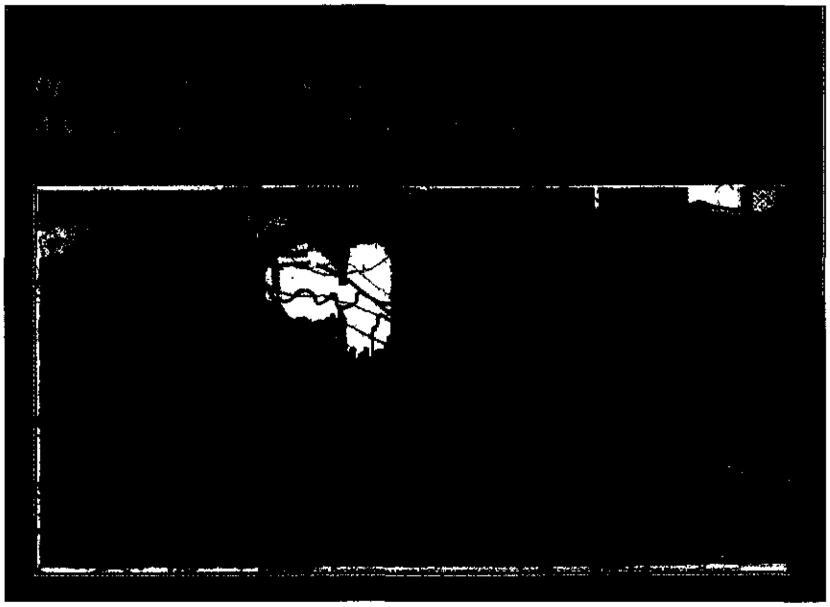

Fig. 17. With the interpretation overlain, note the concentration of high amplitude more vertical and shallow salt bodies of the Main Pass Area located in the lower right hand corner. They are perched over relatively shallow basement and exhibit a more purple colour in the image. In contrast, there is a very subtle more blue colour signature associated with the salt features of the Breton Sound area just to the northwest where basement deepens. The proposed interpretation is that the deep autochthonous salt distribution and thickness provided accommodation space and influenced clastic sediment fairways. Evolution of the alochthonous salt was driven by overburden pro-gradation through time, and resulted in the present day allochthonous features well imaged by HRAM. This provided a key to understanding of the petroleum system as the multiple Mesozoic source systems may remain in varied phases of hydrocarbon generation where the basement is relatively shallow. Where the basement is deep, basin models predict those early sources are over-mature. This could in part explain the results of recent drilling. The MP 36 #2 well tested a salt feature shown by the large star with a red circle that links with a basement fault trend. The foot-wall south of the prospect has the potential for stacked early sources to still be in the generation window with the access to the Middle Miocene aged reservoirs through the basement fault and allochthonous salt system. The two other wells shown by small stars with red circles, and recently drilled in the area do not show the same connection to deep faults nor the proximity to shallower Mesozoic aged source systems. The relationships and location of these deep features as well as the allochthonous salt distribution provided a key to understand the petroleum systems in this region, and they were well imaged with HRAM.

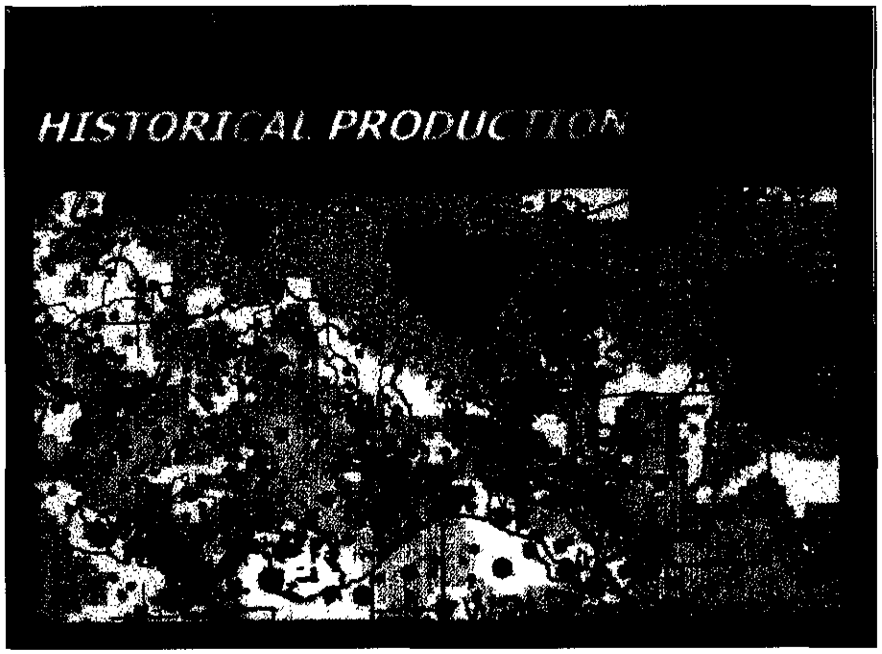

Fig. 18. This image shows the historical petroleum production in southeast Louisiana. The bubble size is related to field size, the red denotes gas and the green denotes oil production. The background colour indicates overall richness by gridding the mean field size across a 50,000 acre square. Yellow regions exceed 100 MMBOE and blue regions have produced less than 10 MMBOE. The overall grain of the map suggests a WNW-ESE grain sub-parallel to the dominant change in basement fabric that underlies the thick Middle Miocene clastic reservoir system deposited in deltaic to slope facies across the area. An understanding of deep source rock distribution, plumbing and migration pathways, timing and salt evolution, in part interpreted from HRAM data helped high grade play scale regions.

Fig. 19. The petroleum industry has often explored along trends such as deltaic reservoir facies belts. The depth to magnetic basement grid is colour contoured from purple 18 300 metres (60,000 feet) to orange 6100 metres (20,000 feet) with a 3050 metres (10,000 feet) contour interval. The green polygons depict the possible and probable salt features. The brown lines depict the basement grains. The pink patterned polygons depict the probable igneous intrusive bodies. The aqua lines depict the 2-D seismically defined faults from the top and base of the Middle Miocene. The blue dashed lines depict the shelf margins at 23.50, 12.50, and 10.50 MYBP. An east to west trend of deltiac and slope facies that track the shelf margins along the blue dashed lines is predicted from these data. This might find reservoir, but it may not find the best reservoir. A more integrated depositional model with high-graded fairways aids the prioritization along strike. Such a model as shown by the red dashed arrows was in part interpreted from the filtered HRAM data. Second, the rest of the system components such as source maturity and distribution, source access, and allochthonous salt traps are critical in finding the significant petroleum accumulations. The filtered HRAM data aided the interpretation of these elements of the hydrocarbon systems.

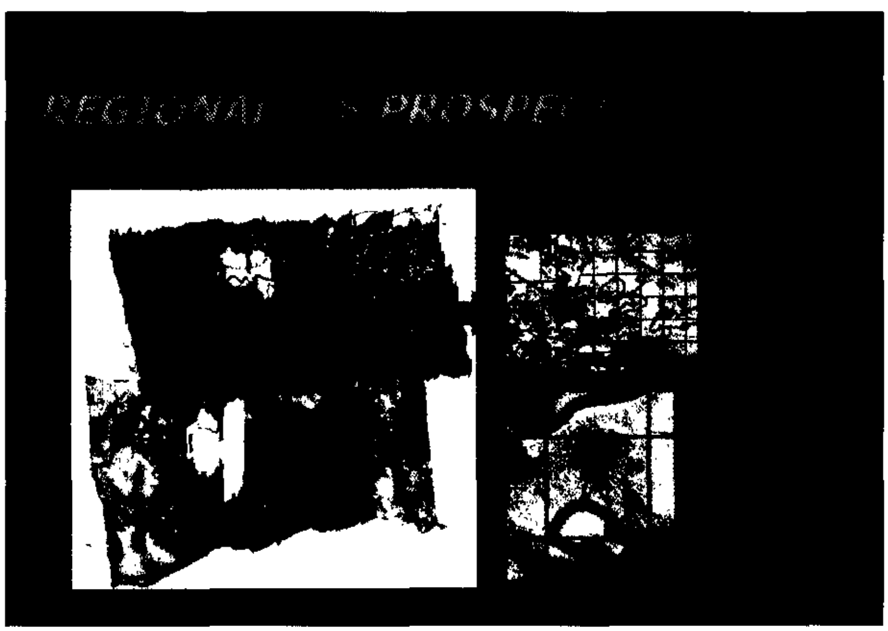

Fig. 20. HRAM can provide a tool to bridge regional to prospect scaled petroleum system analysis. It provides the traditional deep basement information as well as significant intra-sedimentary information for exploration. The 3-D prospective view of the whole map area on the left captures the basement architecture in the lower image and the allochthonous salt distribution from the upward continuation difference filter. The filter has been inverted here for visual effect of the salt features. The upper right map view is an example of the play scale geologic model of the inter-salt reservoir system. The lower right map view characterizes a prospect scale feature. Black culture lines depict 4800 metres (3 mile) OCS block boundaries for a reference scale on the detailed map views.