THE NATURE OF THE NAGA THRUST AND FOLD BELT, ASSAM SHELF, INDIA: INSIGHTS FROM CROSS-SECTIONAL BALANCING

By

BRANDY BRIDGETT MICHAEL

Bachelor of Science in Geology

Oklahoma State University

Stillwater, Oklahoma

2011

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2021

THE NATURE OF THE NAGA THRUST AND FOLD BELT, ASSAM SHELF, INDIA: INSIGHTS FROM CROSS-SECTIONAL BALANCING

Thesis Approved:

Dr. Priyank Jaiswal

Thesis Adviser

Dr. Mohammed Abdel Salam

Dr. Jack Charles Pashin

Dr. James H Knapp

ACKNOWLEDGEMENTS

Pursuing my Master's degree has been an incredible journey that is now a legacy. I say it is a legacy because I truly believe education makes such an impact upon growing your branch of your family tree. I am thankful to be able to achieve this accomplishment for my family and future family.

There are many people I'd like to acknowledge for being apart of this accomplishment.

First, I would like to thank those at the Boone Pickens School of Geology. Thank you to my advisor, Dr. Jaiswal, for the opportunity to work on this project and his dedication toward the success of this project. Thank you to my committee for their contribution toward my academic excellence. Thank you to my own bureaucratic tape cutter, Dr Abdel Salam, who ensured I was able to get past roadblocks especially right there at the end. Thank you to Dr. Pashin who first introduced the idea of a growth basin in my project area and spent many hours working through potential interpretation ideas. Dr. Pashin and Dr. Lao Davila both helped me build a foundation in structural geology.

Second, I would like to thank those outside of Oklahoma State University who contributed to this project. Thank you to Oil India who provided this dataset who made this project possible. Thank you to Dr. Burberry at the University of Nebraska, Lincoln, who also worked through early interpretation ideas with me. Thank you to Dr. Kent for taking the time to discuss his prior research in Assam, India with me. Dr. Kent's research on the Upper Assam Shelf was incredibly valuable to this project.

Third, I'd like to thank Chesapeake Energy for providing scholarships, gifts, and support during my graduate work. I intend to continue sporting my Chesapeake Energy swag.

Fourth, I'd like to thank my family and friends. Your support has meant more than you will ever know. Thank you to my mom, who has truly been my personal cheerleader. Thank you to Dalton Hawkins who provided support and gave feedback about my work when I needed it. Thank you to so many colleagues and friends who provided support even in smallest ways.

Last but not least, I am thankful to the Divine Guidance I have received through this whole journey. I continue to lean toward my favorite passage as I enter into new chapters of my life, accomplish new things and overcome new challenges.

Hebrews 12:1 …..let us throw off everything that hinders and that which so easily entangles and let us run with perseverance the race marked out for us.

Name: BRANDY BRIDGETT MICHAEL

Date of Degree: MAY, 2021

Title of Study: THE NATURE OF THE NAGA THRUST AND FOLD BELT, ASSAM SHELF, INDIA: INSIGHTS FROM CROSS-SECTIONAL BALANCING

Major Field: GEOLOGY

Abstract: The Naga Thrust and Fold Belt of the Assam Shelf, India, is one of the most prolific onshore hydrocarbon provinces in the world remaining underexplored due to limited conceptualization and testing of structural concepts. We have restored two interpretations of a profile across the Jaipore Anticline, the hanging wall anticline of the Naga Thrust, constrained by well-tops and inversion-based imaging. The first is in line with the fault-propagation fold model, commonly applied to the Naga Thrust, but does not agree with dips of the ramp reflections. The second adequately honors the ramp reflections and requires presence of two decollements – shallower in the Upper Barail group (Naga Thrust) and deeper in the Jaintia group (Bally Thrust). The deeper thrust is blind and from inversion of pre-existing growth structures. In both interpretations, the hanging wall exhibits extensive second–order deformations from an antithetic thrust, accommodating over 50% of the total shortening and the footwall is characterized by duplex structures resulting from under-thrusting and triangle zone formation. Results do not refute the existing fault-propagation fold model of the Naga Thrust. Rather, it proposes that there is a change in structural style and kinematics along the thrust belt, which separates the location of our profile from the type-locate of the fault-propagation fold model. A variety of structural prospects emerge from the dual-decollement model, which may provide a new direction to exploration in the Naga Thrust and Fold Belt.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Interpreting onshore seismic profiles from Thrust and Fold belts are challenging not only due to non-intuitive reflector geometries but also their poor imaging/mappability (Bond et al, 2007; Improta et al, 2002). Acquisition and processing advances have greatly enhanced seismic imaging addressing the mappability end of the problem, but the art of geological model building, which is largely conceptual, still hinges on the experience and geological insights that the interpreter possesses (Herron 2009). The conceptualized geological model on seismic sections always run the risk of being over-interpreted due to processing artifacts (Hesthammer 1999). Well control and surface geology are the two critical data types used to validate an interpreted seismic facies. When wells are limited and outcrops are absent, interpretation may have to be restricted to overly-simplified expressions of geology. For example, in their Alberta Foothills experience although Wren and Jain (1978) were able to significantly improve mappability of all key reflectors through their inversion-based imaging, lack of sufficient well and surface control did not allow a usable stratigraphic model to be built. Besides well and outcrops, researchers have also sought other kinds of datasets, such as full-waveform velocities (Operto et al (2004) and Ravaut et al 2004), magnetostratigraphy (Pennock et al. 1989), geomechanical and gravity (Davis and Lillie 1994) and scaled analogue modeling (Bonini 2003) to relate selected reflection characteristics to geology.

An effective method of validating a structural interpretation is through first-principles based restoration and cross-sectional balancing (Dahlstrom (1969), after Hunt (l957), Goguel (1952), Carey (1962) and Bally et al. (1966). The underlying assumption of balancing is that post-seismic concentric deformation produces no *significant* change in rock volume. Under plane strain assumptions an interpreter unfolds the geological-model/interpretation to put the beds put back into their depositional position without introducing inexplicable bed length or thickness anomalies (Boyer & Elliott, 1982). Since the method's original testing in the Alberta foothills, it has been applied successfully in other fold and thrust belts, such as Jura Mountains Fold and Thrust Belt (Malz et al 2005), Himalayan frontal fold-thrust belt (Mukhopadhyay and Mishra, 2005), Alaskan Brooks Range Mountain Front (Cole et al, 1999), South African Cape Fold Belt (Spikings et al, 2015), Peruvian Subandean Belt (Richards et al, 2003) Castellane fold and thrust belt (Jourdon et al, 2014), Fila Costena thrust belt (Stitchler et al, 2007), southwestern Taiwan foreland thrust belt (Mouthereau et al, 2001), and Papau fold belt (Mason, 1997).

Bed restoration assumes that there is no movement in or out of the plane of a balanced profile (Kley et al, 2008). Therefore, balancing is typically done on profiles parallel to the direction of motion. Typically, a pin (reference location) is selected in an undeformed area, e.g. the foreland, with respect to which the beds are restored (Woodward et al, 1989). Balancing may fail under certain conditions. A cross section may not balance if there is out of plane movement in the profile through features such as lateral ramps and tear faults that are associated with limbs that dip at variable angles to the direction of transport (Woodward et al, 1989). An interpretation may not be balanced if fault blocks are not restored in the reverse order of their formation. Particularly, in the subthrust, the order of restoration can determine whether the thrusted imbricates are dipping toward the foreland, hinterland or an antiformal stack (Butler, 1986). Misidentified complex hanging-wall geometries can also lead to balancing pitfalls since ramps and flats in the hanging wall and footwall must fit back together. Further, excessive dissolution

(Diehl and Anderson, 2010) and salt flow (McQuarrie, 2004) may not allow a cross section to be balanced.

In this paper we have applied cross-sectional balancing as a multiple hypotheses approach to validate the interpretation of a 2D seismic profile from the Assam Shelf, India, which has been one of the most prolific hydrocarbon provinces of all sedimentary basins (Mathur et al, 2001). Northeast Assam, hosts one of the oldest known oilfields, the Digboi field, which has paved the way for the exploration of the shelf. The initial cross section of the Naga Thrust as a fault propagating fold were developed by Mathur and Evans (1964) in the vicinity of the Digboi field. More recently Kent et al. (2002) applied Mathur and Evans (1964) model to test the hydrocarbon potential of the southern limb of an anticlinal feature known as Jaipore Anticline (Figure 1), located southwest of the Digboi oilfield. Kent et al. (2002) developed the flat-ramp model with a limited dataset and showed that the thrust-fault flat occurs in a coaly interval of upper Oligocene age (the Barail-Group) and the ramp is localized by preexistent normal faults and stratigraphic discontinuities. It also concluded that the proven productive foreland trend extends several kilometers beneath the Naga thrust. Their model was calibrated at the Kusijan No. 1 well with a set of vintage profiles. Approximately 1 km southwest of the Kusijan No. 1 well, a right-lateral fault, known as the Assam Railroad tear fault intersects Jaipore Anticline offsetting it by ~1.5 km. Kent et al. (2002) hypothesized that pre-existing normal faulting could have displaced the decollement prior to thrusting. A recent set of 2D lines were acquired southwest of the tear fault in 2004 and a well, Lakhi-1, was drilled to test the sub-thrust prospects along one of the dip-perpendicular profiles, PO-03 (Figure 1). Profile PO-03 processed using an advanced inversion-migration method (Jaiswal and Zelt 2008) showed a complex reflection structure and a variety of dip domains that could not be easily explained by a flat-ramp model. Using a set of well logs along the PO-03 profile that constrain the key horizon and waveform-inversion velocities that constrain the shallow (1.5 km) stratigraphy, we present and validate an alternate interpretation that the Naga Thrust along PO-03 has been deformed by the presence of a blind thrust, the Bally Thrust.

While more than one structural interpretation has been proposed for the Naga thrust, a fault propagating fold has been interpreted and modeled at Digboi field and later at the Kusijan field (Kent et al, 2002.). Fault propagating folds are considered common traps associated with thrust and fold belts developing an asymmetrical folded structure at the tip of the propagating thrust fault (Woodward et al, 1989) that mechanically develops by flexural slip (Suppe and Medwedeff, 1990.) Fault propagation folds are commonly not seismically imaged well from steeply dipping beds and require cross section balancing methods to aid identification of complex geometries with low seismic resolution (Mitra, 1990). Poor seismic resolution could lead to misidentification of structural models such as the fault propagation fold which closely resembles a faulted detachment fold (Nemcok, 2009). Saini and Mukhopadhyay applied a fault propagating fold to their modeling and demonstrated an increase in shortening from Digboi to Kusijan from balanced cross sections. There are significant bed dip changes that occur between Digboi and Kusijan and along the trend of the Naga thrust over the Jaipur anticline that was recorded by Kent et al. Kent et al attributed the changes between Digboi and Kusijan due to the Assam Railway Tear fault that separates the fields and the surface dip changes across the Jaipur anticline due to concealed imbricate faults. The Assam Railway Tear fault is a right-lateral strikeslip fault that is evidence for structural inversion of normal faults in the Assam area

Bally's conceptual model on inverted half-graben systems describe how blind thrusts might develop from extensional faulting. Bally proposed that complete inversion of the extensional fault system would also propagate the stratigraphic wedge as the inverted half-graben edge is developing as a blind thrust beneath the sedimentary cover. Additional conceptual models have been extended by others such as McClay and Buchanan, and Tari et al validating that inverted basin geometries can be complex. Bally and others have relied upon seismic imaging to aid identification of structural geometries. McClay and Buchanan's (1992) work shows that growth folds from inversion are fault propagation folds with an asymmetric nature that is footwall-vergent. Their work also reveals that the listric portion of the thrust develops hinterland dipping backthrusts in a breakforward sequence. High angle thrust faults are typical of inverted extensional faults however thrust faults developing or growing from the preexisting extensional faults are typically low angle in the upper section with a steepening dip into the deeper section which does not adhere to conventional ramp-flat geometry (McClay and Buchanan, 1992. Listric thrusts are indicative of multiple tectonic phases where inversion has occurred.

Other examples exist in nature of thrusts developed from inverted extensional faults with significant shortening such as the Vicuna area of the Magallanes thrust and fold belt in Southern Chile. Cross sectional balancing found that the Vicuna area has the highest shortening along the thrust belt at approximately 60% shortening with changes in structural style from the north to the south responsible for the differential displacement (Alvarez-Marron et al, 1993.). The Vicuna portion of the thrust belt has an imbricate thrust system with fault propagating folds and thrusts with listric geometry that extend into a sole thrust coinciding with basement level extensional faults. Alvarez-Marron et al showed that multiple detachment levels or decollements are responsible for changes in structure and shortening. This is also present along the Naga thrust with an increase in shortening from Digboi to Kusijan to Jorajan fields from 30% to 50% respectively (Saini and Mukhopadhyay, 2018 and 2019). The geometry of inverted structures is controlled by the shortening (Letouzey, 1990.) which is evident in our study area as the detachment moves deeper in section from Digboi to Jorajan. The detachment in Digboi is in the Surma group moving deeper in section into the Barail formation in Kusijan. Our model shows a deeper detachment in Kopili at the Jorajan field where the highest shortening occurs.

CHAPTER II

STUDY AREA AND BACKGROUND

The Assam geologic province in Northeast India is a cratonic margin characterized from the Indian plate colliding and merging with the Eurasian plates. According to the USGS, the Assam geological province was developed by three distinct tectonic phases. The first tectonic phase is characterized by the Late Cretaceous – Eocene drifting of the Indian Plate toward the Eurasian Plate, southeast tilting of the Assam shelf and activation of block faulting. The second tectonic phase is Oligocene and characterized by clockwise rotation of the Indian plate as it subducted beneath the Eurasian plate, creating the Himalayan orogeny. Basement faults were reactivated during this time while terrestrially sourced sediments were shed from the Eurasian plate onto the trench of the subduction zone. This was followed by extensive alluvial deposition in the Late Miocene through the Pliocene marking the third tectonic phase.

The regional stratigraphy varies across the Assam shelf due to platform tilting and basement involved block faulting, which resulted in regional unconformities and thickness variations (Wandrey, 2004). The stratigraphy associated with this study (Figure 2) begins with the early Paleogene Jaintia Group. The Jaintia Group is composed of four main formations and deposited during the first tectonic phase of the Assam province. The lower formations, Tura and Langpar, are composed of fluvial to marginal marine massive sandstones. The upper Jaintia formations, Sylhet and Kopili, consist of shales, carbonates and sandstones. The Eocene Sylhet formation thickens from northwest to southeast. Sylhet is composed of lagoonal sandstones, interbedded shales, coals, barrier bar thick sands, shallow marine calcareous sandstone and a shelf carbonate with interbedded siltstones and clay. The Kopili Formation, composed of shales and interbedded limestones overly a regional unconformity and represent a change in a shallow marine setting to lagoonal. In our interpretation, the Kopili formation forms the seat of the deeper decollement.

In the second phase, the upper and lower Barail units were deposited. Uplift and erosion during this time truncated this group by an unconformity which exists north of the study area (Wandrey, 2004). The deposition pattern in the upper Paleogene changes to a transgressive deltaic sequence depositing the lower arenaceous Barail unit. Lithologically, this unit is divided into sandstones and minor shales. The upper Barail, which is the argillaceous unit, shows a change from a delta front to a delta plain environment. This group consists of coal and shale sequences with an overlying clay unit. In our interpretation, the upper, Argillaceous unit forms the seat of the shallower decollement. Regionally, where the stratigraphic succession is continuous, the Lower Miocene Surma Group comprising thin siltstones, sandstones and shales deposited in a fluvial deltaic to estuarine environment overlies the Barail unit (Wandrey, 2004). However, in the study area, the Lower Miocene is eroded. Barail is overlain by a mid-Miocene unconformity which is overlain by a fining-upward succession of the Tipam group which begins as a fluvial sequence with several minor transgressions turning into deltaic facies toward the end.

The third phase initiates with extensive deposits of alluvial sediments of the Girujan formation from Late Miocene to Pliocene. The Girujan formation is interpreted as shales and clays from lacustrine and floodplain deposits. This is essentially a non-marine environment with the upper surface of the formation marking a major unconformity. The third tectonic phase was still continuing during deposition of the Dhekiajuli formation. The regressive Dhekiajuli argillaceous sandstone has minor amounts of clay (Bhandari et al, 1973) and correlates with the basal part of the Dihing formation east of the Jaipore anticline (Kent et al, 2002.). The Pliocene to

Pleistocene age Dihing group is immature under-compacted sediments of sand and mud that thicken to the north. These clastic sediments onlap the Miocene unconformity in a southerly direction. Two active petroleum systems are present in the region. The middle Eocene – Oligocene petroleum system comprising the Kopili Formation and the Barail Group from the upper petroleum systems in the Assam Basin. The Tipam Sandstone is a reservoir and the Girujan Clay is the seal for the upper petroleum systems. In general all formations thicken toward the South and Southeast. To date, exploration has been restricted to structural anticlines in the foreland of thrust belts after the initial commercial discovery of Digboi. While this has led to several large discoveries such as the Nahorkatiya Field, Kent et al (2002) and Kent and Dasgupta (2004) have argued for the prospect potential of the sub-thrust part of the hanging wall.

Current compression of Northeast India is trending northwest to southeast. The Nahorkatiya Anticlinorium located northwest of the Jaipur Anticline is evidence of inversion of normal faults in the foreland. The nose of this feature plunges underneath the Naga Thrust pointing to the southeast which reoriented 90 degrees from its original northeast-southwest direction during the late Miocene (Kent and Dasgupta, 2004.). This was due to rotation of the Indian plate drifting North-Northeasterly during compression with the Eurasian and Burmese plates (Dikshit and Dikshit, 2014). This collision resulted in the Upper Assam Shelf overthrusted to the North by the Eastern Himalayan Thrust Belt and to the South by the Assam-Arakan Thrust Belt. Current regional basement structures such as grabens trend normal to the active continental margin (Kumar et al, 2012). Kumar et al found that two distinct fault patterns have been recognized in the Upper Assam Basin, Eocene and Post Eocene, trending East-West and Northeast-Southwest respectively (Kumar et al, 2012). The overall trend of these faults in surface expression from E-W to NE-SW changes orientation around the Nahorkatiya Anticlinorium. The convergence of the Naga thrust with the Jaipur anticlinal axis captures a structural transition along the thrust belt. Likewise, the Assam Railway Tear fault pinpoints the location of stress accommodation along the thrust belt. The Assam Railway Tear fault is flanking the eastside of the Jaipur anticline oriented approximately N-S. This tear fault is suspected to have basement level involvement from the pre-existing extensional fault system (Kent et al, 2002). The development of this right-lateral strike-slip fault corresponds to the clockwise rotation of the Indian Plate.

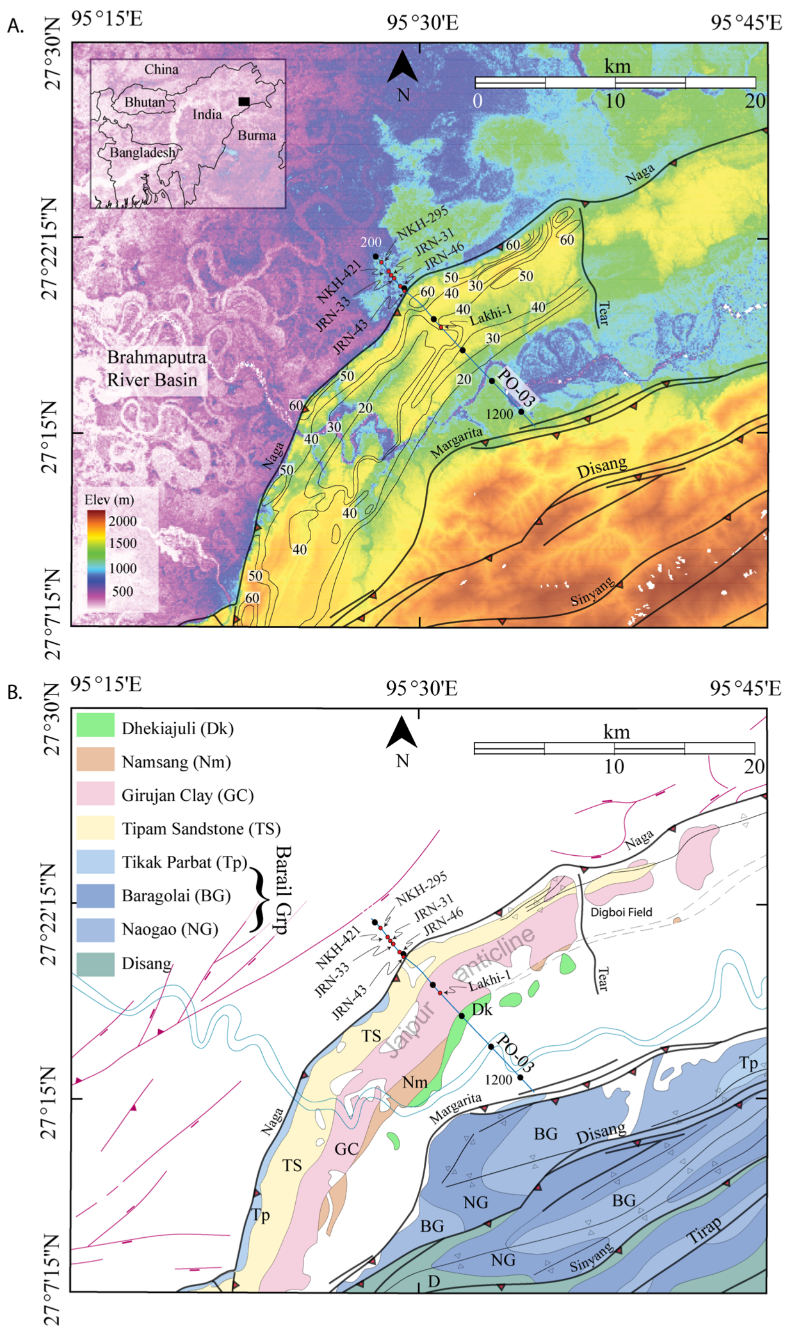

Figure 1 Basemap. a) Digital elevation, and b) geological map of the study area. In a) and b) Key thrusts – Naga, Margarita and Disang, are labeled along with a right lateral strike slip tear fault that offsets the Naga Thrust. Profile PO-03 oriented normal to the Naga Thrust is shown with solid back line. Solid black dots along PO-03 indicate CMPs at intervals of 200. Solid red dots indicate well locations. In a) contours in the ramp anticline of the Naga Thrust are the dip domains. Inset shows the location of the study area in context of the geopolitical map of the region. In b) Key formations are color coded and labeled. Feature labeled as Jaipore Anticline generally refers to the ramp anticline of the Naga Thrust.

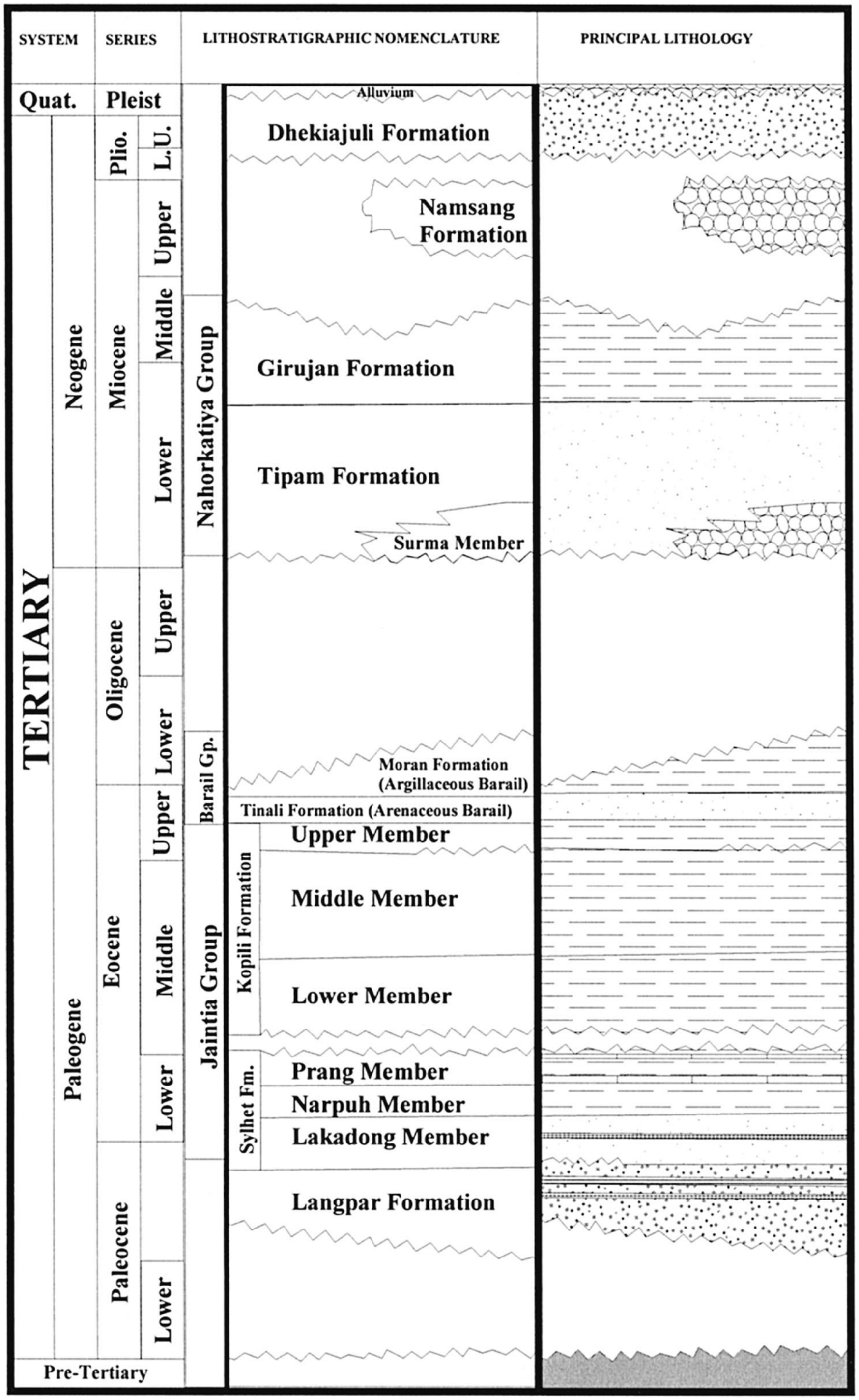

Figure 2 Stratigraphic Chart. Figure shows the lithostratigraphic changes in the key formation from the foreland into the thrust belt. The middle Eocene – Oligocene petroleum system comprising the Kopili Formation and the Barail Group from the upper petroleum systems in the Assam Basin. The Tipam Sandstone is a reservoir and the Girujan Clay is the seal for the upper petroleum systems. In general, all formations thicken toward the South and Southeast. From Kent et al, 2002.

CHAPTER III

INTERPRETATIONS

Dataset Description

Seismic

The seismic profile used in this study is approximately 11 km long trending northnorthwest –southsoutheast, perpendicular to the strike of the Naga Thrust at a location in the Jaipore Anticline which is most advanced toward the foreland (Figure 1). Data were acquired in a split-spread style and processed using a novel imaging algorithm known as Unified Imaging (Jaiswal and Zelt, 2008). Unified Imaging seeks a common structural solution of key interfaces through pre-stack migration (moving seismic energy in a known velocity model) and inversion of reflection times (perturb existing velocity model to fit a known structure). Inversion describes the large-scale features and migration describes the small-scale features. A wild cat well, the Lakhi-1, which penetrated both the hanging wall and the sub-thrust footwall, along the profile was available for image validation (CMP 625; Figure 3 and 5). Jaiswal and Zelt (2008) used the Lakhi-1 sonic log to validate the UI velocity model. Interpretation of Lakhi-1 (Figure 5) in the subthrust indicated a thickened section of footwall strata also observed in the seismic imaging. Jaiswal and Zelt (2008) interpreted the UI depth section following the flat-ramp hanging wall model of Kent et al. (2002). Key features of the UI image are as follows. First, although not continuously, the Naga thrust was imaged well in both the ramp and the flat of the hanging wall and could be readily tied to the corresponding top after the Lakhi-1 trajectory was overlaid on the image. Second, the projection of the ramp stratigraphy had clear surface expressions in the digital elevation map. Third, a reflector dipping in the opposite direction to Naga Thrust was imaged in the foreland. It was interpreted as a back thrust fault with its detachment at the same level as the Naga Thrust. The region between the Naga Thrust, the back thrust and a floor detachment was interpreted as a triangle zone in the footwall.

A characteristic feature of the current seismic profile was sub-horizontal reflectors in the shallow hanging wall that did not fit the classic flat-ramp geometry. To test whether these reflectors are real or data artifact, Jaiswal et al. (2009) improved the resolution of the UI velocities using multi-scale full-waveform inversion to try and independently constrain the shallow structure of the hanging wall stratigraphy. Jaiswal et al. (2009) found that the velocity perturbations from waveform inversion were also sub-horizontal with similar structure as the hanging wall reflections, suggesting strong second-order deformation in the hanging wall. Jaiswal et al. (2009) constrained the suprathrust reflections in the hanging wall using Lakhi-1 markers following which they jointly interpreted the depth image and the perturbation model suggesting that the second order deformation was due to layer parallel slip. However, they could not sufficiently develop their ramp interpretation to connect the reflection in the hanging wall flat to the shallower sub-horizontal reflections. They speculated presence of an antithetic thrust below the Miocene unconformity dividing the shallower sub-horizontal reflections in the ramp zone and the sub-horizontal reflections in the flat zone.

Wells

Formation-top depths at various well locations are presented in Table 1. In context of the profile PO-03, Well NHK-295 is located at CMP 268. It penetrated though ~784 m of Girujan, ~784 of Tipam, ~297m of Argillaceous Barail and terminated within the Arenaceous Barail at a total depth (TD) of 3520.14m. NHK-421 is located at CMP 311. It penetrated though ~836m of

Girujan and terminated within the Tipam at TD of 2507m. Well JRN-33 is located at CMP 327. It penetrated though ~848m of Girujan and terminated within the Tipam at TD of 2502m. Well JRN-31 is located at CMP 344. It penetrated though ~871m of Girujan and terminated within the Tipam at a TD of 2529 m. Well JRN-46 is located at CMP 403. It penetrated though ~963m of Girujan and terminated within the Tipam at a TD of 2554 m. Well JRN-43 is located at CMP 435. It penetrated though ~986 m of Girujan and 808 m of Tipam and terminated within the Argillaceous Barail at a TD of 3382 m. Well Lakhi-1 is located at CMP 650 within the Thrust Belt. It penetrated ~8m of outcropping Girujan, followed by 267m of Tipam and 1155 m of Argillaceous Barail before reaching the Naga Thrust at 1637m depth. Below the Naga Thrust, Lakhi-1 logs cannot be easily correlated with their foreland counterparts (Figure 5a) and were interpreted in context of the local structure (e.g., Figure 5b) and the two interpretations (Figure 4), present two possibilities of the specific formation the well might have encountered immediately below the Naga Thrust (Figure 4). Key observations solely based on well markers are as follows. First, the formations in the foreland thicken slightly toward the thrust. Second, the stratigraphy and structure dips 3 degrees to the Southeast which matches the regional dip for the Assam region. Third, the Naga thrust is seismically imaged down the ramp into the flat with sub-horizontal beds at Lakhi -1. Fourth, the thickness of the package spanning from Top Tipam to Top Argillaceous Barail in Lakkhi-1 is ~370 meters and ~345 meters thicker than the same package in NHK-295 and JRN-43, respectively. This thickening in the hanging wall is indicative of inversion of a growth structure. Layer parallel slip is interpreted for the secondary deformation in the hanging wall. Layer parallel slip assumes constant thickness therefore the secondary deformation does not contribute to the thickening in the hanging wall. This infers that bed thickening in the hanging wall relative to the foreland must have occurred prior to thrusting based on the conservation of layer thickness assumption.

We are extending the interpretation of PO-03 based on concepts developed by Jaiswal and Zelt (2008) and Jaiswal et al. (2009) by integrating the more recently released surface and well data. Surface structural dips (personal communication, Norman Kent, 2015) of the strata along the Naga thrust add constraints to the complexity of the hanging wall interpretation for this profile. The dip map generated in Kent's work indicate the dips in the back dip panel for the Jaipore anticline are not constant which may suggest a concealed imbricate thrust. The dips on the back dip panel of the Jaipore anticline range from 70 to 20 degrees. These surface dips correspond to this seismic profile as follows. At CMP 450 and 500, 35 degree and 25 degree dips respectively correspond to the Tipam sandstone in the seismic profile. The Girujan clay has dips corresponding of 35˚ at CMP 550, 28˚at CMP 600, 22˚ at CMP 650, 45˚ at CMP 700, and 35˚ at CMP 800. The Dhekiajulis Fm is approximately 25˚ degrees at CMP 800 to 1200. The 35 degree dips along the Tipam sandstone are applied to projected beds at the surface between the Naga Thrust and Lakkhi-1. These dips when combined with well markers confine the stratigraphic thickness and bed geometry for the hanging wall.

Two final structural interpretations are derived from rigorous iterations, a trial and error process of repeated restorations. Important assumptions were applied to the interpretation process. The Naga thrust fault trace, minor faulting in the footwall and hanging wall, and the Miocene unconformity were assumed from Jaiswal and Zelt, 2008. The decollement for the Naga thrust is assumed to be in the Upper Barail formation based on Kent et al (2002). Key faults have been identified in the seismic profile that are critical to the restoration process. Other minor faulting is present that does not impact each restoration. The first interpretation (figure 4; a and b) is conceived along the lines of the traditional ramp-flat model of a fault propagating fold for the Naga Thrust. It is an important distinction that this model does not fully honor the reflector geometry of the ramp. The second interpretation (Figure 4 c and d), as convinced in this paper, honors the reflector geometry of the ramp and proposes the presence of a blind thrust below the Naga Thrust (N). Both structural interpretations share common features however there is a distinct contrast of interpreted components in the footwall and hanging wall.

Foreland

In the foreland, duplex structures are under thrusting the suprathrust while triangle zone formation develops with the Upper Barail as the detachment surface. The stacked horses beneath the triangle zone are bound with the Upper Barail unit and the Kopili formation as the roof and basal detachments respectively. The foreland wells provide the most control points with the least deformation to begin correlating across the seismic profile. Constant bed thickness is assumed however we know from regional geology that there is a slight thickening toward the southeast. The Tipam sandstone is a more competent bed unit than the Girujan formation or the Barail formation so it was selected as the key bed in the restorations to maintain thickness and bed length. The total Tipam Formation thickness measured in NHK-295 is projected across the foreland to JRN-43.

As previously noted, Lakhi-1 logs below the Naga Thrust cannot be easily correlated with the foreland wells along this profile. Overpressure and fluid encountered in the subthrust section could have affected the resistivity signature and log character. Both the seismic imaging and Lakhi log data were considered for the subthrust interpretation. Seismic character indicates a subthrust package immediately below the Naga Thrust is Tipam however the resistivity signature indicates Girujan. The two interpretations represent different possibilities of this subthrust section where interpretation one follows the log character as Girujan and interpretation two honors the seismic character.

Interp 1

For Interpretation one (Figure 4 a and b), the horizon for the Girujan formation is mapped from the marker in NHK-295 continuously across the foreland toward the thrust correlating with the same formation marker for NHK-421, JRN-33, JRN-31, JRN-46, and JRN-43 terminating into the ramp of the Naga thrust. The Girujan horizon is the top of the bright package in the foreland.

The overlying Dihing group is unconsolidated material that would not be expected to have coherent reflectors. The Upper Tipam, UT, marker corresponding to a continuous reflector is also mapped across the foreland for NHK-295 NHK-421, JRN-33, JRN-31, JRN-46, and JRN-43. terminating into Naga thrust (N). The Upper Tipam horizon is intersected by an inverted normal fault without measurable displacement around CMP 600 prior to Fault N. The Tipam formation in the foreland has thicker and more coherent reflectors than the overlying Girujan formation at NHK-295. The seismic character changes moving past the subthrust faults toward fault N.

The Upper Barail horizon follows reflector geometry having minor displacement along a dropped fault block at CMP 350 and inverted extensional fault at CMP 450. The UB maps across as the floor detachment for a triangle zone from CMP 550 to CMP 700. The Upper Barail horizon continues extending across the footwall to a cutoff point against the Naga thrust at approximately CMP 850. Reflector strength is discontinuous however overall dips of the reflectors at this depth are more horizontal indicating horizon geometry is consistent with UT, and LT. The Arenaceous (Lower) Barail marker is ~0.33 km below the Argillaceous (Upper) Barail in NHK-295. This horizon is mapped across to CMP 350 with some displacement on the dropped fault block. LB horizon maps past CMP 450 with approximately ~0.33 km displacement down to the Kopili regional dip line. The LB horizon maps across the overlying horse and continues along the regional LB dip line until CMP 950. The LB horizon maps just beneath the flat of fault N. Thickness for the Lower Barail unit at NHK-295 is assumed from thickness of the overlying Upper Barail unit. The Kopili horizon is the base of the LB unit which maps across to the first dropped fault block close to CMP 500. The displacement for the Kopili horizon is ~40km below the LB horizon. The Kopili horizon continues mapping across the football at the base of the duplex structures generally following the trend of the LB horizon to the flat of Fault N.

Interp 2

In Interpretation two (Figure 4 c and d) horizon correlation in the foreland is generally equivalent with interpretation two with respect to features Northwest of Blind thrust (B). The decollement surface for Fault B is indicated at the top of the Kopili formation ramping up through the Lower and Upper Barail Formation in the foreland. The Girujan formation maps across the footwall with a cutoff point at approximately CMP 650 into fault B. Fault B overthrusts the stacked duplexes with an interpreted fault tip at CMP 600 indicating upward displacement approximating 0.75 km. UT maps across the top of Fault B past Lakhi-1 terminating into Fault N close to CMP 650. The Upper Barail horizon follows the regional dip line below fault B with a cutoff point close to CMP 800. The LB and Kopili markers follow the regional dip line with a cutoff point on Fault B at approximately CMP 850 and 900 respectively. Within the blind thrust, the top of the Lower Barail package is at the Upper Barail regional dip line. Both, the LB and Kopili map below the flat of thrust N at their expected regional dip.

The Hanging Wall

Interpretation of the hanging wall is broken into two fault blocks, the upper ramp and the lower ramp flat. Fault M (Figure 6a and Figure 7a) is a prominent listric back thrust of both interpretations with some variation of the fault trace. In interpretation one Fault M soles near the surface close to CMP 850. In interpretation two Fault M is slightly wider at the base and soles near the surface at CMP 800. Additional another backthrust is identified adjacent to Fault M with the fault tip at the top of a bright package at CMP 850. Fault M marks a distinct boundary of dip change between sub-horizontal reflectors in the upper ramp and dipping reflectors in the lower ramp-flat. Minor faults along the upper portion of the ramp are secondary backthrusts. These faults correspond to curving seismic character. Smaller thrusts and backthrusts within the flat do not generally impact horizon continuity. The contrast in the trace of Fault N in the lower ramp flat is a primary distinction between the two interpretations.

Interp 1

Interpretation one extends the trace of the Naga Thrust deeper than the previous fault propagating fold models. The decollement for Fault N is shown in the Lower Barail. Reflectors corresponding to the markers in Lakkhi-1 could not be mapped down the ramp continuously due to the antithetic back thrust, Fault M, dividing these two sections. The formation markers in Lakkhi-1 are used to maintain thickness within both fault blocks of the hanging wall. This assumption led to a significant increase of thickening for all formations down the ramp into the flat. This thickening is not reasonable from regional geology and will not restore with cross section balancing methods. In order to maintain reasonable thickness from Lakkhi-1, the decollement surface for the Naga thrust must be deeper in section below the Upper Barail and the trace of Fault N must extend deeper than the regional dip for LB. The decollement surface is interpreted to be at the top of the Arenaceous (lower) Barail ramping up through the Upper Barail formation to form the secondary detachment in the Upper Barail in the foreland. The upper ramp fault block is rotated along backthrust M due to continued propagation of the Naga Thrust. The Upper Tipam marker in Lakkhi-1 is mapped laterally across to the east following a slightly crenulated reflector that terminates just past CMP 800 at fault M. The UT horizon maps to the west immediately dipping at 35 degrees based on surface data. The LT horizon follows the reflector dips to the east with the same subhorizontal geometry of the UT horizon dipping at the cutoff into Fault M. The LT horizon maps to the east with the same dip as the UT horizon and soles at the surface at CMP 450. These cutoff points maintain the general thickness of the LT Unit from Lakkhi-1. The Upper Barail horizon maps to the east following the same general geometry as the LT horizon curving down into Fault M at CMP 800. The Upper Barail maps to the west toward the ramp terminating against Fault N at CMP 500. The UT, LT and UB horizons map to the west up the ramp with expected geometry for a fault propagating fold with surface data constrained by the Tipam Formation. The inclined geometry of these horizons do not precisely follow the identifiable seismic character. Although reflections within the UT fm west of Lahki-1 are weaker, strong coherent reflections within the LT unit indicate curvature of folding around CMP 550.

Interpretation one's lower ramp-flat fault block is interpreted from maintained thickness from Lakkhi-1 and regional dip lines projected from the foreland. It is assumed that once the upper block is rotated to a predeformed state that the horizons in the upper block should match the horizons on the lower block. Girujan, UT, LT and UB horizons are dotted along the ramp to indicate model expectation where correlation has deviated from the seismic character. The Girujan horizon has a cutoff point along Fault M at CMP 825. Girujan maps to the East below a bright package with reflectors dipping around 30 degrees. UT, LT, and UB have cutoff points on Fault M at CMP 775, CMP 700 and CMP 675 respectively. All horizons follow similar geometry mapping down to the ramp flat at CMP 1100.

Interp 2

Interpretation two traces the Naga Thrust with the expected decollement at the top of the Upper Barail. This interpretation addresses the issue of maintaining formation thicknesses from Lakhi-1 by two definitive components: introduction of Blind Thrust B, and shearing of the Tipam formation on the ramp. Fault B underthrusts Fault N detaching deeper in section at the top of the Kopili formation. Correlation of horizons from Lakhi-1 markers better observe seismic character. The UT, LT, and UB horizons map to the east distinctly following crenulated seismic character before terminating against Fault M at CMP 800, 775, and 750 respectively. The UT horizons maps to the west immediately terminating at the surface close to CMP 600. Both the LT and UB horizons map toward the ramp distinguishing folded character before terminating on Fault N at CMP 475 and 550 respectively.

Interpretation of the lower ramp-flat fault block in the second model adheres to geologic constraints while honoring seismic character. Regional dip lines projected from the foreland guide the interpretation of the horizons. All horizons are mapped down the ramp-flat to CMP 1100. Girujan has a cutoff point on Fault M at CMP 800. The Girujan horizon maps to the East within the lower portion of the bright package. Girujan maps across a fault near CMP 850 without displacement. The Tipam horizon is connected at Fault M at CMP 725. Tipam maps across a minor backthrust to CMP 800 with marginal displacement. Tipam maps to the East crossing two backthrust faults with minor displacement at CMP 950 and CMP 1000. Tipam is interpreted at regional dip along the ramp-flat. Formation thickness in Lakhi-1 is maintained in the flat for Tipam. Thinning of the Tipam formation on the ramp below Fault M is interpreted as sheared.

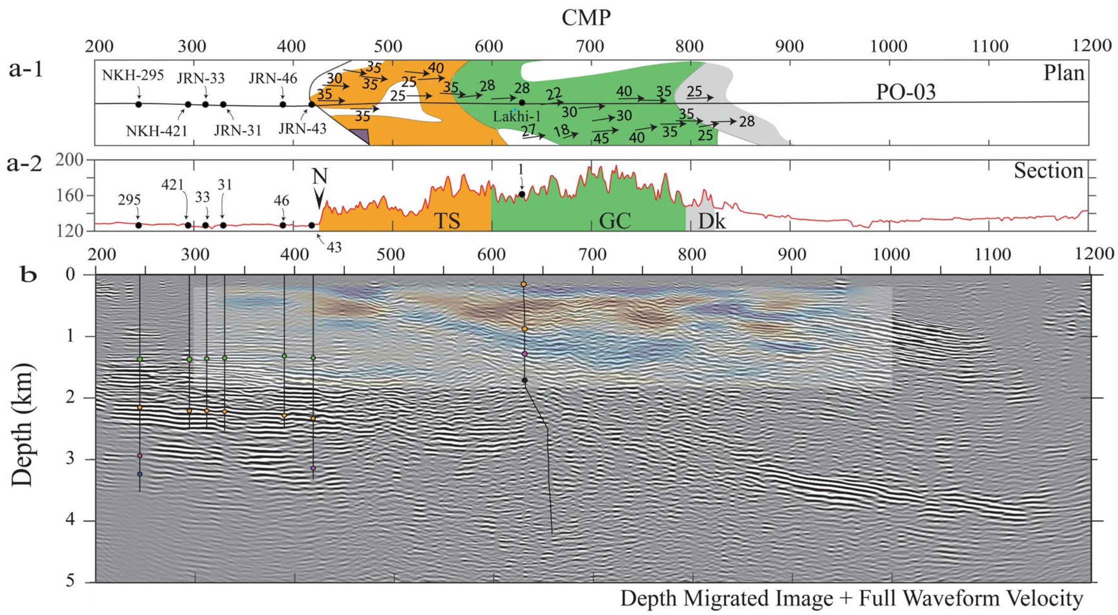

Figure 3 Depth image. a) Surface geology along PO-03 in i) plan view and ii) sectional view. In a.i) and a.ii) key formations – Tipam (orange), Girujan (green), and Dhekiajuli (gray) are color coded and labeled and the wells are indicated with solid dots and labeled. In a.i), arrows indicate formation dips. In a.ii), the elevation is in meters above mean sea level. b) Depth migrated image overlain with velocity perturbations (changes with respected to a reference velocity model) obtained from full-waveform inversion. Perturbations are expected to broadly reflect the stratigraphic transitions. Wells are labeled, their trajectories are posted and the formation tops are indicated using colored dots following the color code in a).

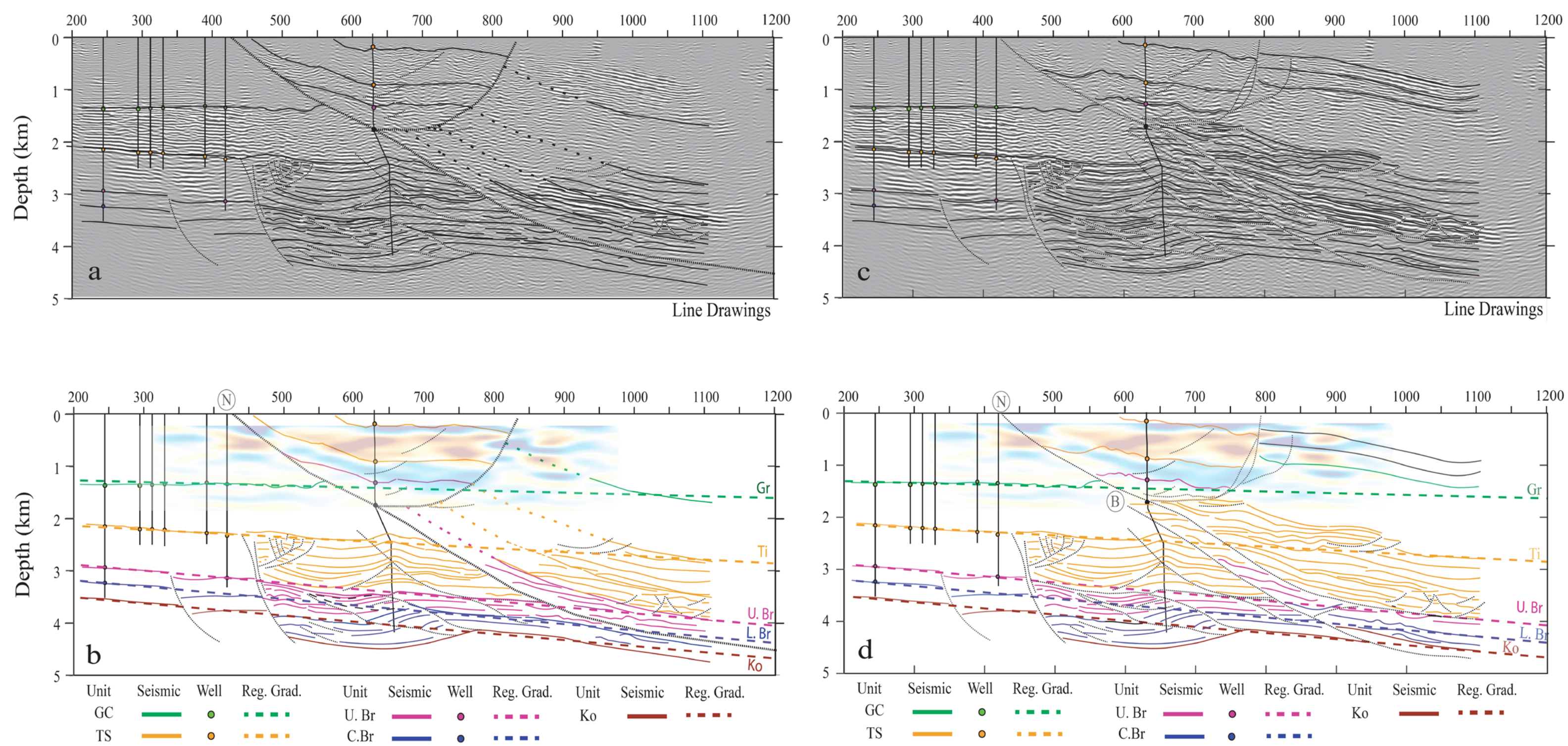

Figure 4 Interpretations. a) and c) are two proposed line drawings of Figure 3b, and b) Interp 1 and d) Interp 2, are the corresponding interpretations. a) and b) are conceived along the lines of the traditional flat-ramp model of the Naga Thrust. Note that this model does not fully honor the reflector geometry of the ramp (dotted lines are model expectations). c) and d), as convinced in this paper, honors the reflector geometry of the ramp and proposes the presence of a blind thrust, the Bally Thrust (B), below the Naga Thrust (N). FWI perturbations model is overlaid in b) and d) to aid interpretation. Symbols and color codes in b) and d) follow Figure 3.

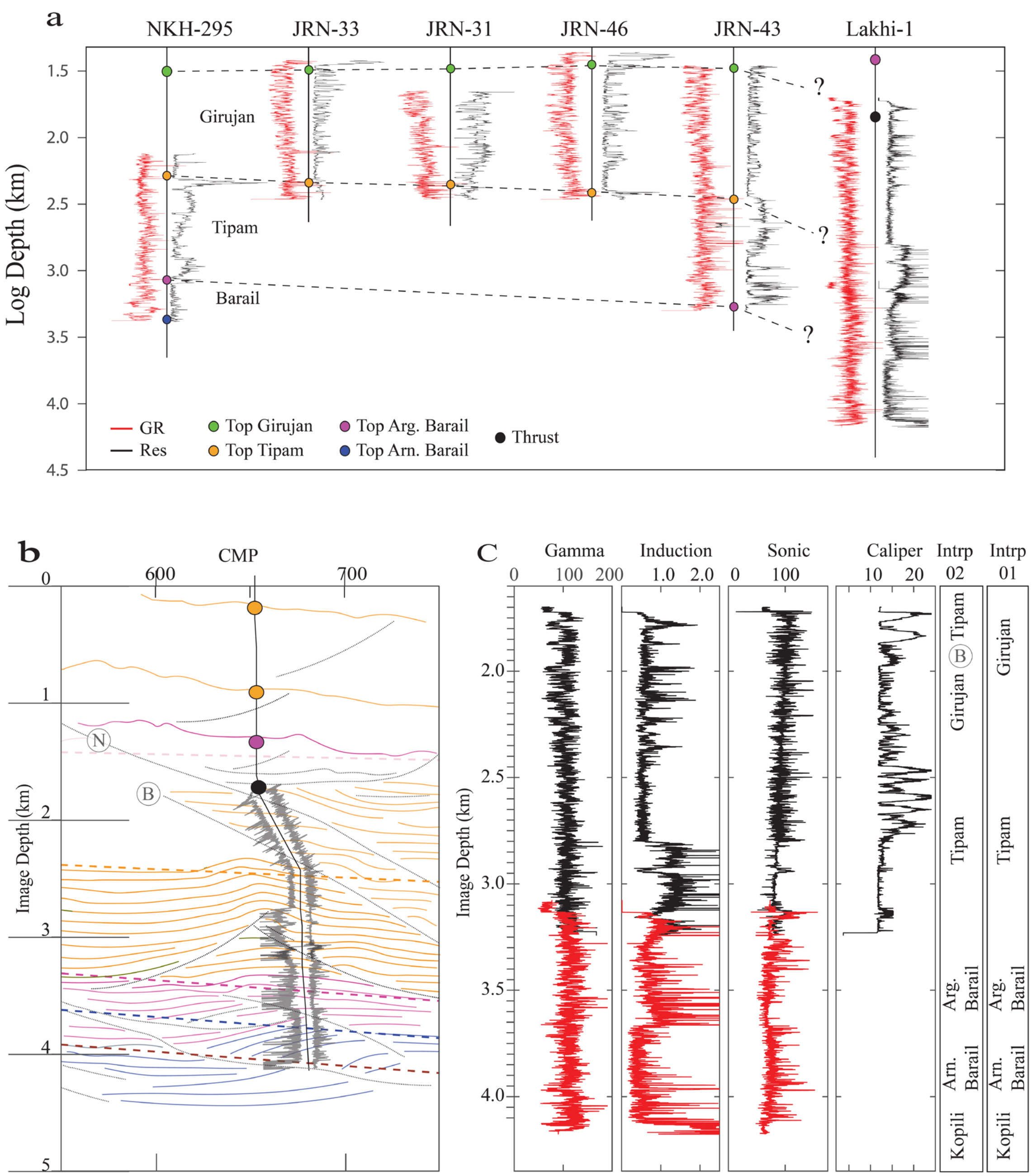

Figure 5 A detailed view of Figure 4c) in the vicinity of the Well Lakhi-1. Deep induction (left) and sonic (right) logs are posted along the well trajectory. Gamma, Deep Induction, Sonic and Caliper logs are independently shown in the image depth-scale. Horizon color codes are from Figure 3. Heavy black lines are major faults. Colored dashed lines are regional dips from Figure 4. Presence of the footwall triangle zone is consistent with both the geometry of the seismic reflectors and the log character.

Well	Formation Top Depth (m)				Total Depth (m)
	Girujan	Tipam	Arg. Barail.	Arn. Barail	
NKH-295	1501	2285	3069	3366	3520
NKH-421	1504	2340	NA	NA	2507
JRN-33	1491	2339	NA	NA	2502
JRN-31	1479	2350	NA	NA	2529
JRN-46	1510	2474	NA	NA	2554
JRN-43	1540	2526	3334	NA	3382

<table>
<tr><th rowspan="2">Lakhi-01</th><th colspan="5">Formation Top Depth (m)</th><th rowspan="2">Total Depth (m)</th></tr>
<tr><th>Girujan</th><th>Tipam</th><th>Arg. Barail.</th><th>Arn. Barail</th><th>Kopili</th></tr>
<tr><td>Supra</td><td>8</td><td>275</td><td>1430</td><td>NA</td><td>NA</td><td rowspan="6">4129</td></tr>
<tr><td colspan="6">Naga Thrust: 1813.72</td></tr>
<tr><td>Sub (Interp01)</td><td>1637</td><td>2315</td><td>3341</td><td>3684</td><td>4028</td></tr>
<tr><td rowspan="3">Sub (Interp02)</td><td></td><td>1637</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Bally Thrust: 1910</td></tr>
<tr><td>1910</td><td>2315</td><td>3341</td><td>3684</td><td>4028</td></tr>
</table>

Table 1 Formation Tops and their true vertical depth below sea surface (TVD). Image Depth = TVD-91

CHAPTER IV

RESTORATIONS

Two structural models (Figures 6 and 7) have been presented for cross-section restoration. Both models have combined geological and seismic data with a geometrically conceivable structural model in the final interpretations. Stratigraphy is projected at the surface to model expected structural geometry. Each model is reconstructed in a step-wise fashion to restore the hanging wall of the Naga Thrust to the footwall in a pre-deformed state. A pin line is assumed at the foreland edge of the profile where the least deformation has occurred. A local line is placed at the hinterland edge of the profile along the hanging wall to provide a reference during the restoration process.

Interp 1

Restoration for Interpretation one is broken into 4 stages (Figure 6 a-c). The initial stage of restoration begins by rotation of the upper-ramp stratigraphy about O and its alignment with the ramp and lower-flat stratigraphy that is retracted along N. Next, the hanging wall stratigraphy retracts along N to obtain alignment with the foreland stratigraphy. N extends outside of the profile to the Southeast and deeper in section in order for the hanging wall to restore to the footwall. Slight unfolding occurs in the final stage of restoration. Restoration of this model results in the hanging wall stratigraphy below regional dip to the South-Southeast and >50% shortening. The model implies that the older thrusts, such as Disang and Margarita (Figure 1), are also likely to have a flat-ramp model. The densely dotted line for the projected stratigraphy indicates the horizon geometry corresponding to the minimum eroded volume required to restore Interpretation one. This results in close to 15% of thickening at the leading edge of N from Lakhi-1.

Interp 2

Restoration of Interpretation two is indicated through several stages (Figure 7 a-c and 8 d-g). The upper-ramp stratigraphy restores as shown with N and M rotating in a clockwise motion before aligning with the stratigraphy on the ramp. As the upper block aligns with the ramp, ramp stratigraphy is un-shearing in response to reverse movements of the upper-ramp block. Figure 7b(v) indicates simple shearing of trailing blocks as they move underneath and uplift the leading blocks. Essentially the reverse motion is applied and mass balance during unshearing of Tipam is maintained by ensuring area (PQT) equals area (QRS). Restoration of the stratigraphy in Figure 7a and 7b also requires rotation of B to balance the mass between B and N. Within the footwall Girujan, this mass can be accounted for by adjusting the top Girujan as indicated by the arrows. The next stages of restoration require retraction and rotation of the upper-ramp block to align the stratigraphy with their counterparts between N and B (Figure 8). Breaking the motion first into a complete retraction and then rotation helps with visualization of the concept. In the field, they are simultaneous; the stratigraphy never descends deeper than N. The eroded Tipam section is completed using a densely dotted line. Figure 8e shows the state of the profile prior to the breaking on N. The densely dotted line is used to complete the eroded Girujan. Note that because the Naga Thrust in this model is on top of Barail, this phase of the restoration mainly extends Tipam. The next step indicates retraction and rotation of the hanging wall stratigraphy along B. Note that because the Bally Thrust in this model is at the base of Barail, this phase of the restoration mainly extends Tipam and Barail. The restoration of the hanging wall is achieved by fault movement within Barail. In this model, the hanging wall stratigraphy is restored at regional dip and contraction in Tipam (>50%) is higher than Barail (<10%).

Evolution Cartoon

An evolution cartoon for Interpretation 2 is presented in Figure 9. The cartoon begins by displaying the Mid_Miocene post-Girujan and pre-collision undeformed state of the profile. Two mini-basins with growth structure in Barail and Tipam are conceived. Both of the bounding normal faults are inverted. The inversion of the Fault B eventually contributes to the formation of the Jaipore Anticline. By Mid-Late Miocene there is thickening of the strata upon the onset of collision. The inception of a tectonic wedge to the southeast is an important observation. Sequentially, the display shows breaking of the Naga Thrust and growth of the tectonic wedge. There is inception of the backthrust fault, M, and rotation of the hanging wall. At this stage, there is strain partitioning between the overlying Tipam and the underlying Barail. This leads to shearing and underthrusting of the ramp Tipam leading to significantly more contraction in Tipam as compared to Barail. The final stage of the cartoon shows the present profile state with B truncated by N. The tectonic wedge to the Southeast ruptures the surface and the main faults are speculated as forming parts of the Margarita-Disang system.

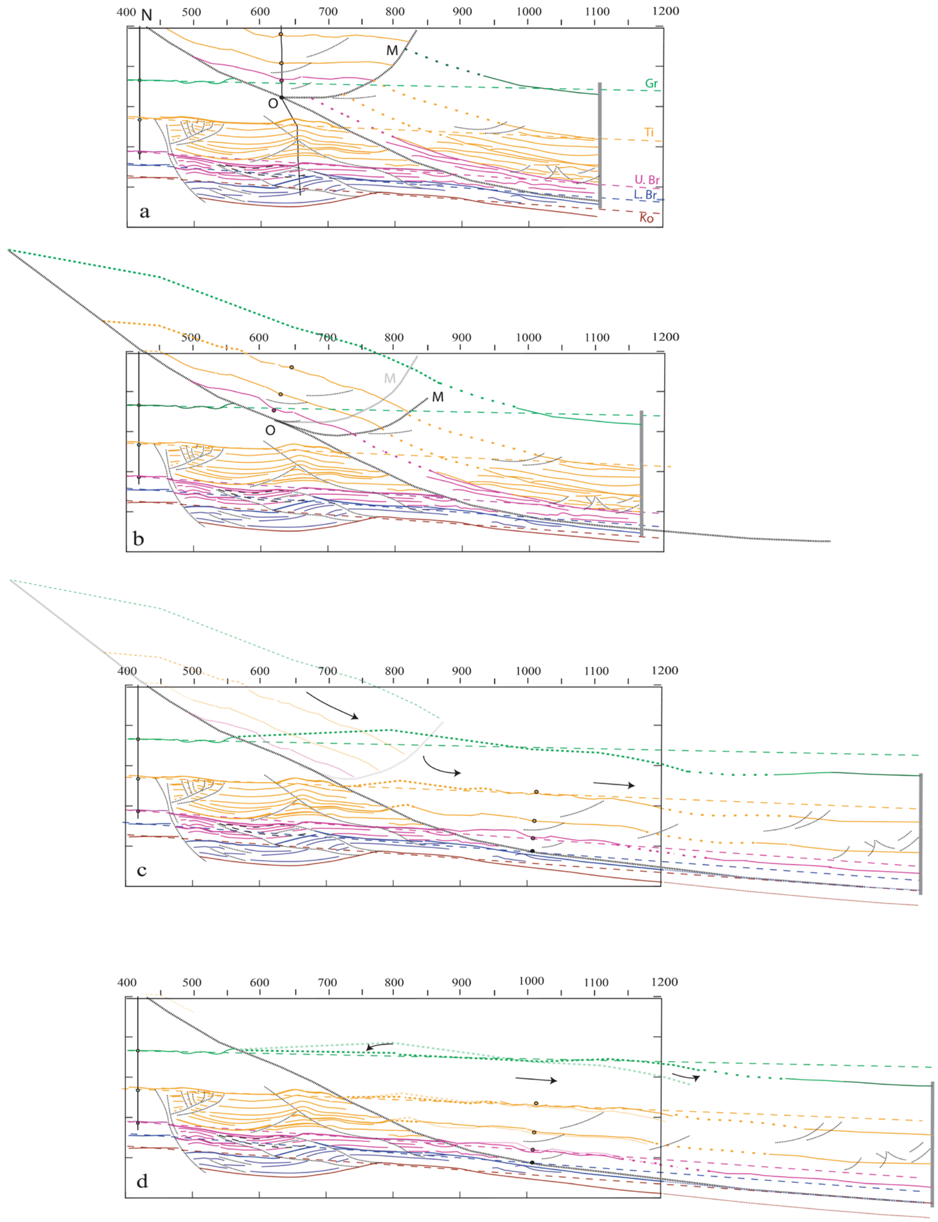

Figure 6 Interp 1 restoration. a) Present profile state (same as Figure 4b). b) Rotation of the upper-ramp stratigraphy about O and its alignment with the ramp and lower-flat stratigraphy that is retracted along N. c) Retraction of the hanging wall stratigraphy along N to obtain alignment with the foreland stratigraphy. Restoration results in the hanging wall stratigraphy below regional dip to the South-Southeast and > 50% shortening. The model implies that the older thrusts, such as Disang and Margarita (Figure 1), are also likely to have a flat-ramp model. In a) – d), the sparsely dotted segments indicate horizon geometry consistent with the flat-ramp concept but not in line with the seismic reflections. Densely dotted line indicate horizon geometry corresponding to the minimum eroded volume required to restore Interp 1.

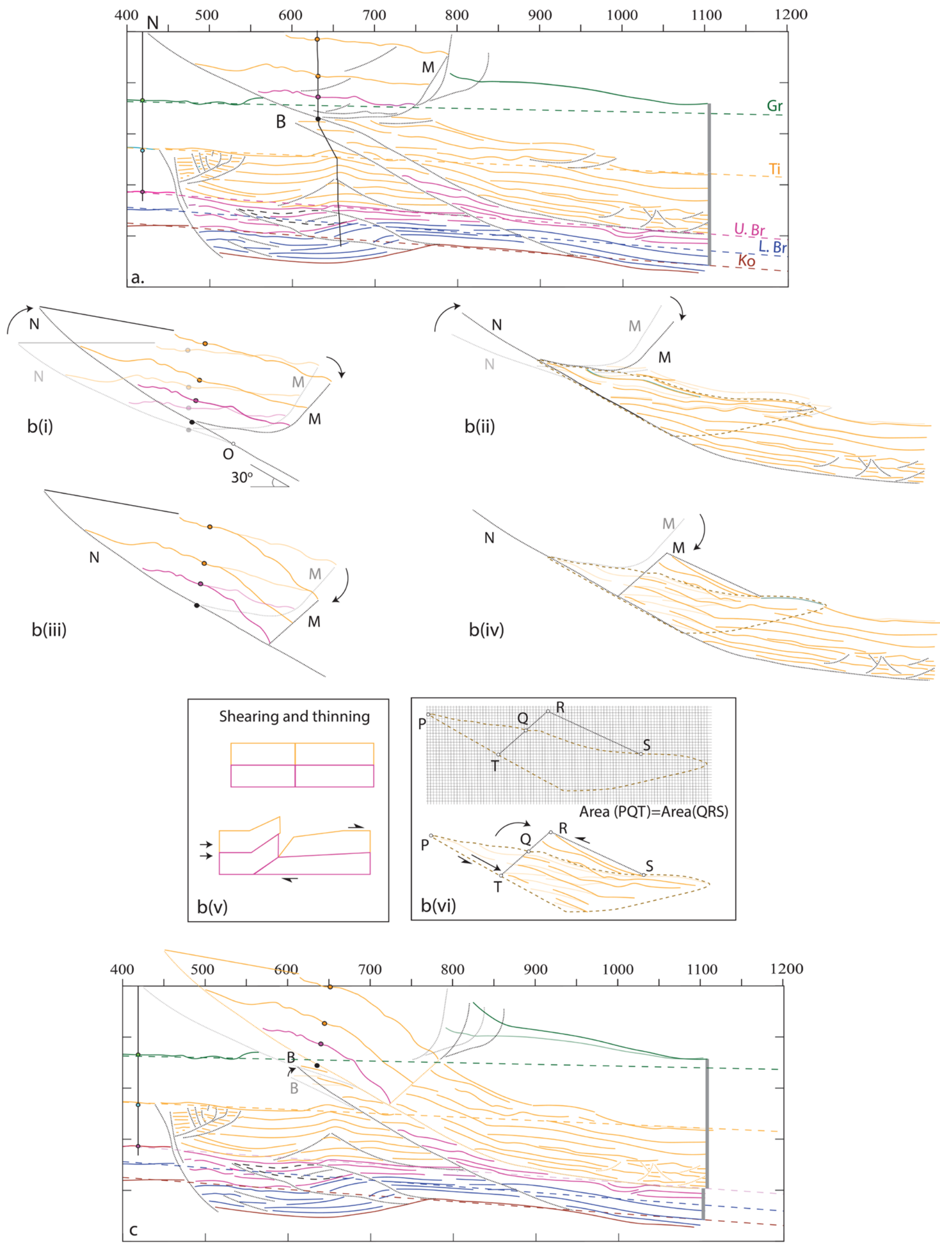

Figure 7 Interp 2 restoration. a) Present profile state (same as Figure 4d). b.i) and b.ii) various stages of the upper-ramp stratigraphy rotation. Arrows indicate the sense of motion for faults N and M. b.iii) and b.iv), various stages of ramp stratigraphy unshearing in response to reverse movements of the upper-ramp block. b.v) Simple shearing of trailing blocks as they move underneath and uplift the leading blocks. b.vi) Mass balance during unshearing of Tipam is maintain by ensuring area(PQT) = area (QRS). c) Restoration of the stratigraphy in a) and b), also requires rotation of B to balance the mass between B and N. Within the footwall Girujan, this mass can be accounted for by adjusting the top Girujan as indicated by the arrows.

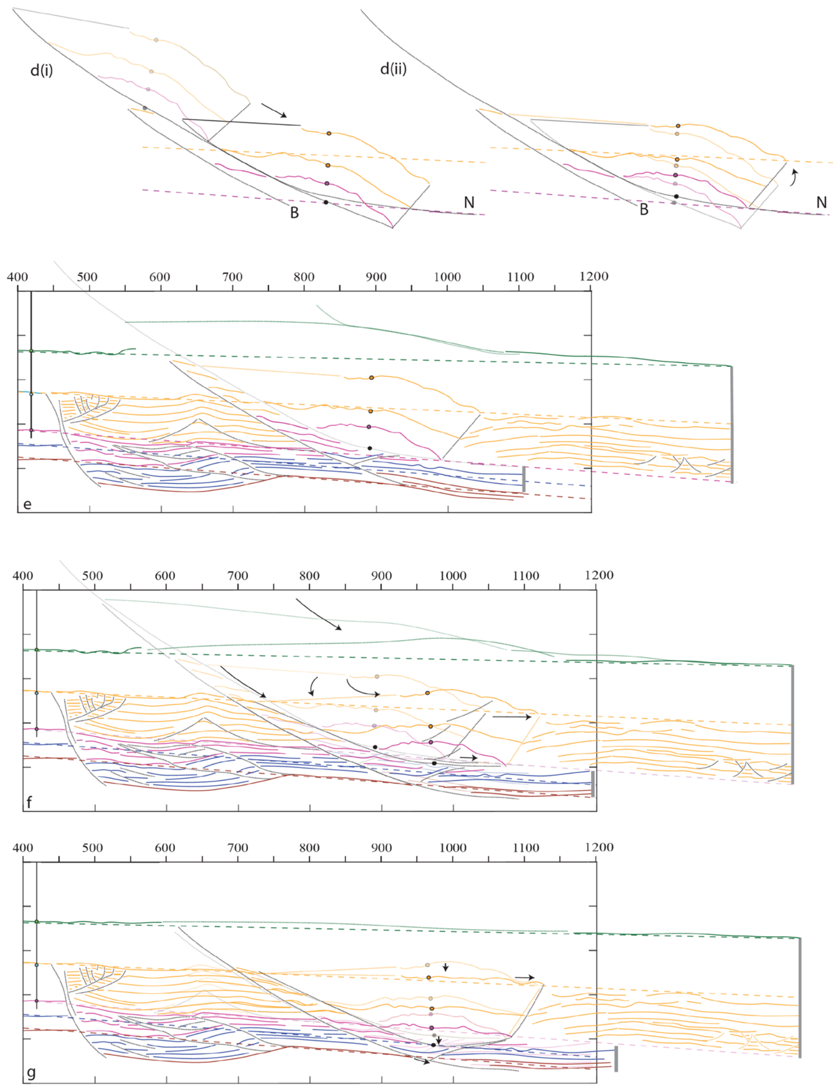

Figure 8 Interp 2 restoration (cont.) d.i) retraction and d.ii) rotation of the upper-ramp block to align the stratigraphy with their counterparts between N and B. Breaking the motion first into a complete retraction and then rotation helps with visualization of the concept. In the field, they are simultaneous; the stratigraphy never descends deeper than N. In d.ii) the eroded Tipam section is completed using a densely dotted line is. e) State of the profile prior to the breaking on N. Densely dotted like is used to complete the eroded Girujan. Note that because the Naga Thrust in this model is on top of Barail, this phase of the restoration mainly extends Tipam. f) retraction and rotation of the hanging wall stratigraphy along B. Note that because the Bally Thrust in this model is at the base of Barail, this phase of the restoration mainly extends Tipam and Barail. g) restoration of the hanging wall fault-bent fold is achieved by fault movement within Barail. In this model, the hanging wall stratigraphy is restored at regional dip and contraction in Tipam (> 50%) is higher than Barail (<10%).

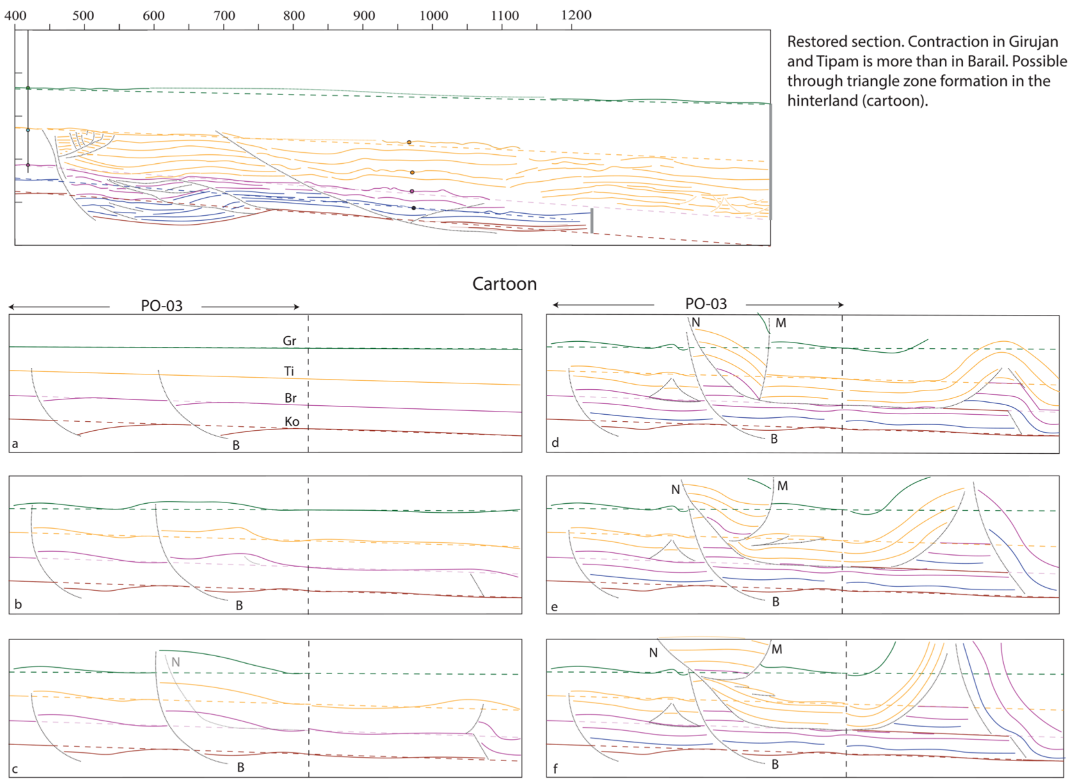

Figure 9 Interp 2 evolution Cartoon. a) Restored section (same as Fig. 8g). b) Mid-Miocene post-Girujan and pre-collision undeformed state of the profile. Two mini-basin with growth structure in Barail and Tipam are conceived. Both the bounding normal faults are inverted. Inversion of the fault B eventually contributes to the formation of the Jaipore Anticline. b) Mid-Late Miocene thickening of the strata upon the onset of collision. Note the inception of a tectonic wedge to the southeast. c) Breaking of the Naga Thrust and growth of the tectonic wedge. d) Inception of the backthrust fault, M, and hanging wall rotation. Strain partitioning between the overlying Tipam and the underlying Barail. e) shearing and under-thrusting of ramp Tipam leading to a significantly more contraction in Tipam as compared to the Barail. f) Present profile state. B is truncated by N. The tectonic wedge to the southeast ruptures the surface and the main faults are speculated forming parts of the Margarita-Disang system.

CHAPTER V

DISCUSSION

The two geometrically valid interpretations along the seismic profile indicate not only the benefits of combining cross-section restoration with improved seismic imaging techniques but increases understanding of the dynamic nature of the Naga Thrust and Fold Belt. Examining the results of the restorations demonstrate that one of these models is more compelling than the other. Both models are restorable however interpretation two aligns more concisely with geological boundary conditions, seismic character and cross-sectional restoration principles.

Interpretation one, while restorable, does not sufficiently integrate all available data. This restoration reconstructs the expected model of a fault propagating fold for the Naga Thrust however in order for this structural model to restore, 3 key conditions are necessary. 1) The interpretation does not honor the seismic reflection character. Deviation from the seismic character along the ramp is necessary to model a fault propagating fold and maintain general thickness from Lakhi -1. 2) Projection of the Girujan formation at the surface results in a thickening toward the thrust from Lakhi-1 along the ramp. The unusual thickening of Girujan is contrary to regional measurements that dictate an increased thickening toward the South-southeast. Well data along the PO-03 profile reflects the regional thickening from foreland to hinterland. 3) The stratigraphy descends deeper than regional dip toward the hinterland. Interpretation one shows the horizons for stratigraphy at regional dip however the decollement and stratigraphy must descend below regional dip outside of the profile in order for the Naga thrust to restore to the footwall. This is inconsistent with regional measurements.

Interpretation two is an admissible restoration that adequately integrates the available data while observing cross-sectional restoration assumptions. The Girujan formation in this restoration does not require unusual thickening along the ramp during the reconstruction. The stratigraphy is also maintained at regional dip in the final stages. Restoration of the sheared section of the ramp validates the thinned interpretation of the Tipam in the seismic imaging. The final restoration including the Bally thrust provides not only the final piece necessary to return the profile to a pre-deformed state but also details the influence of the pre-existing extensional fault system. The half-graben as illustrated in the cartoon (Figure 9) reveals how the blind thrust contributed toward development of the Jaipore anticline and expanded hanging wall stratigraphy proportional to the foreland. The restoration results of this interpretation succinctly tie together seismic imaging with geological boundary conditions to reveal the pre-existing tectonic structural influence on the kinematic evolution of the Naga Thrust.

While the second interpretation better integrates available data, ambiguity around the interpretation of Lakhi-1 immediately below the Naga Thrust remains. Interpretation of datasets in subthrusts are notoriously challenging for both seismic and well logs alike. The primary foreland structural interpretation of this profile is consistent between both models with the immediate distinction through the introduction of the Bally Thrust in interpretation two. Both models show a viable interpretation of the potential subthrust package below the Naga Thrust, one based on the seismic character and the other based on the resistivity signature. The fluid and pressure encountered by Lakhi-1 supports the interpretation of compartmentalized structures for both models. Additional well logs and seismic data within the subthrust region of the Naga Thrust may help to confirm the interpretation of Lakhi-1.

Furthermore, by introducing the Bally Thrust, additional questions remain about the kinematic nature along the Naga Thrust. Interpretation two indicates the rotation of the hanging wall on the upper ramp while the Bally thrust is out-of-sequence from the Thrust Belt. This might imply that the Bally thrust remains fixed in the foreland while the hanging wall block and the Naga thrust are rotating. This out-of-sequence nature is also shown in the evolution cartoon with the shape of the Naga thrust changing over time while the Bally thrust seems to remain fixed (Figure 9f). Both the rotation of the hanging wall and the shape of the Naga Thrust brings into question how this is kinematically possible while the Bally Thrust appears to be stable in the foreland. Considering other structural features in the Upper Assam Shelf indicative of basin inversion, the Bally thrust at the leading edge of the Naga thrust is likely. Extensive and concurrent overthrusting of the Upper Assam shelf has led to flexural extension on both sides of the Assam Valley from load of both the Eurasian and Burma plates. The Nahorkatiya Anticlinorium is an important structural feature demonstrating mild inversion of foreland normal faults west of the Naga Thrust (Kent & Dasgupta, 2004). This feature is not only evidence of basin inversion but may provide some context of structural evolution at the junction of the Naga Thrust and the Jaipore Anticline. The 90-degree clock-wise rotation of this feature marks a transition in the orientation of faults in the Assam Valley and may also mark a transition in the Naga Thrust. Could the rotation of the Nahorkatiya anticlinorium have affected the propagation of the thrust that lies directly above the nose of this feature? Rotation during the propagation of the thrust would lead to an oblique ramp which may explain the change in shape over time of the Naga thrust as illustrated in the evolution cartoon (Figure 9f).

Differential movement along a thrust can also lead to multiple decollements. Analogues of thrust regions in inverted basins show that multiple decollements are associated with higher shortening. Other models along the Naga Thrust indicate increased shortening from Digboi to Jorajan with the highest shortening occurring close to our profile (Saini & Mukhopadhyay, 2018, 2019).The previous model of a fault propagating fold indicates the Barail formation as the decollement for the Naga thrust. While interpretation one modeled a flat-ramp geometry, similar to the prior model, it was necessary to indicate the detachment deeper for a successful restoration. Interpretation two successfully restores the detachment at the Upper Barail; however, an additional detachment is indicated by introduction of the Bally fault. The higher amount of shortening in our study area not only supports a kinematic change along the thrust but indicates that an additional decollement may be present. While more than one structural model may be admissible, boundary conditions confine the plausibility of the results. The second structural model demonstrates the complexity of geometric features associated with the tectonic inversion in this location and the necessary steps to properly validate the interpretation.

This work suggests that imbricate geometry in the subthrust region likely exists along the Naga thrust trending north and south of Jorajan field. Compartmentalization may also be present within the Bally Thrust strata. Hydrocarbon potential in this area is likely. Oil stained sandstone exists in the outcrop along the Naga thrust between Digboi and Jorajan fields indicating that any structures in the hanging wall had the potential to be charged (Kent et al, 2002). Likewise subthrust structures were potentially charged as they existed in the overall migration pathway that moved from south to north. Many productive fields exist in the foreland, in particular, Jorajan field which does not have wells penetrating into these subthrust structures along the PO-03 line. The Girujan formation is an effective regional seal that is present over the imbricate structures under the suprathrust. The imbricate thrusts are primarily composed of the Tipam sandstone indicating reservoir potential. Each imbricate thrust is a potentially compartmentalized reservoir as well as the triangle zone. Lateral closure is a key component to reducing risk. Closure may exist for the subthrust imbricates to the northeast by the Assam Railroad tear fault.

Structural evolution of the Naga thrust hanging wall may provide additional prospects southwest of Digboi field. Anticlinal traps are limited due to tight folds and eroded beds. The hanging wall geometry of the second structural model reveals a possible reservoir beneath the rotated block. The adjacent fault to M on the rotated block terminates below the Dhekiajuli formation providing potential closure. The argillaceous nature of the sandstone and clay beds provide a potential seal. If lateral closure also exists at the Assam Railway normal fault and tear fault, then reserve estimates could be equal or greater than those of Digboi field. Further assessment of rotated block geometry lateral extent may prove accumulations. Proper identification and reconstruction of inverted structural geometries benefit exploration in complex structural histories as demonstrated with this interpretation indicating multiple new potential prospects.

CHAPTER VI

CONCLUSIONS

Integration of improved high-quality imaging with restoration balancing methods revealed a new model which does not view the Naga Thrust only as a fault propagation fold. This model introduces another thrust fault, the Bally Thrust, below the Naga Thrust. The introduction of the Bally thrust accounts for inversion of a pre-existing extensional fault system which in turn allow balancing. Introduction of shearing of the ramp for the Naga Thrust is also a new concept for this area. These results indicate a change in structural style and kinematics along the Naga Thrust. Likewise, the pre-existing extensional fault system in the Assam Valley contributed to this change in fault kinematics along the strike of the Naga thrust belt southwest of the Assam Railway Tear fault. Additionally, this work emphasizes seismic interpretation using integrated traditional and non-traditional seismic processing and cross-section structural methods and kinematic restoration does provide insight into hydrocarbon exploration of this area for the Naga Thrust and Fold Belt.

REFERENCES

Alvarez-Marron, J., & K. R. Mcclay. (1993). Geometry and Evolution of the Frontal Part of the Magallanes Foreland Thrust and Fold Belt (Vicuna Area), Tierra del Fuego, Southern Chile. AAPG Bulletin, 77. doi:10.1306/bdff8f74-1718-11d7-8645000102c1865d

Bally, A. W., Gordy, P. L., & Stewart, G. A. (1966) Structure, Seismic Data, and Orogenic Evolution of Southern Canadian Rock Mountains. Bulletin of Canadian Petroleum Geology, 14(3), 337-381.

Bhandari, L. L., & Fuloria, R. C., (1973). Stratigraphy of Assam Valley, India. *AAPG Bulletin, 57*. doi:10.1306/819a4310-16c5-11d7-8645000102c1865d

Bond, C. E., Gibbs, A. D., Shipton, Z. K., & Jones, S. (2007). What do you think this is?``Conceptual uncertainty"in geoscience interpretation. GSA today, 17(11), 4.

Bonini, M. (2003). Detachment folding, fold amplification, and diapirism in thrust wedge experiments. Tectonics, 22(6). doi:10.1029/2002tc001458

Boyer, S. E., & Elliott, D. (1982). Thrust Systems. AAPG Bulletin, 66. doi:10.1306/03b5a77d-16d1-11d7-8645000102c1865d

Butler, R. W. (1987). Thrust sequences. *Journal of the Geological Society, 144*(4), 619-634. doi:10.1144/gsjgs.144.4.0619

Carey, S. W. (1962). Folding. Bulletin of Canadian Petroleum Geology, 10(3), 95-144.

Cole, F., Bird, K. J., Mull, C. G., Wallace, W. K., Sassi, W., Murphy, J. M., & Lee, M. (1999). A balanced cross section and kinematic and thermal model across the northeastern Brooks Range mountain front, Arctic National Wildlife Refuge, Alaska. ANWR Assessment Team, The oil and gas resource potential of the 1002 area, Arctic National Wildlife Refuge, Alaska: US Geological Survey Open-File Report, 98, 34-60.

Dahlstrom, C. D. (1969). Balanced cross sections. Canadian Journal of Earth Sciences, 6(4), 743-757. doi:10.1139/e69-069

Davis, D. M., & Lillie, R. J. (1994). Changing mechanical response during continental collision: Active examples from the foreland thrust belts of Pakistan. Journal of Structural Geology, 16(1), 21-34. doi:10.1016/0191-8141(94)90015-9

Diehl, S., Anderson, R. E., & Humphrey, J. (2010). Fluid flow, solution collapse, and massive dissolution at detachment faults, Mormon Mountains, Nevada. Miocene Tectonics of the Lake Mead Region, Central Basin and Range. doi:10.1130/2010.2463(19)

Dikshit, K. R., & Dikshit, J. K. (2014). North-east India: Land, people and economy. Dordrecht: Springer. doi:10.1007/978-94-007-7055-3

Goguel, J. (1952). Tectonics (English trans.). Freeman and Company, San Francisco, 384 pp.

Hesthammer, J. (1999). Improving seismic data for detailed structural interpretation. The Leading Edge, 18(2), 226-247. doi:10.1190/1.1438262

Herron, D. (2009). Interpreting depth-imaged data: Case studies, examples, and pitfalls from the interpreters' perspective. The Leading Edge, 28(3), 364-367.

Hunt, C. W. (1957). Planimetric equation. Bulletin of Canadian Petroleum Geology, 5(11), 259-264.

Improta, L., Zollo, A., Herrero, A., Frattini, R., Virieux, J., & Dell'Aversana, P. (2002). Seismic imaging of complex structures by non-linear traveltime inversion of dense wide-angle data: application to a thrust belt. Geophysical Journal International, 151(1), 264-278.

Dahlstrom, C. D. (1969). Balanced cross sections. Canadian Journal of Earth Sciences, 6(4), 743-757. doi:10.1139/e69-069

Jaiswal, P., & Zelt, C. A. (2008). Unified imaging of multichannel seismic data: Combining traveltime inversion and prestack depth migration. Geophysics, 73(5). doi:10.1190/1.2957761

Kent, W., & Dasgupta, U. (2004). Structural evolution in response to fold and thrust belt tectonics in northern Assam. A key to hydrocarbon exploration in the Jaipur anticline area. *Marine and Petroleum Geology, 21*(7), 785-803. doi:10.1016/j.marpetgeo.2003.12.006

Kent, W. N., Hickman, R. G., & Dasgupta, U. (2002). Application of a ramp/flat fault model to interpretation of the Naga thrust and possible implications for petroleum exploration along the Naga thrust front. AAPG Bulletin, 86(12), 2023-2045

Kumar, T., (2011). Basement configuration and structural style in OIL's operational areas of Upper Assam. Conference GeoIndia-2011.

Letouzey, J. (1990). Fault reactivation, inversion and fold-thrust belt. *Petroleum and tectonics in mobile belts*, 101-128.

Malz, A., Madritsch, H., & Kley, J. (2015). Improving 2D seismic interpretation in challenging settings by integration of restoration techniques: A case study from the Jura fold-and-thrust belt (Switzerland). *Interpretation, 3*(4). doi:10.1190/int-2015-0012.1

Mathur, L. P., & Evans, P., 1964, Oil in India: 22nd Session International Geological Congress Proceedings, p. 7-52.

Mathur, N., Raju, S. V., & Kulkarni, T. G. (2001). Improved identification of pay zones through integration of geochemical and log data: A case study from Upper Assam basin, India. AAPG bulletin, 85(2), 309-323. doi: 10.1306/8626C7CB-173B-11D7-8645000102C1865D

Mason, R. (1997). Structure of the Alice anticline, Papua New Guinea: Serial balanced cross-sections and their restoration. *Journal of Structural Geology, 19*(5), 719-734. doi:10.1016/s0191-8141(96)00114-9

Mcclay, K. R., & Buchanan, P. G. (1992). Thrust faults in inverted extensional basins. Thrust Tectonics, 93-104. doi:10.1007/978-94-011-3066-0_8

Mcquarrie, N. (2004). Crustal scale geometry of the Zagros fold–thrust belt, Iran. *Journal of Structural Geology, 26*(3), 519-535. doi:10.1016/j.jsg.2003.08.009

Mitra, S. (1990). Fault Propagation Folds: Geometry, Kinematic Evolution, and Hydrocarbon Traps: ABSTRACT. *AAPG Bulletin, 74*. doi:10.1306/44b4b680-170a-11d7-8645000102c1865d

Mouthereau, F., Lacombe, O., Deffontaines, B., Angelier, J., & Brusset, S. (2001). Deformation history of the southwestern Taiwan foreland thrust belt: Insights from tectono-sedimentary analyses and balanced cross-sections. *Tectonophysics, 333*(1-2), 293-322. doi:10.1016/s0040-1951(00)00280-8

Mukhopadhyay, D. K., & Mishra, P. (2005). A balanced cross section across the Himalayan frontal fold-thrust belt, Subathu area, Himachal Pradesh, India: Thrust sequence, structural evolution and shortening. *Journal of Asian Earth Sciences, 25*(5), 735-746. doi:10.1016/j.jseaes.2004.07.007

Nemčok, M., Schamel, S., & Gayer, R. (2009). *Thrustbelts: Structural architecture, thermal regimes and petroleum systems*. Cambridge: Cambridge University Press.

Operto, S., Ravaut, C., Improta, L., Virieux, J., Herrero, A., & Dellaversana, P. (2004). Quantitative imaging of complex structures from dense wide-aperture seismic data by multiscale traveltime and waveform inversions: A case study. *Geophysical Prospecting, 52*(6), 625-651. doi:10.1111/j.1365-2478.2004.00452.x

Pennock, E. S., & Li, R. J., (1989). Structural Interpretation of Seismic Reflection Data from Eastern Salt Range and Potwar Plateau, Pakistan. *AAPG Bulletin, 73*. doi:10.1306/44b4a27b-170a-11d7-8645000102c1865d

Ravaut, C., Operto, S., Improta, L., Virieux, J., Herrero, A., & Dellaversana, P. (2004). Multiscale imaging of complex structures from multifold wide-aperture seismic data by frequency-domain full-waveform tomography: Application to a thrust belt. *Geophysical Journal International, 159*(3), 1032-1056. doi:10.1111/j.1365-246x.2004.02442.x

Richards, D., Calvert, S., & Yamamoto, H. (2003). 2D And 3D Structural Balancing In A Deformed Foreland Basin, Peruvian Subandean Belt. *8th Simposio Bolivariano - Exploracion Petrolera En Las Cuencas Subandinas*. doi:10.3997/2214-4609-pdb.33.paper16

Saini, D. P. M., & Mukhopadhyay, D. K. (2018). Structural Geometry Across India’s Oldest and Still Producing Digboi Oil Field, North-east India. AGU Fall Meeting Abstracts. T41E-0351

Saini, D. P. M., & Mukhopadhyay, D. K. (2019). Balanced Structural Geometry of India's Oldest and Still Producing Digboi Oil Field, North-East India. EGU General Assembly Conference Abstracts. 2019EGUGA..21..388S

Spikings, A. L., Hodgson, D. M., Paton, D. A., & Spychala, Y. T. (2015). Palinspastic restoration of an exhumed deepwater system: A workflow to improve paleogeographic reconstructions. Interpretation, 3(4). doi:10.1190/int-2015-0015.1

Sitchler, J. C., Fisher, D. M., Gardner, T. W., & Protti, M. (2007). Constraints on inner forearc deformation from balanced cross sections, Fila Costeña thrust belt, Costa Rica. Tectonics, 26(6). doi:10.1029/2006tc001949

Suppe, J., & Medwedeff, D. A. (1990). Geometry and kinematics of fault-propagation folding. Eclogae Geologicae Helvetiae, 83(3), 409-454.

Wandrey, C. J. (2004). Sylhet-Kopili/Barail-Tipam composite total petroleum system, Assam geologic province, India. US Department of the Interior, US Geological Survey.

Woodward, N. B., Boyer, S. E., & Suppe, J. (1989). Balanced Geological Cross-Sections: An Essential Technique in Geological Research and Exploration. doi:10.1029/sc006

Wren, A. E., & Jain, S. (1978) The Application of Inversion to Seismic Interpretation Problems in the Foothills. CSEG Journal, 14(1),66-71.

VITA

Brandy Bridgett Michael

Candidate for the Degree of

Master of Science

Thesis: THE NATURE OF THE NAGA THRUST AND FOLD BELT, ASSAM SHELF, INDIA: INSIGHTS FROM CROSS-SECTIONAL BALANCING

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in May, 2021

Completed the requirements for the Bachelor of Science in Geology at Oklahoma State University, Oklahoma in 2011.

Experience:

Seismic Research Assistant, Dr. Priyank Jaiswal (2010)
Physical Geology Lab Instructor, Oklahoma State University (2010-2012)
Geophysical Intern, Nexxen Petroleum Inc, USA (Summer, 2012)
Geophysicist, SM Energy (2014 – 2019)

Professional Memberships:

Society of Exploration Geophysicists (SEG)
American Association of Petroleum Geologists (AAPG)
Geological Society of America (GSA)