Digital integration of potential fields and geologic data sets for plate tectonic and basin dynamic modeling—the first step toward identifying new play concepts in the Gulf of Mexico Basin

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It has recently been demonstrated (Jacques and Clegg, 2002; Jacques et al., 2003) that an understanding of the plate tectonic history of the Gulf of Mexico Basin is essential if we are to extend our knowledge of the distribution and quality of source rock and reservoir into deep and ultradeepwater frontier petroleum provinces. We need to combine our tectonostratigraphic knowledge of the onshore and shallow water regions with a variety of techniques, both well established and new, if we are to identify and evaluate the petroleum systems of the Gulf of Mexico Basin. To this end, an extensive work program has been developed which integrates tectonics, geophysics, geochemistry, and sedimentology with GIS technology to allow identification of new, and also the extension of existing, play fairways into frontier deepwater and subsalt areas. Although this work program comprises 11 stages (briefly outlined below), the first, and probably most important, phase is the main focus of this article. This is the integration of potential fields data with various geologic data sets to define structural elements, continental block outlines, and crustal types across the basin—the aim of which is to produce a detailed, digital structural, and geologic coverage that defines the "basic building blocks" of the region. Placed in a plate tectonic context, we will demonstrate that this information can be confidently used to create a regional "palaeotemplate" that can be ultimately used to create a series of palinspastic base maps for plate tectonic and basin dynamic modeling purposes. This, in turn, will be used to produce a series of palaeotectonic and depositional reconstructions for key source rock and reservoir horizons. The mapped distribution of different crustal types and intensity of Mesozoic extensional activity will be a principal constraint for predicting palaeoheat flow gradients for determining basin subsidence and source rock maturation histories.

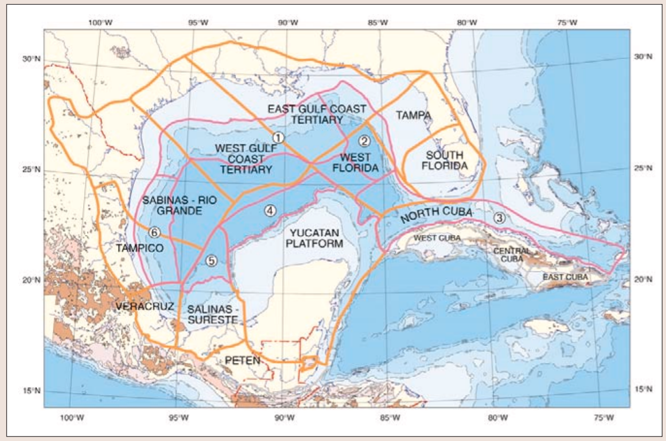

Figure 1. Basins (orange lines) and frontier petroleum provinces (pink lines).

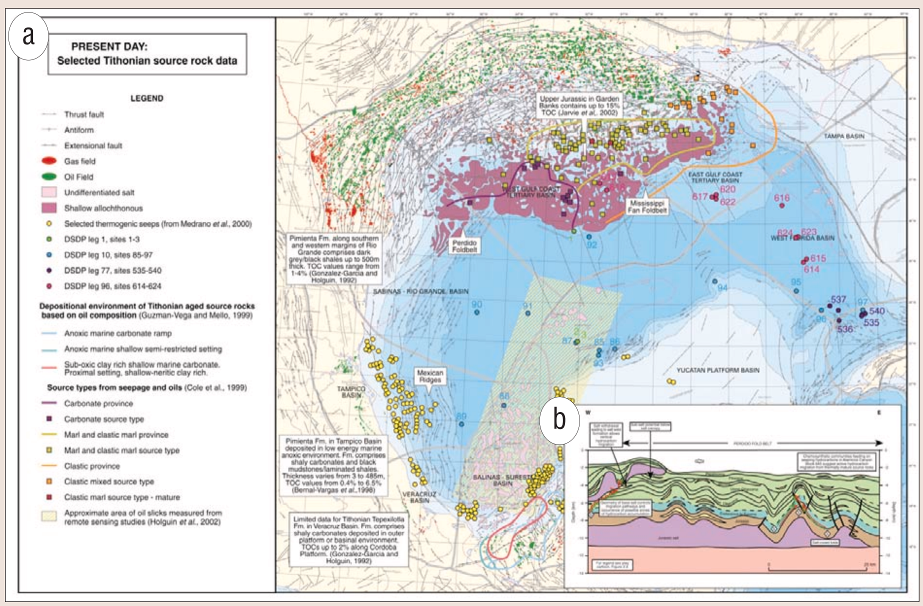

Figure 2. (a) Selected Tithonian source rock data on present-day oil and gas field distribution map (after Jacques and Clegg, 2002a); (b) Inset showing play cartoon for the Perdido Fold Belt province of the Sabinas-Rio Grande Basin (section modified from Peel et al., 1995).

New and existing play concepts. Recent advances in exploration and production in the Gulf of Mexico Basin (Figure 1)—one of the most petroliferous regions of the world—has meant that over the last few years, many companies that are well established in the shallow water regions of the northern Gulf, are now focusing exploration interest on subsalt, and deep (200-1750 m) and ultradeep (>1750 m) water targets. A great deal of this interest centers on both new and existing play concepts (Figures 2 and 3), including: (a) subsalt and deepwater plays beneath Tertiary allochthonous salt canopies in both the northern Gulf and Mexico's Salinas-Sureste Basin (the Mid-Jurassic, Callovian-Oxfordian Louann and Campeche Salt Provinces, respectively); (b) traditional minibasin plays that lie between these large salt bodies; (c) the genetically related salt-cored, structural fold belts of the Mississippi Fan and Perdido Fold Belts of the northern Gulf of Mexico; and (d) the unique contractional structural fold belt of the Mexican Ridges.

Based on evidence available to date, we recognize six subsalt and/or deep to ultradeepwater frontier petroleum provinces in the Gulf of Mexico Basin (Figure 1), which are all considered to have commercial hydrocarbon potential:

- The Texas-Louisiana Slope and Abyssal Plain, including the Mississippi Fan and Perdido Fold Belts
- The West Florida Rise and Abyssal Plain
- The Florida Straits and Cuban Foredeep
- The Northwestern Yucatan Rise and Abyssal Plain (Sigsbee Knolls)

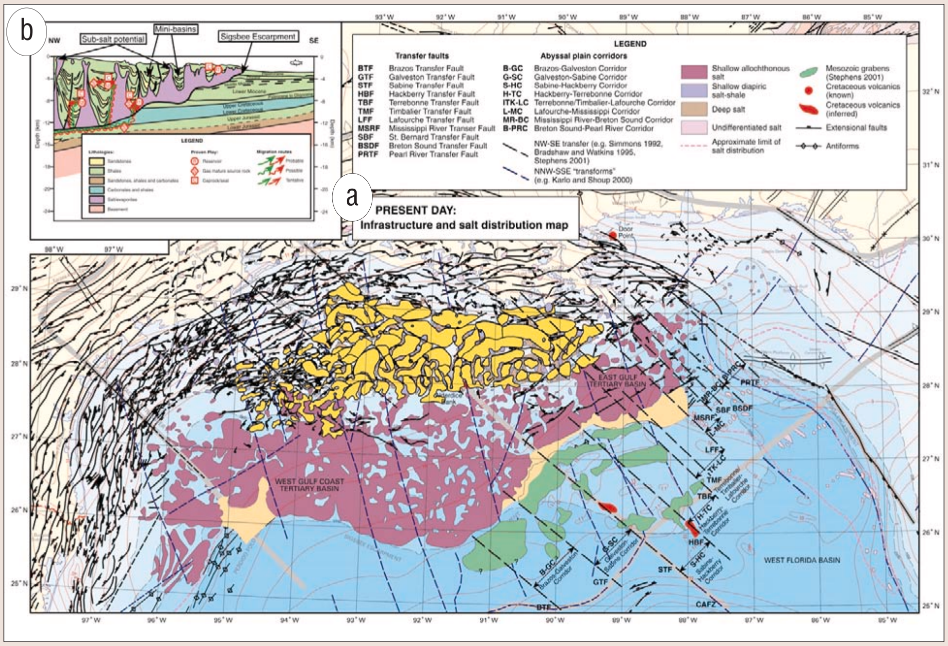

Figure 3. (a) "Clip-out" of the northern Gulf from the "structural framework map" showing structural elements, salt distribution, Abyssal Plain Mesozoic grabens, salt withdrawal minibasins (yellow) and extent of salt-cored folds (orange) in the Perdido and Mississippi Fan areas; (b) Inset showing play cartoon for the minibasin province of the East Gulf Coast Tertiary Basin (section modified from Peel et al., 1995).

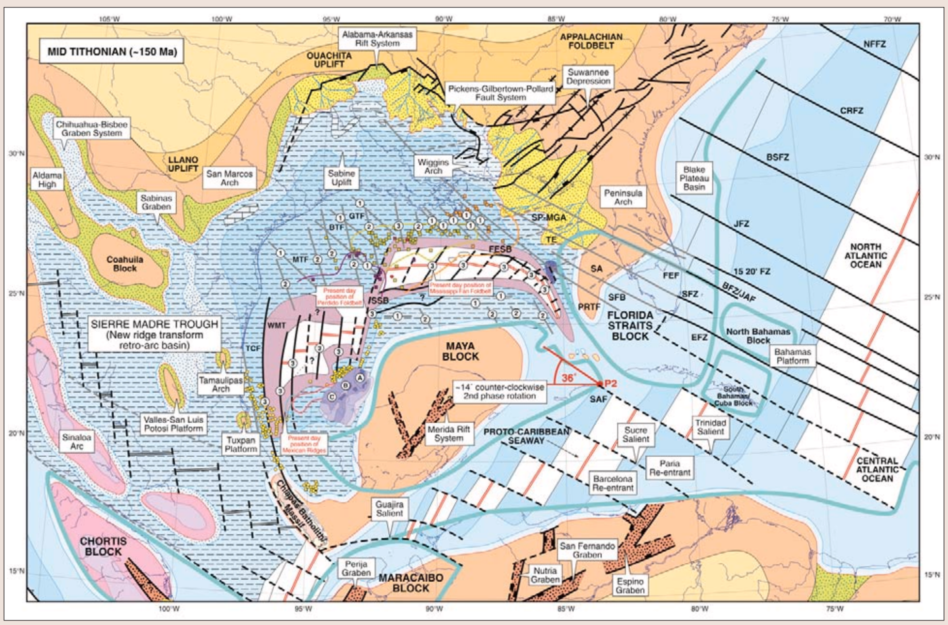

Figure 4. Mid Tithonian palaeotectonic and palaeodepositional map (after Jacques and Clegg, 2002).

- The Campeche Deepwater to Ultradeepwater Salt
- The Mexican Ridges

Several compare in position and geographic extent to the petroleum deepwater frontier provinces described by Watkins and Buffler (1996).

The main hydrocarbon source intervals operating throughout the Gulf of Mexico are of Late Jurassic, Oxfordian and Tithonian age, with smaller but still significant contributions from Aptian/Albian, Cenomanian/Turonian, and Eocene source rock horizons. Oil seeps have been recognized in most of these frontier provinces (Figure 2), suggesting the presence of a world-class source rock sequence; palaeogeographic reconstructions clearly show that the Tithonian interval (Figure 4) offers the best potential for regional development of an extensive organic rich source. Deposited during the opening cycle of the Gulf of Mexico Basin, the distribution and quality of this source rock interval are directly attributable to the palaeotectonic and palaeodepositional environments prevailing at that time.

In defining the distribution and intensity of Mesozoic, synrift activity across the basin, with the view of understanding the mechanistic response of the crust to extensional and thermal subsidence processes, we need to integrate various geologic data sets with potential fields data. It is becoming increasingly clear that the basement rift geometry of fault-bounded grabens and half-grabens created during the opening phase of the basin imposed an important control on the distribution and quality of Late Jurassic source rocks. It has also been demonstrated that this extensional basement fabric had a profound effect on the "original" depositional thickness of Callovian salt. The presence of this salt and its mobilistic behavior can be shown to have retarded the thermal maturation of subsalt petroleum source rocks, determined the sites of minibasin formation by salt withdrawal and the creation of predominantly Cenozoic growth fault systems (Figure 3), formed major barriers to vertical petroleum migration, and created extensive structural traps and faults that served as petroleum migration pathways. In addition to salt evacuation by sediment loading into regional salt canopies, salt inflation and lateral extrusion occurred at depth to produce the salt-cored Mississippi Fan and Perdido Fold Belts.

It is therefore a paramount requisite that the predominant structural basement fabrics of the Gulf of Mexico Basin are recognized, defined, and their kinematics understood. Only with such "building blocks" can a rigorous tectonostratigraphic evolutionary model be developed and used to successfully predict hydrocarbon prospectivity in different parts of the basin.

Background and data sets. The Gulf of Mexico region is one of a series of genetically related sedimentary basin work packets that create a global database of play fairways and petroleum systems. Completed in 2000, the Gulf of Mexico Basins Study recognized 15 basins extending from the Mexican Sierra Madre Oriental in the west to Cuba in the east (Figure 1). This provides a petroleum geologic review for the assessment and prediction of the hydrocarbon potential of each basin. This has been achieved by synthesizing the tectonic, structural, and depositional history of each basin in order to summarize

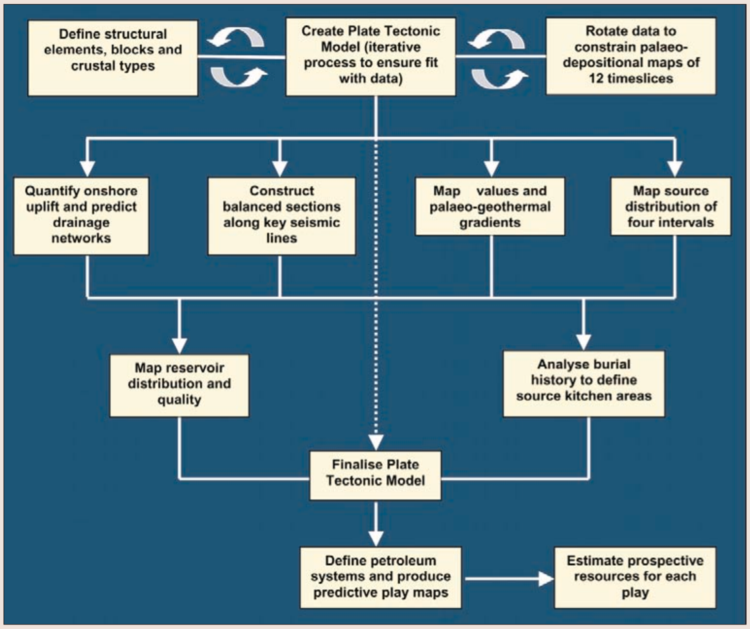

Figure 5. *Work program showing relative timing of key study elements.*

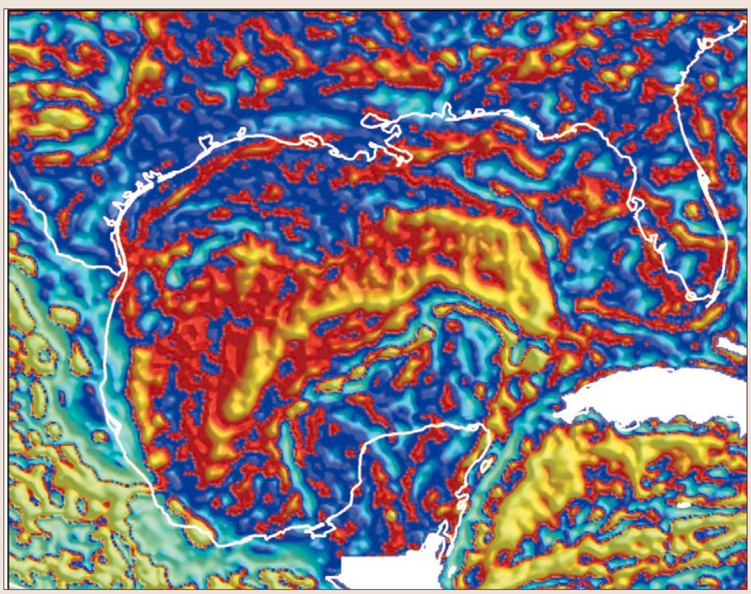

Figure 6. *Example of the pseudolithology compilation of public domain gravity and magnetic data over the Gulf of Mexico. Compilation represents rock properties ratio of apparent susceptibility over density contrast (k/ρ) independent of source geometry or depth of burial.*

proven plays and identify new play concepts as a predictive tool for the assessment of future prospectivity and the identification of regional play fairway trends. Integrated with field and well data, the structure, stratigraphy, and deformational state of each basin are stored in GIS format, providing a powerful means for spatial and temporal relationships associated with petroleum systems to be observed. This digitally captured and databased information thus provides a "tectonostratigraphic database" for the entire region that can be used as a fundamental platform for basin-scale play fairways and petroleum system analyses.

In this article, the term Gulf of Mexico Basin is used to include all basins that clearly define or fall within the coastal margin of the Gulf of Mexico. Thus, the North, West, Central, and East Cuba Basins are omitted from this definition; however, the Florida Straits and Cuban Foredeep are considered as a frontier petroleum province of the Gulf of Mexico Basin.

Elements of this tectonostratigraphic database have been used to integrate with the potential fields data sets for the plate tectonic and basin dynamic modeling. KMS, satellite altimeter derived gravity, NGDC land gravity, and the NAMAG magnetic compilation have been enhanced using proprietary processing and current models.

Work program. Based on work by Jacques (2002), and Jacques and Clegg (2002), a collaborative work program between Robertson and Fugro-LCT has been developed. Although referred to as "stages" for convenience, these are not strictly sequential, with the relative timing of the project key elements, and their association with each other illustrated by the flow diagram (Figure 5). The first phase of this program—Stages 1, 2, and 3—is the main focus of this article, and is discussed in more detail below. This is followed by a brief overview of the remaining stages.

Stage 1: Structural and geologic interpretation. The objective of the first phase of this work has been to define structural elements, continental block outlines, and crustal types across the Gulf of Mexico Basin. Three techniques are being used to produce displays that can be digitally integrated with various geologic data sets for interpretation purposes:

(a) Shaded relief images from map enhancements of potential fields data sets. Three data sets have been widely used: NAMAG Magnetics, KMS 2002 Satellite Altimeter Derived Gravity and Mexico '97 data from the NGDC. These maps are particularly useful for defining deep structural lineaments and basement features (see below);

(b) Pseudolithology maps. By using the Poisson relation equating magnetics and calculated gravity gradients, a map of susceptibility over density contrast has been generated for the entire region that is free from geometric convolution. Developed by Dransfield et al. (1994; see Price and Dransfield, 1995; and references therein), the resultant "pseudolithology map" ("rock property map"; Figure 6) has been used, in conjunction with other data sets, to help identify and define, in particular, the oceanic/continental boundary, basement highs (e.g., Galveston High) and lows (e.g., Sigsbee, West Florida, and "Alaminos" salt basins), the relict spreading axis from east to west across the Abyssal Plain, and first-order tectonic elements that can be related to different stages of the basin's opening cycle;

(c) 2D gravity and magnetic profiles. Several integrated potential fields models have been produced at selected locations to create a series of 2D megaregional gravity/magnetic profiles that traverse the entire basin (e.g., Figure 7). These have been used to help evaluate the position of crustal boundaries, determine the thickness of crustal units and have been developed as full-earth models, so as to encompass gravitational elements as deep as the mantle surface;

(d) Gravity data enhancements. Various data enhancement techniques have been applied and found particularly useful for defining lower density lithologies, such as salt and shale, that contrast with surrounding and overlying sediments, in areas that are particularly difficult to image seismically.

When integrated with various geologic data sets, these potential fields techniques are used to define:

- original continental block outlines (pretectonic shapes);

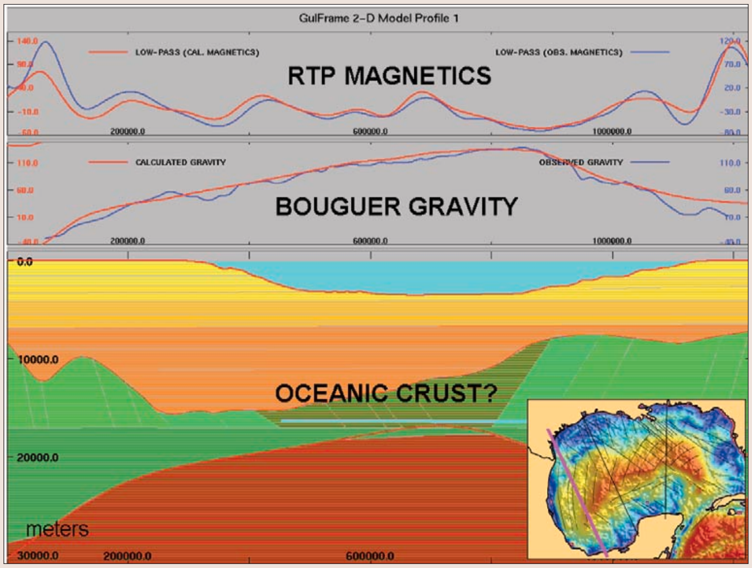

Figure 7. Example megaregional gravity and magnetic 2D profile across the western Gulf of Mexico. Public domain data displayed here.

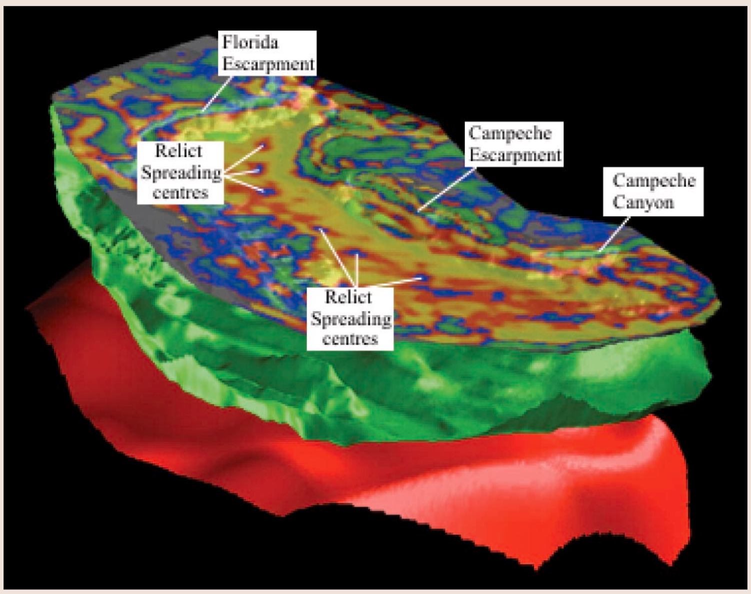

Figure 8. Pseudolithology map draped over digital elevation model. Perspective view toward the southeast.

- first-order tectonic elements and predominant structural
- basement fabrics that characterize the region;
- distribution of different crustal types (continental, oceanic and heterogeneous) and their boundaries;
- salt distribution and geometry;
- extent of igneous intrusives and volcanics.

Present-day structural and geologic framework maps. All structural and geology maps have been compiled digitally using ESRI's ArcView and ARC/INFO GIS formats to create a complete attributed structural coverage for the Gulf of Mexico region. Where possible, a distinction has been made between deep basement faults and crustal domain boundaries derived from potential fields data, and growth fault systems developed throughout the sedimentary cover that sole out into a mobile substrate horizon (salt or shale). A further categorization has been made by distinguishing growth faults inherited from deeper basement structure from those intimately related to salt movement ("hard/soft linkage"). Individual structures have been attributed with respect to reference source, and values are assigned to each structure to illustrate confidence in their position and interpreted sense of movement. This provides a spatial representation of the quality of the data across the entire basin, enabling areas of poor coverage to be identified and updated efficiently as new data become available.

Structural lineaments and basement features derived from enhancement maps of gravity and magnetic data have been interpreted by combining individual shaded relief images (i.e., surfaces illuminated from a unique azimuth). Various illumination directions have been analyzed, allowing features observed to be hierarchically ranked based on confidence. These have been merged into one interpretation and, again, where possible, a distinction made between basement features and structures confined to the sedimentary cover.

Results from Stage 1. The potential fields interpretation reveals so far:

- the extent of oceanic crust is largely confirmed, with different crustal types identified;
- basement highs and lows, in particular, definition of salt basin geometry and distribution;
- relict spreading axes are defined and expressed in the pseudolithology (Figure 8);
- the position and extent of first-order transfer/transform fault sets operative during each stage of the basin's opening cycle.

Stage 2: Plate tectonic modeling. Once the present-day structural/geologic framework of the region has been established, it is then necessary to define individual tectonic units ("building blocks") that will form the basic components for developing a composite plate tectonic model for the region. To achieve this, the "original" continental block outlines (pretectonic block shapes and their positions), the distribution of principal crustal types, and the position of first-order tectonic elements have to be identified and rigorously assessed, again using potential fields data. This iterative process should ultimately result in the development of a constrained palaeotectonic template (e.g., Figure 9a) that can be used to create the composite plate tectonic model.

A very important aspect of this work is to understand the effects of deformation, which need to be quantitatively removed, with overlap problems between adjacent continental blocks addressed (see Pindell et al., 2000). Where possible, this is achieved by using a combination of data sets, such as backstripping sediments progressively through time (total sediment thickness), using well data and seismic profiles perpendicular to the continental shelf, and by using the suite of 2D gravity/magnetic profiles that traverse the continental margins in an attempt to create prerift reconstructed continental block outlines and contoured β values for areas of significant crustal extension.

The results from Stage 1 will be used to modify an ongoing tectonic model. With the basic "building blocks" in place, different crustal types can be defined with greater confidence, the kinematic history of major continental blocks can be determined, and the distribution and timing of deformational activity can be explained across the region. The end result is a thoroughly assessed set of palinspastic base maps, which can be used to create a series of palaeotectonic reconstructions onto which depositional environments can be compiled for key source rock (example in Figure 4) and reservoir horizons.

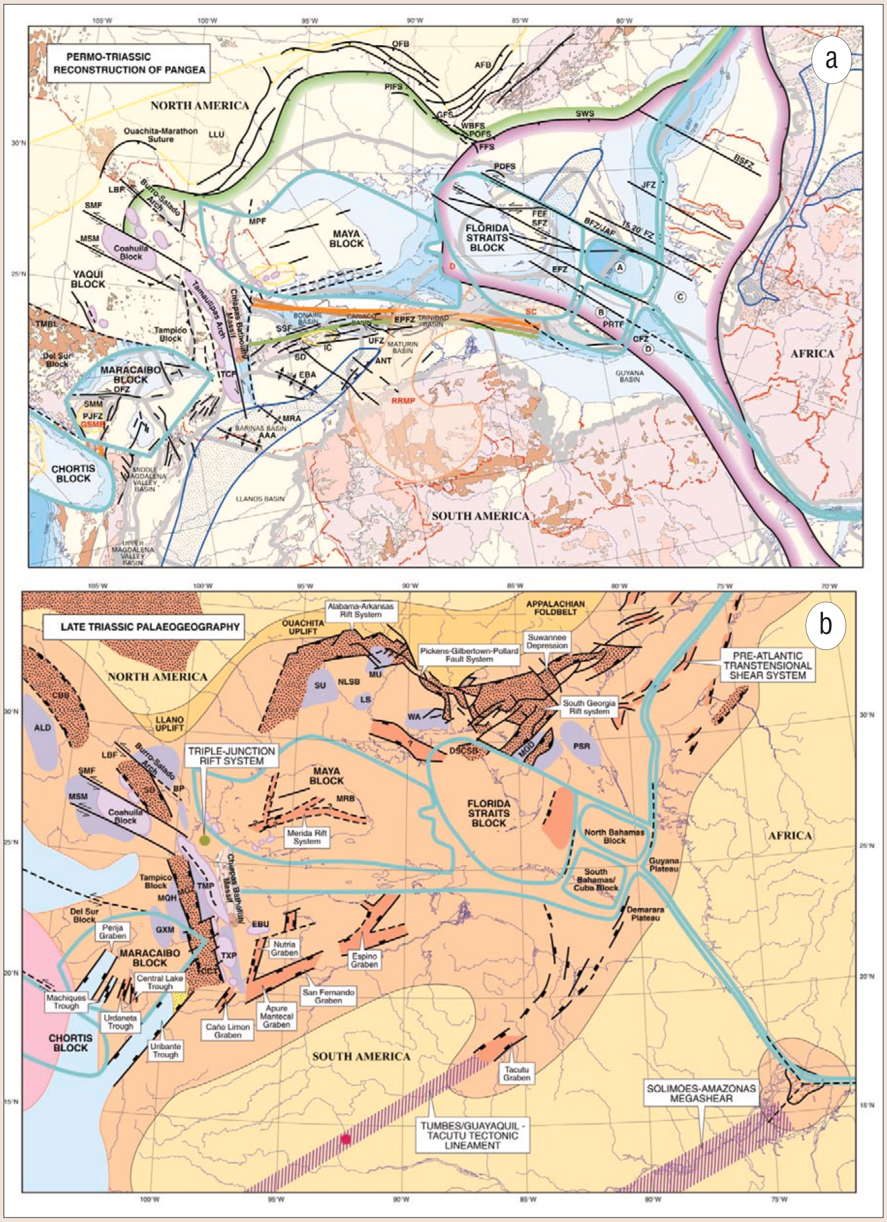

Figure 9. (a) Permo-Triassic reconstruction of Pangea ("palaeotectonic template"; after Jacques and Clegg, 2002a), showing prerift continental block outlines, and their configuration and relationships. Present-day basement, igneous and volcanics, and selected structural elements rotated for reference; (b) Late Triassic palaeotectonic and palaeodepositional map (after Jacques and Clegg, 2002a).

Stage 3: Palaeogeographic reconstructions. In the compilation of any palaeogeographic reconstruction, it is necessary for the scale of the map to best utilize the level of detail available and, at the same time, provide the basis from which reasonable and meaningful extrapolation can be made between data points (structural and lithostratigraphic), to constrain important tectonic and depositional boundaries. A scale of 1:2 000 000 is deemed, in this case, to be most appropriate. The Late Triassic and Tithonian palaeogeographies presented here (Figures 9b and 4; after Jacques and Clegg, 2002a) are a synoptic representation with their palaeodepositional elements derived solely from the public domain.

A series of 12 palaeodepositional maps for selected time-slice intervals are being created, from which computer-generated plate tectonic base maps can be produced. For petroleum system evaluation purposes, five key source rock horizons are of particular interest: Oxfordian, ~155 Ma; Tithonian, ~150 Ma; Aptian/Albian, ~112Ma; Cenomanian/Turonian, ~97-88 Ma; and Eocene, ~52 Ma. Of this series, two key horizons will be the Late Triassic (~210 Ma), which will provide the 'palaeo-template' for the region (see Figure 9a), and a Callovian (~160 Ma) time-slice, with the principal aim of mapping the original distribution and depositional thickness of Callovian salt (now representing the northern Gulf Louann and Mexican Campeche Salt Provinces, and synrift salt basins such as the Sigsbee, 'Alaminos' and West Florida Salt Basins).

Further investigation. Future investigations will include: (a) basin dynamics, to create a series of maps to illustrate subsidence history that show the distribution and timing of Mesozoic extensional activity and distribution of different crustal types. Combined with maps of bathymetry and basement depth, these will be used to produce a map of β values for the entire basin that can be used in a predictive sense to estimate and map palaeoheat flow gradients for selected source rock intervals; (b) palaeodrainage analysis to identify areas of significant onshore uplift (hinterland evolution), sediment influx patterns and predicted reservoir distribution, and past drainage networks; (c) section-balancing of key seismic lines to show timing of salt movement, as a means of providing a greater understanding of salt withdrawal processes and minibasin creation and, in turn, an insight into sediment accumulation patterns; (d) palaeodepositional time-slice work for selected source rock intervals for predicting source rock distribution and quality; (e) recognizing principal phases of subsidence, with particular focus on the thermal maturation history of key source rock intervals; (f) the identification and evaluation of the major petroleum systems and plays identified; (g) proven and potential play, and field reserves data assessment; and (h) spatial and temporal analyses of the multitude of geologic data sets used during the program.

Conclusions. The first, and probably most important phase of any exploration screening program is the integration of potential fields data with various geologic data sets to define structural elements, continental block outlines, and crustal types, with the aim of producing a detailed, digital structural and geologic coverage that defines the "basic building blocks" of the region. Enhanced with data sets of source rock and reservoir characteristics, combined with a variety of other techniques, such as basin dynamic modeling, drainage net analysis, and burial history modeling, such a work program can be successfully used to identify new and extend existing play fairways, into frontier areas. The potential fields data are an invaluable set of data and can be used during these subsequent stages, particularly during the basin dynamic and burial history modeling stages, to predict the amount of crustal thinning to establish palaeoheat flow gradients for the determination of basin subsidence and source rock maturation histories.

Suggested reading. "Lithological mapping by correlating magnetic and gravity gradient airborne measurements" by Dransfield et al. (*Exploration Geophysics*, 1994). "Geographic information systems as an advanced exploration tool" by Jacques (*Offshore Magazine*, 2002). "Late Jurassic source rock distribution and quality in the Gulf of Mexico: Inferences from plate tectonic modeling" by Jacques and Clegg (*GCAGS Transactions*, 2002). "Gulf of Mexico Late Jurassic source rock prediction: Integrating tectonics and geochemistry with GIS technology" by Jacques and Clegg (*Offshore Magazine*, 2002). "Improving geologic understanding with gravity and magnetic data: Examples from Gabon, Nigeria and the Gulf of Mexico" by Jacques et al. (*First Break*, 2003). "Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: a preliminary analysis" by Peel et al. (in *Salt tectonics: a global perspective, AAPG Memoir 65,* 1995. "Lithological mapping by correlation of the magnetic and gravity data from Corsair W.A." by Price and Dransfield (in *The Bulletin of the Australian Society of Exploration Geophysicists*, 1994). "Gulf of Mexico deepwater frontier exploration potential" by Watkins and Buffler (in *Structural framework of the northern Gulf of Mexico: GCAGS Transactions*, 1996). "A removal-restoration project. Parts 1 to 4, 'Regional Plate Kinematics, arm waving, or underutilized exploration tool'" by Pindell et al. (*AAPG Explorer*, 2000). Work program public domain data sets: Mexico '97 Gravity Data from the NGS at NOAA, available at *http://www.ngs.noaa.gov/GEOID/MEXICO97/*; KMS 2002 Satellite Altimeter Derived Gravity offshore, "Global marine gravity field from the ERS-1 and Geosat geodetic mission altimetry" by Andersen and Knudsen (in *J. Geophys. Res.*, 2002, abstract available via *http://www.agu.org/pubs/abs/jc/97JC02198/97JC02198.html*; Onshore U.S. gravity data derived from "Land and Marine Gravity CD-ROMs, 1999" compiled by Dater et al. at the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, CO., available at *http://www.ngdc.noaa.gov/seg/potfld/gravity/welcome.shtml*; Magnetic data compilation at the U.S. Geological Survey, 2002, "Digital data grids for the magnetic anomaly map of North America" (in U.S. Geological Survey Open-File Report 02-414, U.S., available at *http://crustal.usgs.gov/projects/namad/*. TLE

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