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Subsurface Paleo-Stream Reach Reconstruction and Classification Using Seismic Data Interpretation

Benjamin Ward Dotson

**Thesis submitted to the
Eberly College of Arts and Sciences
at West Virginia University
in partial fulfillment of the requirements
for the degree of
Master of Science
in
Geology**

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ABSTRACT

Subsurface Paleo-Stream Reach Reconstruction and Classification Using Seismic Data Interpretation

Benjamin Ward Dotson

Incorporating the techniques and applications used in the 3D seismic geophysical interpretations with the Rosgen (1996) stream classification, this study was able to identify paleo-stream reaches in the Frio Formation within the Stratton 3D seismic data set. Hydraulic geometry variables from Rosgen's classification scheme were used to classify paleo-stream reaches shown in the seismic data. Estimated paleo-discharges were reconstructed to compare the potential magnitude of flow in the paleo-stream reaches to that in modern rivers in Texas and Mississippi. However, classification and discharge results were accompanied with a high margin of error and many uncertainties regarding the stream channel's geometry and features.

Dedication and Acknowledgements

I would like to dedicate this thesis research to my parents, Susan and D. Lyn Dotson, and my fiancée, Kelly Bryant, for their tireless effort and support to help me finish this thesis project.

I would also like to thank my thesis committee for supporting me in this thesis project. Also, I greatly appreciate the advice I received from Albert Babarsky, who helped me to maximize Petrel's capacities and better understand geophysics. Finally, I would like to thank my adviser, Dr. Steve Kite, for introducing me to the fascinating world of geology when I was a freshman in Geology 101 and then encouraging me to apply for and earn my Masters in Geology from West Virginia University.

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Introduction

While seismic data has long been regarded as a tool for finding hydrocarbon traps and subsurface faults, in the last decade other applications have emerged. Now, with the increase in high definition, 3D seismic data and seismic interpretation software, geologists and geophysicists are able to use 3D seismic data for applications related to paleo-geomorphology, including paleo-stream reconstruction and classification.

In contrast, stream classification has been restrained largely to present-day surface topography. This limitation has resulted in stream classification being overlooked as a tool in reconstructing depositional landscapes, which might otherwise lead to better understanding of hydrocarbon reservoirs. Therefore, this research has attempted to show that seismic data interpretations can be used to classify a subsurface paleo-stream reach.

To address the goals of reconstructing and classifying a paleo-stream reach in the subsurface, the research study combined the use of Petrel 2010.2, a 3D seismic modeling and interpretation software, and stream classification schemes to (1) measure paleo-stream sinuosity, width: depth ratio, entrenchment ratio, and bankfull cross sectional area, (2) reconstruct the paleo-stream reach's dominant bankfull discharge, (3) assign a Rosgen classification paleo-stream reach type, and (4) construct stream cross sections that will aid in reconstruction of the paleo-stream's depositional environment. The goal to classify paleo-stream reaches in seismic surveys was shown to be possible, but the study was accompanied by analysis of stream margins and significant uncertainties regarding stream channel geometry and features.

Geologic Setting

The Stratton Field 3D seismic data set used for this project was recorded in the Kleberg and Nueces counties in South Texas over an 8.8 km² (3.4 mi²) survey (Figures 1 & 2) (Hardage *et al.*, 1994). The major hydrocarbon-producing zone in the Stratton field is the Frio Formation. A progradational

Figure 1- Map of Texas highlights the Vicksburg Fault Zone, which underlies the Frio Formation. The Stratton- Agua Dulce field is shown in the northern section of the shaded area (Figured from Hardage et al. 1994, used with author's permission).

wedge containing both marine and nonmarine sands and shales, the Frio Formation is Oligocene-Miocene in age and is considered to have formed on a coastal plain (Galloway *et al.*, 1982) (Figure 3). The Frio Formation includes multiple fluvial units within deltaic systems built into the paleo-Gulf of Mexico (Galloway *et al.*, 1982) (El-Mowafy; Marfurt 2008).

Figure 2 – Map of the Stratton field. Map includes the seismic grid and wells drilled in the area. (Figured from Hardage et al. 1994, used with author's permission.)

Figure 3- Paleo-geographic map of North America in the Oligocene epoch. Locations shown are approximate. (Figure modified from Blakey, 2011, used with author's permission)

Previous Studies

The process of paleo-stream channel classification was previously applied to seismic data from offshore New Jersey to map out and classify the stream within a Pleistocene incised valley. By using a high resolution 3D seismic survey, Nordfjord *et al.* (2005) accurately assigned the stream as a type “D” braided stream in the Rosgen (1996) stream classification scheme, which is characteristic of stream reach containing a large amount of sediment stored in braided channels (Figure 4). Although their study stream was at a shallow depth of 10 m (32 ft), the Nordfjord *et al.* (2005) study provides a model for the process of sub-surface stream channel classification.

Other geologists have been able to use geophysical tools to measure some of the required classification dimensions in deeper strata. In the Widuri and Java fields, Carter (2005) was able to measure meander wavelength, sinuosity, and width of fluvial channel sands at depths of ~1000 m

(3280 ft). These measurements are essential to classifying stream reaches using the Rosgen (1994) stream classification.

Figure 4- Diagram of the Rosgen classification types from U. S. Department of Agriculture (2007). Figure shows the Level I characteristics used in the Rosgen (1994) stream classification system.

Although not a requirement for the Rosgen (1994) stream classification, the dominant discharge of a stream is an important variable in finding modern analogs to paleo-stream reaches. While the discharge in a stream will vary with time, the most effective discharge in terms of sediment transport, or dominant discharge, occurs on average once every one to three years (Wolman; Miller 1960). This discharge is represented by the bankfull stage, the level at which the flow fills the entire channel up to the stream channel's natural bank. Furthermore, bankfull discharge can be estimated by the determining the capacity of a paleo-stream channel's dimensions (Knox, 1987).

One approach used to estimate dominant discharge is based on measuring the stream's water surface height from satellite images (Xu *et al.*, 2004). This concept was tested on the Yangtze River, People's Republic of China, where the known channel geometry was paired with the momentary water surface height as determined from the surface width of the stream at the exact time when the satellite image was made. The satellite derived water-surface height and stream geometry were combined with the Manning equation to ultimately determine the stream discharge at that specific water height (Xu *et al.*, 2004). Although those data were based on satellite imaging, the seismic cross sections used in this study were used to render analogous channel geometry information and provided a similar methodology and process to that employed in this study.

In another study of the Frio Formation in the Stratton Field data set, Hardage *et al.* (1994) looked at the fluvial deposits for the compartmentalization of hydrocarbons in channel sands. While compartmentalization of hydrocarbons is not directly relevant to stream classification, the identification of narrow, meandering paleo-stream channels at depths below 1828 m (6,000 ft) using 3D seismic data analysis is an important stimulus to this research. Hardage *et al.* (1994) showed multiple stacked steam channel deposits, as well as other fluvial features such as splays and floodplains (Figure 5).

Figure 5 – Image representing a smoothed image based on seismic imaging. Three streams (A, B, and C) are shown in different shades. Image shows that stream channels in the subsurface can have defined margins (Figured from Hardage et al. 1994, used with author's permission.).

While Hardage *et al.* (1994) focused on compartmentalization of stream channels using seismic data, other geologists and geophysicists have directed work toward determining the best attributes for identifying stream channels in seismic data sets. Liu and Marfurt (2007) determined that coherence and edge sensitive attributes are the most accurate attributes for determining the width of paleo-stream channels, but they advocated the use of spectral decomposition (an attribute similar to iso-frequency in Petrel 2010.2) for determining paleo-stream channel deposit thickness, a possible proxy for channel depth. Therefore, their study advocated the combined use of coherence and spectral decomposition to identify paleo-stream channels (Liu; Marfurt 2007) and provided a guide to determine which seismic attributes were relevant in this research.

Rosgen Stream Classification

Stream classification is an evolving field used extensively in stream restoration (U.S. Department of Agriculture, 2007). The process of stream classification is generally constrained to surface streams, since most classification systems require measurements relate to width: depth ratio, sinuosity, and stream gradient, none of which can be determined readily from log analysis or outcrop data. Seismic data allows delineation of paleo-stream pathways in all dimensions which log and outcrop lack (Figure 4).

The most frequently used stream classification scheme was created by David Rosgen (1994; 1996) for proposes related to stream restoration. The Rosgen system has been adopted by many federal and state government agencies for stream restoration work, becoming the *de facto* classification scheme of choice among many practitioners (U.S. Department of Agriculture, 2007).

The Rosgen (1996) classification system is a form-oriented system rather than a process-oriented system. Using the Rosgen system to definitively classify a stream reach, which is a stream length with relatively uniform properties equal to at least twenty times the bankfull stream width

(Rosgen, 1994 p.184), the geomorphologist must work through a four-level process with each level becoming more detailed. For the thesis study, only Level I (Geomorphic Characterization) and Level II (Morphological Description) were applied. The final two levels of Rosgen analysis require measurements that cannot be determined using 3D seismic data.

Level I classification in the Rosgen (1996) system allows for an overall understanding of the watershed basin, as well as the drainage pattern, for the selected stream reach. This classification assesses whether the reach is a single channel or multiple, braided or anastomosing channels. Furthermore, the stream reach is differentiated by shape: whether it is a narrow and deep channel, or a wide and shallow channel. From these data, a stream reach is given a provisional classification type of "A" through "G", which can be altered later in the classification process (Figure 4).

Focusing on morphological descriptions, the Level II step uses measurements to further classify the stream channel into a specific category. The required variables for this level are entrenchment ratio, width: depth ratio, sinuosity, and slope (Rosgen, 1996). The texture of channel sediments is also considered. Entrenchment ratio is defined as the width of the flood-prone area divided by the bankfull width (Rosgen, 1994). The flood-prone area, according to Rosgen (1996), is calculated by multiplying the maximum bankfull depth by two, and measuring the width of

floodplain inundation at that flow depth (Figure 6).

Figure 6- Diagram from Natural Resources Conservation Service (2007) showing various levels of entrenchment as indicted in the Rosgen (1994) classification scheme. Entrenchment ratio relates the width of the flood-prone area to bank full channel width.

Once these variables have been measured or calculated, a Level II decision tree (Figure 7) is used to attach letter and number designation to the stream. Possible classification types range from “A1-A6” through “G1-G6” (Rosgen, 1996). The number in the classification designation is based on dominant channel material, bedrock through silt and clay, in the stream channel (Rosgen, 1996).

Figure 7 – Rosgen (1994) Levels I and II stream classification. Text at bottom of the figure indicates the subjective overlap in channel dimension values allowed in assigning stream classes (U. S. Department of Agriculture, 2007).

Methodology

Stratton 3D Seismic Data

The Stratton 3D seismic survey is an 8.8 km² (3.4 mi²), public-domain data set acquired in 1992 by the Texas Bureau of Economic Geology (BEG) at the University of Texas at Austin. Mercury International Technology Company in Tulsa, Oklahoma, processed the data set. The Stratton 3D survey has been used as a template for many published papers and serves as one of the training data sets used by faculty at West Virginia University when teaching geophysics and geology. This data set can be purchased at the BEG website (<http://begstore.beg.utexas.edu/store/cd-rom-sets/1309-sw0003.html>) for a nominal fee.

Petrel 2010.2 Software and Computer Hardware

Petrel 2010.2, produced by Schlumberger Limited, is a 64-bit seismic, analysis software designed for Microsoft's Windows 7 operating system. Petrel 2010.2 provides both 2D and 3D viewing and interpretation, a suite of seismic attributes, as well as integration of well information. The software license was donated to West Virginia University by Schlumberger. Other software used in this research were Microsoft Office Excel 2007 for Microsoft's Windows 7, Microsoft Office Word 2007 for Microsoft's Windows 7, and Microsoft Office Word 2008 for Apple's OS Lion. All research was completed at the Department of Geology and Geography at West Virginia University at Morgantown using a Dell Optiplex 780, computer number 425-26.

Seismic Attributes

Variance (edge method) is a patented attribute (Van Bemmelen *et al.*, 1999) that isolates edges in geophysical data. By isolating edges, the attribute identifies discontinuities in the horizontal continuity of amplitude (Daber *et al.*, 2007). Useful in identifying faults in the subsurface, variance is also commonly used to identify discrete stratigraphic features such as reefs, channels, and splays (Daber *et al.*, 2007; Hart, 2008). The variance attribute can be vertically smoothed, limiting the amount of noise in the image (Daber *et al.*, 2007).

While differing in the signal processing technique and method, variance is similar in purpose and outcome to the attribute coherency, which is the industry standard in edge-detection attributes but not present in the Petrel 2010.2 attribute suite. The difference is that coherency first highlights similarities and then highlights dissimilarities, whereas variance compares differences from a mean value (Bahorich; Farmer, 1995; Daber *et al.* 2007). Additionally, coherency uses the extra step of trace-to-trace cross correlation before averaging the differences in intervals (Daber *et al.*, 2007).

Similar to spectral decomposition, iso-frequency is used to isolate a specific frequency designated by the user. By using a cosine correlation transform to calculate a value based on the similarity to the designated frequency chosen by the user, iso-frequency allows the user to view stratigraphic features not visible in normal amplitude view (Daber *et al.*, 2007). Iso-frequency and spectral decomposition are especially designed to see thin beds, which dominate most subsurface, stream channel deposits. For this research, frequencies of 20Hz, 30Hz, and 40Hz were used because those frequencies provided sharp images of stream channels in the early exploratory phases of the research. Furthermore, spectral decomposition is considered to be one of the better attributes for viewing stream channels in a seismic survey and iso-frequency fills that role in Petrel 2010.2 (Liu; Manfurt, 2007).

Instantaneous frequency was the most useful attribute for creating stream channel cross sections. The attribute measures the rate of change of the instantaneous phase although it is independent of phase and amplitude (Daber *et al.*, 2007). The attribute is best used for determining rock properties relating to hydrocarbon, fracture zones, and thickness and lateral changes in lithology (Daber *et al.*, 2007). Lateral lithology changes were critical for this thesis study because the channel fill and the stream banks in the Stratton Field were known to be composed of different lithologies (Figure 8).

Figure 8- 2D view of alpha stream, cross section X=2187508, in instantaneous frequency. White arrow showing sandstone channel fill and the black arrow showing shale layer. Image generated in Petrel 2012.2.

Another edge detection attribute, dip deviation, is designed to highlight distinct changes in the orientation of the reflector beds in the seismic horizon (Daber *et al.*, 2007). These changes in dip could represent a stream channel where the dip angles of beds within a channel fill differ from surrounding rock layers. The dip deviation attribute works by comparing a smooth estimation of local dip generated from a large multi-trace operator to the localized dip estimation from the neighboring traces (Daber *et al.*, 2007). To add accuracy, the user can set the minimum dip difference allowing for an image with less noise.

The first derivative signal processing attribute is useful for stratigraphic analysis as well as facies estimation (Daber *et al.*, 2007). The attribute is defined as the time rate of change in the input trace (Daber *et al.*, 2007). First derivative can be used to determine a horizontal well placement (Daber *et al.*, 2007).

Gradient magnitude uses the same algorithm used for the first derivative, but applies it to all three axis planes (inline, cross line, and z-plane) (Daber *et al.*, 2007). Daber *et al.* (2007) described the attribute as helpful in discriminating regions of weak coherent signals from those with significant reflectivity and signal strength.

RMS (root mean squared) amplitude was the last seismic attribute used in the study. Daber *et al.* (2007) stated that the RMS amplitude attribute is the square root of the sum of the squared amplitudes, divided by the number of active samples. Classified as an amplitude attribute, RMS amplitude is directly sensitive to changes in the seismic impedance (Chopra; Marfurt, 2008). RMS amplitude is also considered a hydrocarbon indicator and was considered potentially useful since some stream channels in the Stratton field were identified as known natural gas traps (Hardage *et al.*, 1994; Daber *et al.*, 2007)).

Effectiveness of Attributes in Identifying Paleo-Channels and Constructing Cross Sections

Crucial to the process of constructing paleo-stream channel cross sections and paleo-stream reach surface maps is the effectiveness of the various seismic attributes in Petrel 2010.2 to portray channel geometry. Without informative attributes, use of classification systems would be impossible. Of the attributes applied in this research project, the most useful either alter or isolate frequency of the seismic waves (instantaneous frequency and iso-frequency) or identify variability in seismic waves (variance attribute) that confirmed previous studies. Other attributes that process amplitude, such as gradient magnitude and first derivative, are not as useful in identifying a stream channel.

Iso-frequency (20Hz-40Hz) provided varied images of channel cross sections (Figure 9 & Appendix Figures A49, C55, C57, & C37). This variability is attributed to the different frequencies highlighting differing bed thicknesses, possibly caused by changes in channel facies. Those changes could be thicker lag deposits vs. thinner point-bar sands. Furthermore, in some cross sections the stream channel was not represented as the normal double apex lens shape (Figure 10), but instead the channel appeared as a trough shape (Figure 11). This variability in shape could be attributed to a situation where no differential compaction occurred.

Figure 9 - 2D, iso-frequency (20Hz) view of fox stream, cross section X=2183218. The horizon line represents the stream channel cross section. Image generated in Petrel 2012.2.

Figure 10 - 2D, iso-frequency (30Hz) view of delta stream, cross section X=2189499. The white oval shows the double apex image typical of a stream that has undergone differential compaction. Image generated in Petrel 2010.2.

Figure 11– 2D, instantaneous frequency view of alpha stream, cross section X=2186023. The white oval shows the trough-shaped image of a stream channel without discernible modification due to differential compaction. Image generated in Petrel 2010.2.

Instantaneous frequency was the most useful attribute for paleo-stream channel cross section construction and provided a template for comparison to all other attributes. Instantaneous frequency also shed light on the lithology of the channel fill from which the cross sections were made. A lower frequency was considered a sandstone layer with higher frequencies translating to shale (Hart, 2008). In multiple cases the channel fill was dominated by shale, not sandstone (Figure 12), possibly caused by infilling during rapid transgression. In other cases the channel fill was sandstone (Figure 13) representing steady in filling.

Figure 12- 2D, instantaneous frequency view of charlie stream, cross section Y=713102. The white arrow shows dark blue and purple areas that denote high instantaneous frequency values associated with shale. Image generated in Petrel 2010.2.

Figure 13- 2D, instantaneous frequency view of delta stream, cross section X=2188608. The white arrow shows the dark orange to black section indicative of low instantaneous frequency values typically associated with sandstones. Image generated in Petrel 2010.2.

Although, the RMS (root mean squared) amplitude attribute does not incorporate frequency, the almost non-existent representation of paleo-stream channels by this attribute was surprising. Many instances occurred where a clear outline of a paleo-stream channel was present in variance, iso-frequency (20-40Hz), instantaneous frequency, and dip deviation, but RMS amplitude attribute provided an image that was weak or inconsistently shown in the data (Figure 14 & Appendix Figures C40 & D23). With the data set being located in Stratton- Agua Dulce field, a proven natural gas field (Hartage *et al.*, 1994), some paleo-stream channels would be expected to contain hydrocarbons. My original hypothesis in this study was that RMS amplitude would produce indicate high concentrations hydrocarbon concentrations, but no strong indications were shown.

Figure 14 – 2D, RMS Amplitude view of fox stream, cross section X=2182778. Notice that the there is no representation of a paleo-stream channel is not present. Image was generated in 2010.2.

Upon further discussion of the depositional setting of the Frio formation, the RMS should not have been considered a direct hydrocarbon indicator since the RMS amplitude was most heavily affected by lithology and rock hardness (Personal communication

Mosab Nasser, Maersk Oil

Company, Houston TX, January 30, 2013). The RMS amplitude attribute image was further complicated when RMS amplitude was applied to a full stack seismic volume, which could lead to the cancelling out of negative or positive traces creating an inaccurate representation (Personal communication Mosab Nasser, Maersk Oil Company, Houston TX, January 30, 2013).

Like RMS amplitude, attributes emphasizing amplitude were ineffective at displaying channels in the research. Attributes such as gradient magnitude rarely provided clear-cut evidence of a stream channel although values increased marginally in some channels (Figure 15). Similarly, first derivative images never revealed any semblance of a channel (Figure 16). Of the amplitude related variables, only dip deviation provided an image indicative of a stream channel (Figure 17), but only corroborated the paleo-stream channel indicated by non-amplitude attributes such as iso-frequency and instantaneous frequency, because dip deviation highlights a change in the dip angle of a reflective surface while other amplitude attributes analyze a change in the amplitude values (Daber *et al.*, 2007). Gradient magnitude, dip deviation, and first derivative are normally considered structural attributes and, although there was a lithographic change in many of the stream channels and channel fills, in general no dramatic change in dip occurred that would have highlighted a change in structure and thereby provided paleo-channel confirmation based on the attribute highlighting a change in lithologic change.

Figure 15 – 2D, gradient magnitude view of delta stream, cross section X=2189488. The image displays the ineffectiveness of the gradient magnitude to determine the stream channel. Image was generated in Petrel 2010.2.

Figure 17 – 2D, dip deviation view of delta stream, cross section X=2188938. Image displays that dip deviation was effective to validate the channel, but not to interpret on. Image generated on Petrel 2010.2.

Variance proved to be the most useful attribute indicating a stream channel in map view as well as cross line and inline views. Focused on waveform variability, variance showed a channel-like image for all stream channels used in this project. The variance attribute highlighted the channel edges (Figure 18), however, was rarely a successful tool for constructing the actual channel cross section since large amounts of noise were associated with the attribute when viewing streams in an inline or cross line 2D view (Figure 19 & Appendix Figures A15, C15, & F26). Variance served better in the role of an exploratory attribute, being useful for mapping potential paleo-streams on the stream reach surface map in the beginning stages of the research.

Figure 18 – 3D time slice, variance volume displaying the alpha stream channel. Image generated in Petrel 2010.2.

Figure 19 – 2D, variance attribute view of charlie stream, cross section Y=713047. The image displays how the variance attribute created noise around the stream channel make it difficult to interpret the paleo-stream channel. Image generated in Petrel 2010.2.

Finally, while not an attribute, the use of geobodies (isolated, customized box probes projected on a 3D view) in creating paleo-stream channel cross sections proved to be unsuccessful. By isolating a specific value using opacity, paleo-stream channels could be identified, but picking a cross section and measuring hydraulic geometry along the cross sections was too complicated and imprecise for cross section construction (Figure 20). With the channel isolated from the rest of the seismic volume using opacity filters, it was difficult to determine the elevation of the channel margins, especially when differential compaction was apparent.

Figure 20 – 3D variance volume with opacity and geobodies applied. While helpful to see stream channels in seismic, the opacity in conjunction with the geobodies did not prove to be useful when construction stream cross sections. Image generated in Petrel 2010.2.

Stream Reach Surface Map

The first step in the construction of a paleo-stream channel cross section was to create a paleo-stream reach surface, which served as a contour map of the paleo-stream reach as well as a starting point for creating individual cross sections of the paleo-stream channel. The paleo-surface map also constrained the problems of creating cross sections of a paleo-stream channel that deviated in vertical location due to stream avulsion, elevation change, or simple errors in the manual picking of seismic horizons. To construct the surface map of a paleo-stream reach, the variance attribute was selected to highlight or “pick” the actual paleo-stream channel because variance is considered the best identifier of stream margins (Bahorich & Farmer, 1995). Once the actual paleo-stream channel was picked manually, the floodplains and any other portion of the

seismic layer were picked, when applicable, using the auto tracking tool in the amplitude attribute view. This method of using auto tracking when possible proved the most consistent for honoring an actual stratigraphic surface for which paleo-stream reach could have been associated.

Stream Channel Cross Sections

Reconstructing the paleo-stream channel cross section required the sequence of procedures listed below to allow consistent representations of the stream in different sections of the paleo-stream reach:

Step 1 – The cross section location must have been identified on the paleo-stream surface map.

Step 2 – The stream channel must have been discernible in the instantaneous frequency image in either cross line or inline views.

Step 3 – The stream channel must have shown in the instantaneous frequency or iso-frequency (20Hz, 30Hz, or 40Hz) as either a simple trough channel configuration (Figure 10) or a lens geometry, which represented a trough fill deformed by differential compaction (Figure 11).

Step 4 – To be a candidate considered for a stream cross section, the stream channel must have been apparent in the instantaneous frequency image and images based on two other attributes.

Step 5 – The channel shown by instantaneous frequency should have matched bright spots (points with an elevated color value) revealed in variance and RMS amplitude attributes. The geometries did not have to match precisely, but should have been close in pattern.

Step 6 –The attribute with the highest contrast was used to delineate the stream channel when picking a horizon line, a line representing a plane in seismic interpretations, that would serve as the stream channel cross section’s outline in the seismic survey (Figure 21).

Step 7 – During cross section construction, a horizon line was traced across the floodplain adjacent to the channel. Cross sectional stream channel geometry was traced by following a specific color boundary or value in the attribute that provided sharpest boundaries of the stream channel margins.

Figure 21 - 2D, instantaneous frequency view of delta stream, cross section X=2188883. The blue arrow shows the single horizon line used to outline the paleo-stream channel. Image generated in Petrel 2010.2.

Using this sequence of steps allowed for more accurate cross sections and limited problems related to offset images when switching from one attribute view to another. One important note should be added to Step 7. Since Petrel 2010.2 is a seismic interpretation software and stream classification is not considered its main purpose, the use of a single line seismic horizon on one cross line or inline was the most logical tool for delimiting paleo-stream channel cross sections in

the interpretation window. A horizon line, which normally serves as a surface marker of a specific value across a seismic survey, also served as the most appropriate way to track the cross section

Figure 22 - Surface map of alpha stream. The different color horizon lines represent the locations that cross sections were created. Image generated in Petrel 2010.2.

locations on the 3D and 2D windows (Figure 22).

Additionally, each cross section was organized and designated by the paleo-stream reach on which it was located and by the constant X or Y coordinates in the paleo-stream channel.

The measuring of paleo-stream channel geometry began after a cross section horizon line was developed. This process was a combination of manual and computer-aided measurement. As per step 7, the horizon line showing the paleo-stream channel cross section was not followed in stream channel proper for recording of paleo-channel geometry because the process of manually picking the stream channel combined with the fixed minimum distance between horizons points caused the horizon to lack precision. Instead, the paleo-stream channel was picked based on following an attribute value, usually represented by a color or color boundary, along the base of the channel and on to the adjacent floodplains where the picked horizon line was followed. This method of following an attribute value in the channel proper proved to be more precise than following the picked horizon line. Within the paleo-channel and near the channel's banks a point was measured every 4.5 m (15 ft) horizontally, with a 1.5 m (5 ft) horizontal and vertical precision.

The horizontal measurement increment between two points across the floodplain averaged approximately 18 m (60 ft). This increment could vary due to Petrel 2010.2's "export" tool exporting values varying by a rate of 15 m (49 ft). These values were derived from the X, Y, and Z values listed on the status bar in the bottom right of the Petrel 2010.2 window (Figure 23). After a series of X, Y, and Z values delineating the stream channel and adjacent floodplains were measured, the horizontally distance to points on the cross section farther than 60 m (200 ft) away from the stream channel were measured using the export tool in Petrel 2010.2. This tool allows the user to export horizon values into a Microsoft Excel data sheet. Measurements closer than 60 m (200 ft) to the stream channel were manually taken and entered into the Microsoft Excel data sheet and combined with these data exported from Petrel 2010.2. By exporting the horizontal data points in wide flat sections of the seismic cross section, the cross section construction time was reduced by half.

Figure 23- Screen shot of a Petrel 2010.2 window showing the various tools used to create a stream channel cross section.

Cross section values were converted from time to depth using a “macro” equation generated from check shot values in “Well 3” of the Stratton data set. The depth-converted data were then graphed on an X-Y scatter plot to create the paleo-stream channel cross section.

Bankfull Cross-Sectional Area

After cross sections were entered into Microsoft Excel data sheets and depth converted, the bankfull cross-sectional areas were calculated by first assigning the bankfull stage of the stream represented in the cross section, and then determining the area of the channel below that level. Defined as the point where the natural stream channel is completely filled, bankfull stage is usually the topographic break at which the one-to-three year recurrence interval flood spread on to the floodplain (Wolman; Miller, 1960) (Figure 24). The paleo-stream channel bankfull stage’s depth was then subtracted from the depth (Y axis) of cross section data points and multiplied by the average distance between the

corresponding width points (X axis) and the points on either side of it. All the cross-sectional area increments within each cross section were calculated, and the individual areas were summed to provide a total bankfull cross-sectional area. Total areas for each cross section were then compared to other cross sections in the same stream channel

to determine the average cross-sectional area along the reach and to identify any outliers that could be caused by confluences of channels or an inconsistent bankfull stages.

Figure 24 – Microsoft Excel graph of delta stream, cross section Y=717557 displayed in feet.

Sinuosity

One of the required measurements for Rosgen (1994) stream classification, channel sinuosity, is the measure of the stream's path between two points divided by the shortest distance between the two points. Sinuosity indicates if the stream is meandering or relatively straight. The paleo-stream's sinuosity required determination of which meander bends should be considered as part of an isochronous single channel, and which apparent channels should be considered diachronous oxbow lakes and excluded from the sinuosity measurement. Generally, the pathway with the least number of meander bends in each of the surface maps was followed.

To measure the paleo-stream areal pattern, the stream's surface map was shown in a Petrel 2010.2 map view window with the variance attribute displayed as well to show the center of the paleo-stream channel. Next, the Petrel 2010.2 "Measure Distance" tool was used to measure the reach length. Once the reach length was measured and a pathway discerned, the straight-line distance was measured from the beginning point to the end point of the reach. Finally, the reach length was divided by the straight-line distance. While this procedure was considered the most effective way to measure sinuosity, it does have one drawback in that the Measure Distance tool only measures line segments, so instead of a curving line measuring the stream reach, the line is made of a chain of numerous straight line segments, resulting in increased potential for measurement error.

Width: Depth Ratio

Width: depth ratio, an important variable in Rosgen (1994) stream classification, was determined using the Microsoft Excel cross sections generated from each paleo-stream reach. By averaging the depth of all points in the bankfull channel and then dividing by the width of the bankfull stream channel, it was possible to determine width: depth ratio. As with other

measurements based on bankfull elevation, lower and higher bankfull depths were calculated in some cases to account for uncertainty in bankfull stage.

Entrenchment Ratio

The degree of entrenchment is a significant factor in Rosgen (1994), classification and is assessed by entrenchment ratio: the width of the flood-prone area (the width at a stage equal to twice the maximum bankfull depth), divided by bankfull width (Figure 6). Entrenchment ratio helps to show if the bottomlands adjacent to the channel are part of the floodplain or are terraces disconnected from the floodplain (Rosgen, 1994).

In every cross section in all four paleo-streams the entrenchment ratio was ≥ 2.4 because no elevation equaling twice the bankfull depth made contact with any of the cross section points. Assuming no measurement or interpretation errors occurred in delineating the channels during the cross section construction process, this common high entrenchment ratio attribute indicates the paleo-stream reaches in question were either type “C”, “D”, “DA”, or “E” channels .

Stream Gradient

Stream gradient is typically the most straightforward of the variables used in Rosgen (1994) stream classification, but it resulted in the most uncertainty when measured in the subsurface because of potential post-depositional tilting and warping. Stream gradients were calculated by determining the change in elevation of the bankfull stage along the paleo-stream reach, measuring the distance between cross sections using the Petrel 2010.2's Measure Distance tool, and dividing the measured length by change in bankfull surface elevation. A cross section-to-cross section scale was used as well as a full reach scale. When high and low bankfull stage indicators were present in the same stream, both stages were used in separate gradient calculations because a difference in elevation could affect the gradient value.

Water flows downhill on earth's surface and, therefore, slope should never be a negative number over meaningful distances. In this study, however several streams displayed negative slopes between cross sections along the stream path (Figure 25). Assuming no errors were made during the cross section

construction or

measurement, this unrealistic

negative gradient could be

explained by post-

depositional tilting structural

or deformation due to

differential compaction along

a reach overlying varied

geologic materials.

Figure 25 – Microsoft Excel graph of the gradient values at different points in charlie stream starting from West to East. Notice that the gradient reverses slope at one point.

Stream Discharge

Discharge was the final diagnostic variable for each of the paleo-streams delineated in the Stratton data. Although discharge was not required for Rosgen (1994) stream classification, determining the discharge for each stream aided in providing a clearer perspective on the actual size and scale of each of the paleo-streams when compared to modern-day streams in the Gulf of Mexico Coastal Plain.

To determine the stream discharge, the equation following was used.

$$Q = A \times V = W \times D \times V \text{ (Rosgen, 1996)}$$

Q = Discharge

A= Cross-Sectional Area

V= Mean Velocity

W= Width

D= Depth

While cross-sectional area was already determined, the more problematic discharge variable was mean flow velocity, which was determined from the Manning Equation:

$$V = \frac{1.49 R^{2/3} S^{1/2}}{n} \quad (\text{Rosgen, 1996})$$

V= Mean Velocity
R= Hydraulic Radius
S= Slope (Stream Gradient)
n= Manning Coefficient

All three variables in the Manning equation: hydraulic radius, slope, and the Manning roughness coefficient may introduce error in determining stream discharge. Hydraulic radius is the bankfull cross-sectional area divided by the wetted channel perimeter, wherein the most significant error is likely in hydraulic radius due to incorrect bankfull stage assignment. Much greater margins of error are likely in stream gradient. In many instances the calculated gradients were

Figure 26 – Microsoft Excel chart displaying both the estimated average paleo-stream reach discharge and the estimated adjusted paleo-stream reach discharge for the paleo-streams.

beyond comparison with any large coastal plain stream anywhere in the world. Therefore, the slope of the stream was adjusted to 0.00001 an average slope of the current rivers in the East Texas area (Phillips; Lutz, 2008) (Figure 26).

The last of the variables used to calculate velocity, the Manning roughness coefficient, presented a problem in that no precise value could be determined since it was not possible to precisely determine bedload grain size or determine if the stream bed had large amounts of vegetation. Hence, a number of 0.025 was used because it has been deemed representative of major rivers and other natural channels (Dackombe; Gardiner, 1983).

Comparing Paleo-Stream Reaches to Modern Analog Rivers

Potential modern analog rivers studied in the region were the Mississippi River at Vicksburg, Mississippi, the Rio Grande River in western Texas, and the Bravos, Trinity, and Colorado rivers in East Texas (Figure 27). The Bravos, Trinity, and Colorado rivers flow into the Gulf of Mexico near the Galveston-Houston metro area and are representative of the Coastal Plain landscape of the Frio Formation

with the patterns of avulsion and meandering. To better represent lower Coastal Plain streams, all of the comparative stream gage data, except for a portion of the Rio Grande, were obtained from gage stations located near the Gulf Coast. Three to four river data gages were used to determine drainage area, peak flow, and 1.5

year recurrence discharge, for each of the East Texas rivers (Table 1). The Mississippi River data were collected at the gage station near Vicksburg, Mississippi, since most stream gages farther downstream in Louisiana were either in greatly modified reaches or lacked extensive historical

Figure 27 – Microsoft Excel chart of the modern analog stream's 1.5 year flow and peak flow. Data gathered from US Geologic Survey (2012A: 2012B).

data (Table 2). The four Rio Grande data gages were used to represent a stream in an arid climate (Table 2).

River	Gage Name	Gage station #	1.5 year (cfs)	1.5 Flow (m ³ /s)	Max flow (cfs)	Max Flow (m ³ /s)	Drainage Area (mi ²)	Drainage Area (km ²)
Bravos	Brazos Rv at Richmond, TX	8114000	43,800	1,240	123,000	3,483	35,541	92,051
Bravos	Brazos Rv nr Rosharon, TX	8116650	37,300	1,056	84,400	2,390	35,773	92,652
Bravos	Brazos Rv nr Hempstead, TX	8111500	37,600	1,065	143,000	4,049	34,314	88,873
Trinity	Trinity Rv nr Crockett, TX	8065350	24,900	705	109,000	3,087	13,911	36,029
Trinity	Trinity Rv at Trinidad, TX	8062700	25,500	722	94,500	2,676	8,538	22,113
Trinity	Trinity Rv at Riverside, TX	8066000	25,100	711	121,000	3,426	15,589	40,375
Trinity	Trinity Rv at Romayor, TX	8066500	34,800	985	122,000	3,455	17,186	44,512
Colorado	Colorado Rv at Wharton, TX	8162000	20,300	575	159,000	4,502	30,600	79,254
Colorado	Colorado Rv nr Bay City, TX	8162500	19,600	555	84,100	2,381	30,837	79,867
Colorado	Colorado Rv at Columbus, TX	8161000	23,800	674	190,000	5,380	30,237	78,313

Table 1 - East Texas streams serving as modern-day analogs to streams in Stratton data set, with gage station locations and flow data. Data obtained from U. S. Geological Survey (2012A).

River	Gage Name	Gage station #	1.5 year (cfs)	1.5 Flow (m ³ /s)	Max flow (cfs)	Max Flow (m ³ /s)	Drainage Area (mi ²)	Drainage Area (km ²)
Mississippi	Mississippi Rv at Vicksburg, MS	7289000	1,282,000	36,302	2,278,000	64,506	1,140,500	2,953,881
Rio Grande	Rio Grande at Roma, TX	8462500	55,100	1,560	630,000	17,840	166,464	431,140
Rio Grande	Rio Grande at San Antonio Crsg nr Laredo, TX	8458700	23,000	651	912,000	25,825	129,226	334,694
Rio Grande	Rio Grande nr Zapata, TX	8460500	50,900	1,441	261,000	7,391	163,344	423,059
Rio Grande	Rio Grande nr Brownsville, TX	8475000	9,760	276	31,700	898	176,333	456,700

Table 2- Rio Grande and Mississippi rivers serving as modern-day analogs to streams in Stratton data set, with gage station locations and flow data. Data obtained from U. S. Geological Survey (2012A; 2012B).

Results

Once all cross sections and measurements were completed, each of the paleo-stream reaches were classified and compared to each other and modern stream analogs (Table 3). Two over-arching characteristics were found in all of the paleo-stream reaches: (1) each of the paleo-streams appear to have had a flood-prone area that extended beyond the cross section limits, so all of the paleo-stream channels entrenchment ratios were ≥ 2.4 units and (2) the channel gradients and discharges based on the measured gradients were so high as to be highly unlikely to occur in a natural state, and when adjusted to the gradient of 0.00001, the bankfull (1.5 year) discharges for all the paleo-stream channels were lower, but relatively high (Tables 1, 2, & 3) (Figure 28).

Figure 28 – Microsoft Excel chart comparing the modern stream analogs' peak flow and 1.5 year flow to the paleo-stream channels' estimated adjusted bankfull discharges.

Paleo-stream	Slope	Cross Sectional Area (ft ²)	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge (cfs)	Discharge (m ³ /s)	Drainage Area (mi ²)	Drainage Area (km ²)
Alpha	Average	77470.16	7197.22	1.07	14.59	2.3	0.0074	10,671,916	302,195	1,134,698	2,938,856
Alpha	Adjusted	77470.16	7197.22	1.07	14.59	2.3	0.0001	1,238,768	35,078	7,583	19,641
Charlie	Average	19564.90	1817.64	1.78	15.25	2.3	0.0000	77,127	2,184	12	31
Charlie	Adjusted	19564.90	1817.64	1.78	15.25	2.3	0.0001	176,467	4,997	81	211
Delta (high)	Average	35430.88	3291.64	1.27	19.12	2.3	-0.0015	4,031,593	114,162	117,951	305,493
Delta (high)	Adjusted	35430.88	3291.64	1.27	19.12	2.3	0.0001	1,049,022	29,705	5,152	13,343
Delta (low)	Average	23980.57	2227.87	1.27	18.11	2.3	0.004	3,858,021	109,247	106,478	275,778
Delta (low)	Adjusted	23980.57	2227.87	1.27	18.11	2.3	0.0001	607,695	17,208	1,447	3,748
Fox (high)	Average	17984.00	1670.77	1.32	12.55	2.3	0.3411	8,968,442	253,958	757,251	1,961,273
Fox (high)	Adjusted	17984.00	1670.77	1.32	12.55	2.3	0.0001	153,583	4,349	59	153
Fox (low)	Average	15352.77	1426.32	1.32	12.51	2.3	0.1982	6,035,700	170,912	301,486	780,845
Fox (low)	Adjusted	15352.77	1426.32	1.32	12.51	2.3	0.0001	135,573	3,839	44	114

Table 3 – Paleo-stream channel averaged values for each stream listing the averaged gradient for the stream channel and the adjusted stream gradient of 0.0001. If there were two possible bankfull surfaces for a stream channel both are listed (i.e., Fox (high) and Fox (low)). Measurements for individual stream cross sections can be accessed in the Stream Channel Appendix.

Alpha Stream

Alpha stream is the widest and deepest stream and the most easily identified in the variance and instantaneous frequency attributes showing the most clear and distinct stream margins (Figure 21). Alpha stream differs from smaller streams in the Stratton data set in that it shows little meandering or likely avulsions, which made it easier to determine a single stream path. Alpha channel has a southeast-trending branch, but this branch was not analyzed due to relatively poor imagery in variance and instantaneous frequency attributes' imagery compared to the main branch.

Using Rosgen (1994) terminology, alpha stream was single channel stream, slightly entrenched, with moderate to high width: depth ratio and moderate to highly sinuous (Table 3). The various stream channel attributes show that alpha stream was a type "C" stream (Figure 4).

A modified Manning equation was used to estimate discharge for Alpha stream:

$$Q = A \times \frac{1.49 R^{2/3} (\Delta D \times \Delta Z)^{1/2}}{n}$$

Q= Estimated Discharge
A= Cross-Sectional Area
R= Hydraulic Radius
D= Distance
Z= Elevation
n= Manning Coefficient

Alpha stream had an estimated bankfull discharge of 302,000 m³/s (10,700,000 ft³/s) (Table 3 & Figure 26) which is extremely high compared to historical discharge on the Mississippi River (Table 2 & Figure 27); however when the stream slope was adjusted by substituting a typical regional channel slope (0.0001) in lieu of the gradient determined from geophysical data,

$$Q_A = A \times \frac{1.49 R^{2/3} 0.0001^{1/2}}{n}$$

Q_A = Adjusted Estimated Discharge
A = Cross-Sectional Area
R = Hydraulic Radius
n = Manning Coefficient

the stream's calculated discharge was only 35,000 m³/s (1,240,000 ft³/s) (Table 3).

This number was still very high compared to historical discharges on Texas coastal plain rivers, but was approximately equal to the Mississippi River during bankfull flood events or the Rio Grande River during an extreme historical flood discharge (Table 2 & Figure 28) (U.S. Geological Survey, 2012B).

Charlie Stream

While alpha stream is a very large stream with discrete channel margins, charlie channel is more representative of paleo-stream reaches in the Stratton data set (Figure 29). Unlike alpha stream (Figure 22), no differentiation exists between charlie

Figure 29- A map view of the charlie stream surface with the six cross sections shown generated in Petrel 2010.2.

stream's channel margin and the middle of the channel in the variance time slice (Figure 30). Several highly sinuous sections, interpreted to be oxbow lakes, are evidence of the stream's meandering.

Figure 30-2D window time slice view of charlie stream in the variance attribute in Petrel 2010.2. The image shows that variance attribute cannot provide a clear distinction between the banks of a stream channel and the stream channel center in smaller stream reaches.

Since no definitive method exists to determine if the paleo-stream channel is a single channel or a network of multiple channels, both a multi-channel and a single channel stream pattern must be considered in classification. Using the Rosgen (1994) stream classification, charlie stream was either a multi-channel or single channel stream, with a depth moderate to high width: depth ratio and was slightly entrenched. Charlie stream could have been either a single or multi-channel stream it was classified as either “DA” or “C” type (Figure 4). Charlie stream was likely a “DA” stream since a type “DA” stream was more closely associated with delta.

Charlie stream (Figure 29) demonstrated the problems in trying to create an accurate representation of a stream from seismic data. While easily identifiable in the variance attribute image (Appendix Figures C15 & C43), there was little visible evidence of the stream in the other

attributes used: iso-frequency (Appendix Figures C46 & C47) and instantaneous frequency (Appendix Figure C16). In other cross sections, the bright spot representing the stream channel in instantaneous frequency was shifted east when compared to the view in the variance attribute (Compare Figures 31A & 31B). This shifting cast doubts as to which image was the more accurate depiction of the subsurface paleo-stream channel.

Figures 31 A – 2D, instantaneous frequency view of charlie stream, cross section Y=716952. The black horizon line matches the instantaneous frequency attribute's display of the stream channel. Compare to Figure 19B. Image generated in Petrel 2010.2.

Figure 31 B- 2D, variance view of charlie stream, cross section Y=716952. The blue horizon line is the same horizon line from figure 19A does not match where the variance attribute displays of the stream channel (indicated by the bright yellow to red spot). Compare to Figure 19A. Image generated in Petrel 2010.2.

Going

beyond the issues attributed to different seismic attributes, charlie stream presents a fundamental question: Is charlie stream actually two streams that meet outside the viewing area? This question stems from the calculated negative gradient on the west-east trending reach (Table 4), whereas the reach running north-south has a positive gradient (Figure 25 & Figure 29). Therefore, charlie stream could have actually been two separate branches of a larger stream, but more likely the gradient measurements are in error due to deformation, varying compaction, or measurement error since all the other paleo-streams seemed to have distorted gradient measurements as well (Table 3).

Cross Section	Bankfull Depth (ft)	Distance Between (mi)	Change in Depth (ft)	Stream Gradient
Y=716402	4907.06			
Y=713707	4849.72	400.56	57.34	0.1432
Y=716952	4895.13	4711.48	-45.41	-0.0096
Y=713102	4849.62	785.71	45.51	0.0579
X=2186683	4871.90	4055.19	-22.28	-0.0055
X=2188883	4906.82	2611.35	-34.92	-0.0134
Total		12564.29	0.24	0.0000

Table 4- Stream gradient values for Charlie stream. The cross sections are color code to match the cross section lines in figure 18. Notice the stream gradient values between X=2186683 and X=2188883 are both negative and have an east west trending, while cross sections Y=71402 through Y=713102 have an overall positive value and trend north southeast.

Delta Stream

Of the four streams, delta stream (Figure 32) is the second deepest at approximately 600 m (1,900 ft) below the surface and is two to three times larger than charlie stream in cross-sectional area. Unlike charlie stream, which has both groups of meander bends and straight stretches, delta stream has many more

Figure 32- A map view of the delta stream surface with the five cross sections shown. Generated in Petrel 2010.2.

Figure 33 - Microsoft Excel graph of delta stream, cross section Y=715082 displayed in feet. The blue line represents higher estimated bankfull elevation (1,888.19 ft) while the pink line represents the lower estimated bankfull elevation (1,916.54 ft).

Figure 34 - Microsoft Excel graph of delta stream, cross section X=2188608 displayed in feet. The blue line represents higher estimated bankfull elevation (1870.92 ft) while the pink line represents the lower estimated bankfull elevation (1902.57 ft).

meanders and multiple convergences along the stream reach.

In the cross section construction process and subsequent analysis, the bankfull stage for both delta stream cross sections Y=715082 and

X=2188608 could have

been picked at two different depths (Figures 33 & 34). Because two possible bankfull stages exist, all measurements affected by a bankfull location were run at both stages, yielding a difference of 32% in average cross-sectional area and 42% in

adjusted discharge

(Table 3). These

differences did not affect the Rosgen classification, with both bankfull surfaces having the same

slightly entrenched, moderate sinuosity, and moderate to high width: depth ratio both would have been classified as either a type “C” or a “DA” depending on whether the stream had single or multiple channels.

Much like alpha stream, the estimated discharge for delta stream based, on the measured channel gradient, was unrealistically high at 114,000 m³/s (4,030,000 ft³/s) at the higher bankfull stage and 109,000 m³/s (3,860,000 ft³/s) at the lower bankfull stage (Table 3). When adjusted to an average slope of 0.0001 typical of large modern-day East Texas rivers, discharges of 29,700 m³/s (1,050,000 ft³/s) for the higher bankfull stage and 17,200 m³/s (607,000 ft³/s) for the lower bankfull stage were on the order of large floods on the Mississippi River (Table 2 & 3).

Fox Stream

Fox stream is the smallest in both average cross-sectional area and paleo-discharge (Figure 35). It also is the most deeply buried paleo-stream reach to be analyzed at ~ 2,012 m (6,600 ft). As with delta stream, one cross section (X=2182318) (Appendix Figure F5) in fox stream presented two choices for a bankfull stage, so key classification variables and paleo-discharge were calculated using both bankfull stages. The higher adjusted bankfull stage discharge was 4,349 m³/s (153,583 ft³/s) while the lower adjusted bankfull stage discharge was 3,839 m³/s (135,573 ft³/s) (Table 3). The differences in the calculated results were not as significant as in delta stream (14% difference in average cross-sectional area and 12% difference in adjusted discharge (Table 3)). Fox stream had a high sinuosity and was slightly entrenched. The most unusual variable of fox stream was a low width: depth ratio of 12.55 for the higher bankfull stage and 12.51 for the lower bankfull stage. This smaller width: depth ratio allowed fox stream to be classified as not only a type “C” or “DA”, but a type “E” due to the “continuum of physical variables,” which allowed for +/- 2.0 units variability in width: depth ratio in the Rosgen (1994) stream classification (Figure 7).

Figure 35 - A map view of the fox stream surface with the five cross sections shown. Generated in Petrel 2010.2.

Discussion

Stream Channels or Incised Valleys?

Classification of a modern stream reach may have many factors such as dams or bridges that alter the stream's geometry from its natural state, but determination of bankfull stage was relatively simple on surface streams compared to picking bankfull stage for subsurface stream classification. During the research, no reliable method was found to determine where along a cross section of a paleo-stream channel began and where a paleo-stream valley ended. The most straight forward approach was to infer that the bankfull surface was located at the first level section of the paleo-stream channel cross section. In all cases this method produced a stream channel with very a large cross-sectional area as well as a very high discharge.

Exceptionally large cross-sectional areas and discharges led to this question: are the identified features stream channels or incised valley fills? No definitive method was found to determine from those data in the Stratton survey if the lenticular and trough shaped features apparent on the seismic images were simple channels or stacked channel deposits in valley fills. Consider that the adjusted discharge of the alpha stream at bankfull discharge is 35,000 m³/s

(1,200,000 ft³/s) (Table 3). This discharge is comparable to bankfull discharge (36,000 m³/s (1,300,000 ft³/s)) (Table 1 & Figure 28) of the Mississippi River at Vicksburg, Mississippi, suggesting that alpha stream was one of the largest rivers on the planet in its day (U.S. Geological Survey, 2012A; 2012B). Entrenchment ratios shed light on this question as well. With entrenchment ratios too high to be calculated, the channels must be a “C”, “D”, “E” or “DA” type stream (Rosgen, 1994), but if treated as an incised valley, the entrenchment ratios would have been much lower (Figure 6). Furthermore, few if any stream terraces outside of the stream channel proper were discovered in the cross sections, unlike the abundant terraces today on the Bravos and Trinity rivers (Phillips, 2007). The lack of stream terraces could also be caused by measurement error or compaction rates, but the lack of terraces could also be explained by the paleo-stream channel being an incised valley with the stream cutting down too quickly to create extensive terraces.

The other possibility to explain the seemingly large scale of all the paleo-stream channels could be that the bankfull surface recorded in the cross section was not the bankfull event, but instead a low frequency, high magnitude flood event. Therefore, the alpha channel cross sections could reflect a 500-year or greater interval flood event. In addition, when the Paleo-stream reaches’ sinuosity and width: depth ratios are compared there is no significant relationship between the two measurements which could be explained by the Paleo-channels being valley fill instead of channel fill (Figure 36).

Figure 36 – Microsoft Excel chart comparing width: depth ratio vs. sinuosity. The chart displays a linear regression line as well.

Although the bankfull is the dominant flow for determining the hydraulic geometry of most surface streams according to Dunn and Leopold (1978), and Wolman and Miller (1960) demonstrated and later confirmed by Hurricane Agnes (Costa, 1974) that moderate frequency, moderate magnitude floods such as bankfull stage floods control the channel geometry of modern stream channels, but this principle could be violated since the thesis is studying the sedimentary fill as instead of the hydraulic geometry and the discharges controlling sedimentary fill represent the paleo-stream channel could have been controlled by very low-frequency, high-magnitude events. If this were the case, the Rosgen (1994) classification for all of the paleo-stream channels would be invalid because the Rosgen (1994) scheme is based on bankfull stage floods.

Minimum Drainage Area Determined from Extreme Discharge

Assuming discharges for all of the paleo-stream channels were associated with extreme flood events and were accurate reconstructions of paleo-flows, the minimum size of the

contributing drainage area for each of the paleo-stream reaches can be calculated using the equation:

$$Q=500A^{0.43} \text{ (Herschy, 2002)}$$

Q = Known Adjusted Extreme Flood Discharge (m^3/s)

A = Contributing Drainage Area (km^2)

This regression equation for extreme floods was created by Herschy (2002) for drainage areas over 100 km^2 by plotting the 55 greatest recorded flood discharges, as compiled by the International Association of Hydrological Sciences.

The minimum drainage areas calculated from the gradient adjusted paleo-stream discharges were significantly smaller than modern analogous river basins in East Texas (Figure 36, Table 1 & 3). The charlie stream had an gradient adjusted bankfull discharge of $5,000 \text{ m}^3/\text{s}$ ($180,000 \text{ ft}^3/\text{s}$) which, when incorporated into the drainage equation estimated a minimum drainage area of 211 km^2 (81.5 mi^2) (Table 3) while the modern-day Bravos River, with a bankfull discharge of $1,200 \text{ m}^3/\text{s}$ ($44,000 \text{ ft}^3/\text{s}$)(Table 3) and peak flow of $3,480 \text{ m}^3/\text{s}$ ($123,000 \text{ ft}^3/\text{s}$) (Table 1) (U.S. Geological Survey, 2012A) has a drainage area of $92,000 \text{ km}^2$ ($35,000 \text{ mi}^2$) (Table 1) (U.S. Geological Survey, 2012A).

Figure 37 - Microsoft Excel chart comparing the minimum estimated drainage area of the paleo-stream reaches to the drainage area of the modern stream analog streams gathered from the US Geologic Survey (2012A; 2012B).

A smaller drainage area with a large discharge is possible in watersheds that have significantly higher runoff per unit area related to climates with large amounts of rain or have certain physiographic conditions such as extensive exposed bedrock, high relief and high drainage densities (O'Connor; Costa, 2004). Rivers such as the Trinity River in East Texas rank high in average annual discharge compared to other Texas rivers, even though the Trinity has a relatively small drainage area but is dominated by a sub humid climate prone to intense precipitation (Lankford; Rehkemper, 1969). Modern-day streams draining the Edwards Plateau and the East Texas Coastal Plain can experience extreme accumulations of rainfall in incredibly short periods of time (Smith *et al.*, 2000). For example, Alvin, Texas, holds the 24-hour rainfall record for the United States with 1,090 mm (43 in) of precipitation (Smith *et al.*, 2000). These conditions could be possible in the Stratton paleo-streams, since the climate in the region during the Oligocene was considered sub-arid (Galloway, 2009). When compared to the modern-day Rio Grande River at

Roma TX, with runoff per unit area of $0.0036 \text{ m}^3/\text{km}^2$ ($0.3310 \text{ ft}^3/\text{mi}^2$) (Table 5) (U.S. Geological Survey, 2012A), all the paleo-stream's had a runoff per unit area higher than $1.0 \text{ m}^3/\text{km}^2$ when using the gradient adjusted discharge (Table 5). The likelihood that these paleo-streams could have had such high runoff per unit area conditions is plausible if physiographic conditions like extensive exposed bedrock, high relief and high drainage densities could be combined with small basins to produce extreme discharges.

An alternate explanation of the high paleo-discharges could be that the drainage areas were much larger prior to the paleo-streams losing drainage area to other drainage basins through stream piracy or divide migration due to isostatic warping. Larger watersheds would allow channel forming events to be less extreme than world record flows studied by Herschy (2002), but compared to modern climate analogs, the paleo-discharges appear far too large to be 1-3 year events for watersheds significantly smaller than the Mississippi River.

	Stream gradient from alluvial deposit dip			Gradient adjusted to modern analog stream slopes		
Modern Streams				1.5 Year Discharge (m ³ /s)	Drainage Area (km ²)	Runoff per unit area (m ³ /km ²)
Rio Grande at Roma, TX				1,560	431,140	0.0036
Bravos Rv at Richmond, TX				1,240	92,051	0.0135
Trinity Rv nr Crockett, TX				3,087	36,029	0.0857
Paleo-Streams	Reconstructed Bankfull Discharge (m ³ /s)	Inferred Minimum Drainage Area (km ²)	Runoff per unit area (m ³ /km ²)	Reconstructed Bankfull Discharge (m ³ /s)	Inferred Minimum Drainage Area (km ²)	Runoff per unit area (m ³ /km ²)
Alpha	302,195	2,938,856	0.10	35,078	19,641	1.79
Charlie	2,184	31	70.45	4,997	211	23.68
Delta (high)	114,162	305,493	0.37	29,705	13,343	2.23
Delta (low)	109,247	275,778	0.40	17,208	3,748	4.59
Fox (high)	253,958	1,961,273	0.13	4,349	153	28.42
Fox (low)	170,912	780,845	0.22	3,839	114	33.68

Table 5- Runoff per unit area calculated from both the stream gradient from alluvial deposit dip and the gradient adjusted to modern analog stream slopes (Phillips, 2007; U. S. Geological Survey, 2012A).

Effectiveness of Rosgen Classification Using Seismic Data

With the overall study's focus on Rosgen (1994) stream classification, it is important to address the benefits and shortcomings of the Rosgen (1994) scheme when applied to seismic interpretation. Rosgen's scheme presents many difficulties, including the need to define a specific bankfull stage and other issues with specific hydraulic variables and calculations.

The bankfull stage interpreted from the imagery may not be the true bankfull stage at all, and if this is the case the classification effort as a whole is null since essential variables of entrenchment ratio and width: depth ratio are based on bankfull stage. Sinuosity is the only variable that could be used in both modern stream classification and seismic analysis with confidence since it is not dependent on an interpreted stage. However, sinuosity presents the problem of determining which bends in the paleo-stream channel were connected meander bends and which were disconnected cut-off oxbow lakes.

Rosgen's reliance on stream gradient as a classification criterion is also problematic. Paleo-stream gradients cannot be determined accurately from seismic data due to post-depositional differential compaction, faulting and other subsurface deformation.

If the channel was a single or multiple channel stream is very important, since number of channels will fundamentally determine Rosgen (1994) classification (Figure 4). No accurate method exists to determine if a paleo-stream channel fill is composed of laterally stacked sand deposits formed in braided stream or a simple single channel fill formed by stream avulsion in single channel. Therefore, the classification effort must accommodate the potential for both single and multiple thread options, ultimately limiting the precision of the whole classification process.

The seismic data collection and conversion to depth domain also presents potential issues for precision when applying the Rosgen (1994) classification to seismic data. The Stratton data had

a trace spacing of 18 m (55 ft), a limit of vertical resolution between 31 m (101.7 ft) to 68 m (223.1 ft) and Fresnel zone radius of between 7 m (23 ft) to 16 m (52 ft)(Table 6). Therefore, the measuring the paleo-stream channels below those limits could be impacted by limited precision and effect the cross-sectional area, width: depth ratio, and entrenchment ratio.

Paleo-Stream Channel	Peak Frequency (Hz)	Limit of Vertical Resolution (m)	Fresnel Zone Radius (m)
Alpha	63	31.0	16
Charlie	44	44.4	11
Delta	45	43.4	11
Fox	28	69.7	7

Table 6 – Limit of vertical resolutions and Fresnel zone radii. Values calculated from the peak frequencies for each of the paleo-stream reaches.

Rosgen (1994) stream classification's small increments of measure when constructing a paleo-stream channel cross section could also limit its practicality in seismic data since in this data the optimum distance between two points in a cross section was 4.5 m (15 ft). Therefore an small changes in elevation could be over looked. For example, to have the vertical precision of 1.5 meters the required a dominant frequency of the seismic section would be 6 Hz which was not the dominate frequency in any of paleo-stream reaches.

Finally, Rosgen (1994) stream classification has margins of overlap allowed for diagnostic variable of width: depth ratio (+/-2.0), entrenchment ratio (+/-0.2), and sinuosity (+/-0.2) (Figure 7). This overlap between defining criteria, combined with inherently high margins of error involved in construction of paleo-stream cross sections from seismic data led to multiple classification types for fox stream (Table 3) and could be a factor of uncertainty in classifying other paleo-stream channels.

Future Research

While the goal of the research was achieved and a Rosgen stream type was assigned to each of the paleo-stream reaches, additional research could be added to this study regarding calibration of the seismic's domain as well as using different seismic attributes. To increase the precision of the study, future work should incorporate a 3D seismic volume that includes a velocity model with multiple compartments, checkshot data and time depth curves to depth convert the 3D seismic volume. Interpreting the stream channels in a depth domain would increase the precision of the channel interpretations and lead to cross sections that are more closely aligned with the image in the seismic.

Another area for further research would be using higher and lower iso-frequency values. While 20 Hz, 30 Hz, and 40 Hz were successful in displaying paleo-stream channels, the peak frequency in the Alpha channel was calculated at 62 Hz; therefore, a higher iso-frequency value would have increased the visibility of the paleo-stream channel. Also, applying different attributes to other volumes might have led to greater success using that seismic attribute volume.

The final portion of the future research would be to calibrate the seismic volume using well log data that intersects the paleo-stream channel. Using a gamma ray curve, a researcher could determine whether the paleo-stream channel is composed of a sandstone or shale and elaborate on the compaction rate. Using well data, a researcher could calculate the seismic curve and compare the value of the curve to other locations in the well paths where another stream channel intersects a stream channel. Finally, if core data were available, the researcher could estimate grain-size, allowing for a more specific Rosgen classification type.

Conclusion

The Rosgen (1994) classification of paleo-stream reaches using seismic interpretation software like Petrel 2010.2 is possible to a certain extent, but is accompanied by a significant level of error. This research showed that a stream type can be assigned, but classification accuracy is limited by uncertainty about stream gradient, width: depth ratio, seismic depth conversion, lack of well calibration, and as to whether the paleo-stream had a single- or multiple-thread channel at any given time.

The study was able to generate estimated bankfull discharges and estimated minimum drainage area for each of the stream channels from these bankfull discharges. The discharge levels were much higher than expected, but the streams could have produced such extremely large floods in a climate similar to that in the modern-day Edwards Plateau and East Texas Coastal Plain.

Overall, the software performed well in a task for which and would probably provide even better images with a seismic survey shot since the Stratton survey was created in the early 1990's. With technology improving every year the possibilities for paleo-stream reach classification as a reliable and useful tool in paleo-environment reconstruction will increase and allow for further research in the area of study.

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Stream Channel Appendix

Alpha Stream

Figure A1- A map view of the Alpha stream surface with the five cross sections shown. Image generated in Petrel 2010.2.

Cross Section	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge (m ³ /s)	Drainage Area (km ²)
X=2183548	6502.67		7.77	2.30			
X=2184703	9812.35		15.71	2.30			
X=2186023	3496.97		12.04	2.30			
X=2187508	11408.85		12.08	2.30			
X=2189213	4765.27		25.37	2.30			
AVERAGE	7197.22	1.066616	14.59	2.30	0.0074	302194.57	2,938,856
ADJUSTED SLOPE	7197.22	1.07	14.59	2.30	0.00	35077.82	19,641

Figure A2 – The Excel table shows all measurements for each of the stream cross sections. The Stream cross sections are color coordinated matching Figures A1 and A3.

Figure A3- The excel graph shows all the stream channel cross sections in alpha stream reach based on their location on the Z or depth plain.

X=2183548

Figure A4 –The excel graph shows the alpha stream, cross section at X=2183548 and is measured in feet.

Figure A5- Image of alpha stream, cross section at X=2183548 in the variance attribute generated in Petrel 2010.2.

Figure A6- Image of the alpha stream, cross section at X=2183548 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure A7- Image of the alpha stream, cross section at X=2183548 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure A8- Image of the alpha stream, cross section at X=2183548 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure A9- Image of the alpha stream, cross section at X=2183548 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure A10- Image of the alpha stream, cross section at X=2183548 in the dip deviation attribute generated in Petrel 2010.2.

Figure A11- Image of the alpha stream, cross section at X=2183548 in the amplitude attribute generated in Petrel 2010.2.

Figure A12- Image of the alpha stream, cross section at X=2183548 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure A13- Image of the alpha stream, cross section at X=2183548 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2184703

Figure A14- Microsoft Excel graph shows the stream channel cross section created for alpha stream, cross section X=2184703 and is measured in feet.

Figure A15- Image of the alpha stream, cross section X=2184703 in the variance attribute generated in Petrel 2010.2.

Figure A16- Image of the alpha stream, cross section X=2184703 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure A17- Image of the alpha stream, cross section X=2184703 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

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Figure A19- Image of the alpha stream, cross section X=2184703 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure A20- Image of the alpha stream, cross section X=2184703 in the dip deviation attribute generated in Petrel 2010.2.

Figure A21- Image of the alpha stream, cross section X=2184703 in the amplitude attribute generated in Petrel 2010.2.

Figure A22- Image of the alpha stream, cross section X=2184703 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure A23- Image of the alpha stream, cross section X=2184703 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2186023

Figure A24- Microsoft Excel graph shows the alpha stream, cross section X=2186023 which was generated in Petrel 2010.2 and measured in feet.

Figure A25- Image of the alpha stream, cross section X=2186023 in the variance attribute generated in Petrel 2010.2.

Figure A26- Image of the alpha stream, cross section X=2186023 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure A27- Image of the alpha stream, cross section X=2186023 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure A28- Image of the alpha stream, cross section X=2186023 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure A29- Image of the alpha stream, cross section X=2186023 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure A30- Image of the alpha stream, cross section X=2186023 in the dip deviation attribute generated in Petrel 2010.2.

Figure A31- Image of the alpha stream, cross section X=2186023 in the amplitude attribute generated in Petrel 2010.2.

Figure A32- Image of the alpha stream, cross section X=2186023 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure A33- Image of the alpha stream, cross section X=2186023 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2187508

Figure A33- Image of the alpha stream, cross section X=2186023 in the gradient magnitude attribute generated in Petrel 2010.2.

Figure A35- Image of the alpha stream, cross section X=2187508 in the variance attribute generated in Petrel 2010.2.

Figure A36- Image of the alpha stream, cross section X=2187508 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure A37- Image of the alpha stream, cross section X=2187508 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure A38- Image of the alpha stream, cross section X=2187508 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure A39- Image of the alpha stream, cross section X=2187508 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure A40- Image of the alpha stream, cross section X=2187508 in the dip deviation attribute generated in Petrel 2010.2.

Figure A41- Image of the alpha stream, cross section X=2187508 in the amplitude attribute generated in Petrel 2010.2.

Figure A42- Image of the alpha stream, cross section X=2187508 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure A43- Image of the alpha stream, cross section X=2187508 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2189213

Figure A44- Microsoft Excel graph shows the alpha stream, cross section X=2189213 which was generated in Petrel 2010.2 and measured in feet.

Figure A45- Image of the alpha stream, cross section X=2189213 in the Variance attribute generated in Petrel 2010.2.

Figure A46- Image of the alpha stream, cross section X=2189213 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure A47- Image of the alpha stream, cross section X=2189213 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure A48- Image of the alpha stream, cross section X=2189213 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure A49- Image of the alpha stream, cross section X=2189213 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure A50- Image of the alpha stream, cross section X=2189213 in the dip deviation attribute generated in Petrel 2010.2.

Figure A51- Image of the alpha stream, cross section X=2189213 in the amplitude attribute generated in Petrel 2010.2.

Figure A52- Image of the alpha stream, cross section X=2189213 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure A53- Image of the alpha stream, cross section X=2189213 in the gradient magnitude attribute generated in Petrel 2010.2.

Charlie Stream

Figure C1- A map view of the charlie stream surface with the six cross sections shown generated in Petrel 2010.2.

Cross Section	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge (m ³ /s)	Drainage Area (km ²)
X=2186683	1056.22		22.21	2.3			
X=2188883	2083.41		24.28	2.3			
Y=713102	467.63		10.75	2.3			
Y=713707	2783.81		12.96	2.3			
Y=716402	1982.85		13.76	2.3			
Y=716952	2531.92		7.55	2.3			
Average	1817.64	1.78	15.25	2.3	0.00002	2183.9	31
Adjusted slope	1817.64	1.78	15.25	2.3	0.00010	4996.9	211

Figure C2- The Microsoft Excel table shows all measurements for each of the charlie stream cross sections. The stream cross sections are color coordinated matching appendix figures C1 and C3.

Figure C3 - Microsoft Excel graph shows all the charlie stream channel cross sections based on their location on the Z or depth plain and is measured in feet.

Y=716402

Figure C4- Microsoft Excel graph shows the charlie stream, cross section Y=716402 which was generated in Petrel 2010.2 and measured in feet.

Figure C5- Image of the charlie stream, cross section Y=716402 in the variance attribute generated in Petrel 2010.2.

Figure C6- Image of the charlie stream, cross section Y=716402 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure C7- Image of the charlie stream, cross section Y=716402 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure C8- Image of the charlie stream, cross section Y=716402 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure C9- Image of the charlie stream, cross section Y=716402 in the is-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure C10- Image of the charlie stream, cross section Y=716402 in the dip deviation attribute generated in Petrel 2010.2.

Figure C11- Image of the charlie stream, cross section Y=716402 in the amplitude attribute generated in Petrel 2010.2.

FigureC12- Image of the charlie stream, cross section Y=716402 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure C13- Image of the charlie stream, cross section Y=716402 in the gradient magnitude attribute generated in Petrel 2010.2.

Y=713707

Figure C14- Microsoft Excel graph shows the charlie stream, cross section Y=713707 which was generated in Petrel 2010.2 and measured in feet.

Figure C15- Image of the charlie stream, cross section Y=713707 in the variance attribute generated in Petrel 2010.2.

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Figure C21- Image of the charlie stream, cross section Y=713707 in the amplitude attribute generated in Petrel 2010.2.

Figure C22- Image of the charlie stream, cross section Y=713707 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure C23- Image of the charlie stream, cross section Y=713707 in the gradient magnitude attribute generated in Petrel 2010.2.

Y=716952

Figure C24- Microsoft Excel graph shows the charlie stream, cross section Y=716952 which was generated in Petrel 2010.2 and measured in feet.

Figure C25- Image of the charlie stream, cross section Y=716952 in the variance attribute generated in Petrel 2010.2.

Figure C26- Image of the charlie stream, cross section Y=716952 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure C27- Image of the charlie stream, cross section Y=716952 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure C28- Image of the charlie stream, cross section Y=716952 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure C29- Image of the charlie stream, cross section Y=716952 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure C30- Image of the charlie stream, cross section Y=716952 in the dip deviation attribute generated in Petrel 2010.2.

Figure C31- Image of the charlie stream, cross section Y=716952 in the amplitude attribute generated in Petrel 2010.2.

Figure C32- Image of the charlie stream, cross section Y=716952 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure C33- Image of the charlie stream, cross section Y=716952 in the gradient magnitude attribute generated in Petrel 2010.2.

Y=713102

Figure C34- the Microsoft Excel graph shows the charlie stream, cross section Y=713102 which was generated in Petrel 2010.2 and measure in feet.

Figure C35- Image of the charlie stream, cross section Y=713102 in the variance attribute generated in Petrel 2010.2.

Figure C36- Image of the charlie stream, cross section Y=713102 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure C37- Image of the charlie stream, cross section Y=713102 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure C38- Image of the charlie stream, cross section Y=713102 in the iso-frequency attribute generated in Petrel 2010.2.

Figure C39- Image of the charlie stream, cross section Y=713102 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure C40- Image of the charlie stream, cross section Y=713102 in the dip deviation attribute generated in Petrel 2010.2.

Figure C41- Image of the charlie stream, cross section Y=713102 in the amplitude attribute generated in Petrel 2010.2.

Figure C42- Image of the charlie stream, cross section Y=713102 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure C43- Image of the charlie stream, cross section Y=713102 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2186683

Figure C44- Microsoft Excel graph shows the charlie stream, cross section X=2186683 which was generated in Petrel 2010.2 and measured in feet.

Figure C45- Image of the charlie stream, cross section X=2186683 in the variance attribute generated in Petrel 2010.2.

Figure C46- Image of the charlie stream, cross section X=2186683 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure C47- Image of the charlie stream, cross section X=2186683 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure C48- Image of the charlie stream, cross section X=2186683 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure C49- Image of the charlie stream, cross section X=2186683 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure C50- Image of the charlie stream, cross section X=2186683 in the dip deviation attribute generated in Petrel 2010.2.

Figure C51- Image of the charlie stream, cross section X=2186683 in the amplitude attribute generated in Petrel 2010.2.

Figure C52- Image of the charlie stream, cross section X=2186683 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure C53- Image of the charlie stream, cross section X=2186683 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2188883

Figure C54- Microsoft Excel graph shows the charlie stream, cross section Y=713102 which was generated in Petrel 2010.2 and measured in feet.

Figure C55- Image of the charlie stream, cross section Y=713102 in the variance attribute generated in Petrel 2010.2.

Figure C56- Image of the charlie stream, cross section Y=713102 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure C57- Image of the charlie stream, cross section Y=713102 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure C58- Image of the charlie stream, cross section Y=713102 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure C59- Image of the charlie stream, cross section Y=713102 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure C60- Image of the charlie stream, cross section Y=713102 in the dip deviation attribute generated in Petrel 2010.2.

Figure C61- Image of the charlie stream, cross section Y=713102 in the amplitude attribute generated in Petrel 2010.2.

Figure C62- Image of the charlie stream, cross section Y=713102 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure C63- Image of the charlie stream, cross section Y=713102 in the gradient magnitude attribute generated in Petrel 2010.2.

Delta Stream

Figure D1- A map view of the delta stream surface with the five cross sections shown generated in Petrel 2010.2.

Cross Section	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge (m ³ /s)	Drainage Area (km ²)
Y=715082	6618.53		25.37	2.30			
Y=717557	2521.45		15.35	2.30			
X=2188608	3056.37		18.12	2.30			
X=2189488	1820.05		24.76	2.30			
X=2190313	2441.79		12.00	2.30			
Average	3291.64	1.27	19.12	2.30	-0.0015	114,162	305,493
Adjusted Slope	3291.64	1.27	19.12	2.30	0.0001	29,705	13,343

Figure D2- Microsoft Excel table shows all measurements for each of the delta stream cross sections at the higher bankfull surface. The stream cross sections are color coordinated matching Figures D1 and D4.

Cross Section	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge m ³ /s	Drainage Area (km ²)
Y=715082	3220.13		16.56	2.30			
Y=717557	2521.45		15.35	2.30			
X=2188608	1135.91		21.87	2.30			
X=2189488	1820.05		24.76	2.30			
X=2190313	2441.79		12.00	2.30			
Average	2227.87	1.27	18.11	2.30	0.0040	109,247	275,778
Adjusted Slope	2227.87	1.27	18.11	2.30	0.0001	17,208	3,748

Figure D3- The Microsoft Excel table shows all measurements for each of the delta stream cross sections at the lower bankfull surface. The stream cross sections are color coordinated matching Figures D1 and D4.

Figure D4- Microsoft Excel graph shows all the delta stream channel cross sections based on their location on the Z or depth plain and measured in feet.

Y=717557

Figure D5- Microsoft Excel graph shows the delta stream, cross section Y=717557 which was generated in Petrel 2010.2 and measured in feet.

Figure D6- Image of the delta stream, cross section Y=717557 in the variance attribute generated in Petrel 2010.2.

Figure D7- Image of the delta stream, cross section Y=717557 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure D8- Image of the delta stream, cross section Y=717557 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure D9- Image of the delta stream, cross section Y=717557 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure D10- Image of the delta stream, cross section Y=717557 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure D11- Image of the delta stream, cross section Y=717557 in the dip deviation attribute generated in Petrel 2010.2.

Figure D12- Image of the delta stream, cross section Y=717557 in the amplitude attribute generated in Petrel 2010.2.

Figure D13- Image of the delta stream, cross section Y=717557 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure D14- Image of the delta stream, cross section Y=717557 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2190313

Figure D15- Microsoft Excel graph shows the delta stream, cross section X=2190313 which was generated in Petrel 2010.2 and measured in feet.

Figure D16- Image of the delta stream, cross section X=2190313 in the variance attribute generated in Petrel 2010.2.

Figure D17- Image of the delta stream, cross section X=2190313 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure D18- Image of the delta stream, cross section X=2190313 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure D19- Image of the delta stream, cross section X=2190313 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure D20- Image of the delta stream, cross section X=2190313 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure D21- Image of the delta stream, cross section X=2190313 in the dip deviation attribute generated in Petrel 2010.2.

Figure D22- Image of the delta stream, cross section X=2190313 in the amplitude attribute generated in Petrel 2010.2.

Figure D23- Image of the delta stream, cross section X=2190313 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure D24- Image of the delta stream, cross section X=2190313 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2189488

Figure D25- Microsoft Excel graph shows the delta stream, cross section X=2189488 which was generated in Petrel 2010.2 and measured in feet.

Figure D26- Image of the delta stream, cross section X=2189488 in the variance attribute generated in Petrel 2010.2.

Figure D27- Image of the delta stream, cross section X=2189488 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure D28- Image of the delta stream, cross section X=2189488 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure D29- Image of the delta stream, cross section X=2189488 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure D30- Image of the delta stream, cross section X=2189488 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure D31- Image of the delta stream, cross section X=2189488 in the dip deviation attribute generated in Petrel 2010.2.

Figure D32- Image of the delta stream, cross section X=2189488 in the amplitude attribute generated in Petrel 2010.2.

Figure D33- Image of the delta stream, cross section X=2189488 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure D34- Image of the delta stream, cross section X=2189488 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2188608

Figure D35- Microsoft Excel graph shows the delta stream, cross section X=2188608 which was generated in Petrel 2010.2 and measured in feet.

Figure D36- Image of the delta stream, cross section X=2188608 in the variance attribute generated in Petrel 2010.2.

Figure D37- Image of the delta stream, cross section X=2188608 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure D38- Image of the delta stream, cross section X=2188608 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure D39- Image of the delta stream, cross section X=2188608 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure D40- Image of the delta stream, cross section X=2188608 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure D41- Image of the delta stream, cross section X=2188608 in the dip deviation attribute generated in Petrel 2010.2.

Figure D42- Image of the delta stream, cross section X=2188608 in the amplitude attribute generated in Petrel 2010.2.

Figure D43- Image of the delta stream, cross section X=2188608 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure D44- Image of the delta stream, cross section X=2188608 in the gradient magnitude attribute generated in Petrel 2010.2.

Y=715082

Figure D45- Microsoft Excel graph shows the delta stream, cross section X=2188608 which was generated in Petrel 2010.2 and measured in feet.

Figure D46- Image of the delta stream, cross section X=2188608 in the variance attribute generated in Petrel 2010.2.

Figure D47- Image of the delta stream, cross section X=2188608 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure D48- Image of the delta stream, cross section X=2188608 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure D49- Image of the delta stream, cross section X=2188608 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure D50- Image of the delta stream, cross section X=2188608 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure D51- Image of the delta stream, cross section X=2188608 in the dip deviation attribute generated in Petrel 2010.2.

Figure D52- Image of the delta stream, cross section X=2188608 in the amplitude attribute generated in Petrel 2010.2.

Figure D53- Image of the delta stream, cross section X=2188608 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure D54- Image of the delta stream, cross section X=2188608 in the gradient magnitude attribute generated in Petrel 2010.2.

Fox Stream

Figure F1- A map view of the fox stream surface with the five cross sections shown generated in Petrel 2010.2.

Cross Section	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge (m ³ /s)	Drainage Area (km ²)
X=2182318	2729.26		14.96	2.30			
X=2182503	906.17		9.54	2.30			
X=2182778	887.12		15.46	2.30			
X=2185033	2160.54		10.24	2.30			
Average	1670.77	1.32	12.55	2.30	0.3411	253,958	1,961,273
Adjusted Slope	1670.77	1.32	12.55	2.30	0.0001	4,349	153

Figure F2- Microsoft Excel table shows all measurements for each of the fox stream cross sections at the higher bankfull surface. The stream cross sections are color coordinated matching figures F1 and F4.

Cross Section	Cross Sectional Area (m ²)	Sinuosity	Width: Depth Ratio	Entrenchment Ratio	Stream Gradient	Discharge (m ³ /s)	Drainage Area (km ²)
X=2182318	1751.46		14.81	2.30			
X=2182503	906.17		9.54	2.30			
X=2182778	887.12		15.46	2.30			
X=2185033	2160.54		10.24	2.30			
Average	1426.32	1.32	12.51	2.30	0.1982	170,912	780,845
Adjusted Slope	1426.32	1.32	12.51	2.30	0.0001	3,839	114

Figure F3- Microsoft Excel table shows all measurements for each of the fox stream cross sections at the higher bankfull surface. The stream cross sections are color coordinated matching figures F1 and F4.

Figure F4- The Microsoft Excel graph shows all the fox stream channel cross sections based on their location on the Z or depth plain and is measured in feet.

X=2182318

Figure F5- Microsoft Excel graph shows the fox stream, cross section X=2183218 which was generated in Petrel 2010.2 and measured in feet.

Figure F6- Image of the fox stream, cross section X=2183218 in the variance attribute generated in Petrel 2010.2.

Figure F7- Image of the fox stream, cross section X=2183218 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure F8- Image of the fox stream, cross section X=2183218 in the Iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure F9- Image of the fox stream, cross section X=2183218 in the Iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure F10- Image of the fox stream, cross section X=2183218 in the Iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure F11- Image of the fox stream, cross section X=2183218 in the dip deviation attribute generated in Petrel 2010.2.

Figure F12- Image of the fox stream, cross section X=2183218 in the amplitude attribute generated in Petrel 2010.2.

Figure F13- Image of the fox stream, cross section X=2183218 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure F14- Image of the fox stream, cross section X=2183218 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2182503

Figure F15- Microsoft Excel graph shows the fox stream, cross section X=2183218 which was generated in Petrel 2010.2 and is measured in feet.

Figure F16- Image of the fox stream, cross section X=2183218 in the variance attribute generated in Petrel 2010.2.

Figure F17- Image of the fox stream, cross section X=2183218 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure F18- Image of the fox stream, cross section X=2183218 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure F19- Image of the fox stream, cross section X=2183218 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure F20- Image of the fox stream, cross section X=2183218 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure F21- Image of the fox stream, cross section X=2183218 in the dip deviation attribute generated in Petrel 2010.2.

Figure F22- Image of the fox stream, cross section X=2183218 in the amplitude attribute generated in Petrel 2010.2.

Figure F23- Image of the fox stream, cross section X=2183218 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure F24- Image of the fox stream, cross section X=2183218 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2182778

Figure F25- Microsoft Excel graph shows the fox stream, cross section X=2182778 which was generated in Petrel 2010.2 and measured in feet.

Figure F26- Image of the fox stream, cross section X=2182778 in the variance attribute generated in Petrel 2010.2.

Figure F27- Image of the fox stream, cross section X=2182778 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure F28- Image of the fox stream, cross section X=2182778 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure F29- Image of the fox stream, cross section X=2182778 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure F30- Image of the fox stream, cross section X=2182778 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure F31- Image of the fox stream, cross section X=2182778 in the dip deviation attribute generated in Petrel 2010.2.

Figure F32- Image of the fox stream, cross section X=2182778 in the amplitude attribute generated in Petrel 2010.2.

Figure F33- Image of the fox stream, cross section X=2182778 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure F34- Image of the fox stream, cross section X=2182778 in the gradient magnitude attribute generated in Petrel 2010.2.

X=2185033

Figure F35- Microsoft Excel graph shows the fox stream, cross section X=2185033 which was generated in Petrel 2010.2 and is measured in feet.

Figure F36- Image of the fox stream, cross section X=2185033 in the variance attribute generated in Petrel 2010.2.

Figure F37- Image of the fox stream, cross section X=2185033 in the instantaneous frequency attribute generated in Petrel 2010.2.

Figure F38- Image of the fox stream, cross section X=2185033 in the iso-frequency (20Hz) attribute generated in Petrel 2010.2.

Figure F39- Image of the fox stream, cross section X=2185033 in the iso-frequency (30Hz) attribute generated in Petrel 2010.2.

Figure F40- Image of the fox stream, cross section X=2185033 in the iso-frequency (40Hz) attribute generated in Petrel 2010.2.

Figure F41- Image of the fox stream, cross section X=2185033 in the dip deviation attribute generated in Petrel 2010.2.

Figure F42- Image of the fox stream, cross section X=2185033 in the amplitude attribute generated in Petrel 2010.2.

Figure F43- Image of the fox stream, cross section X=2185033 in the RMS amplitude attribute generated in Petrel 2010.2.

Figure F44- Image of the fox stream, cross section X=2185033 in the gradient magnitude attribute generated in Petrel 2010.2.