Paper 2

Quantifying clinothem geometry in a forced-regressive river-dominated delta, Panther Tongue, Utah, USA

Håvard D. Enge[1,2], John A. Howell[2], Simon J. Buckley[2]

[1] *Department of Earth Science, University of Bergen, Box 7800, 5020 Bergen, Norway*

[2] *Centre for Integrated Petroleum Research, University of Bergen, Box 7800, 5020 Bergen, Norway*

Corresponding author: havard.enge@cipr.uib.no

Abstract

This study presents a methodology for the quantitative description of small scale delta clinothems. The quantitative bed-data analysis is based on three-dimensional virtual outcrop models (VOMs) generated by ground-based laser scanning (lidar). A large number of clinothem bed-measurements have been collected from the ancient forced regressive delta system of the Panther Tongue that crops out in Utah, USA. In river-dominated marginal marine environments, clinothems separated by clinoform surfaces represent the former position of the delta front as it prograded.

Systematic collection of data from VOMs has allowed for accurate, spatially-constrained measurement of individual bed thicknesses and the compilation of a detailed database on clinothems and associated clinoform geometries. Measurement locations were selected so that each measurement was 10 m down depositional dip from the previous one. The study area covers 5km^2 within which 2376 measurements were made from the 50 separate clinothems in 320 different positions within the virtual outcrop.

A decay gradient parameter permitted the thinning of the clinothems to be described as a single number and thus allowed relative comparison between beds, and combined measurements were also used to calculate the average (not maximum) dip angle. Analysis of the vertical and lateral stacking of the clinothems has revealed a series of stratigraphic cycles which are termed bedsets. A cyclic depositional pattern interpreted to be related to autocyclic processes in deltaic mouth bars is documented. Mapped length/thickness trends constrain the spread of these variables, and can be used as a reservoir analogue.

Introduction

Clinoforms are seaward dipping surfaces that define the palaeo-depositional surface in shallow marine, shelf and slope systems (Gilbert, 1885; Barrell, 1912; Rich, 1951).Within deltaic systems clinoforms represent the palaeo-position of the delta front surface as it prograded (Howell et al., 2008). Basinward dipping beds, bounded by clinoforms are termed clinothems (Rich, 1951).The gradient of the clinoform surfaces and the thickness and character of the clinothems associated with them are dependent on a variety of factors including the grain size of the sediment, sediment dispersal and the interplay of different depositional processes and the depth of the receiving basin (Orton and Reading, 1993; Reading and Levell, 1996). Changes in relative sea-level and the gradient of the sea-floor during deposition also influence clinothem geometry (Posamentier and Morris, 2000).

This study is based upon a high resolution, virtual outcrop dataset from the Panther Tongue Member of the Star Point Formation, which crops out in the area around Helper in central Utah, USA (Fig. 1). A series of parameters are introduced that quantify aspects of the clinothems. The methods that have been used were developed for the falling to low stage system tract deposits of the Panther Tongue, but are also equally as applicable to other deltaic outcrops. The bed parameterisation and data analysis are based heavily on three dimensional virtual outcrop models generated by ground-based laser scanning (lidar), which have allowed the accurate, spatially constrained measurement of over 2376 individual bed thickness measurements. The statistical data provide insight into the evolution of deltaic systems. The data also have important implications for the correlation and computer based modelling of subsurface hydrocarbon reservoirs, where dipping siltstones associated with clinoforms generate important barriers and baffles to fluid flow (e.g. Tyler and Finley, 1991; Alexander, 1993; Dreyer et al., 1993; Ainsworth et al., 1999; Tye et al., 1999; Willis and White, 2000; Bhattacharya and Willis, 2001; Howell et al., 2008).

Deltas, clinoforms and clinothems

Deltas have been classified as “discrete shoreline protuberances formed where rivers enter oceans, semi-enclosed seas, lakes or lagoons and supply sediment more rapidly than it can be redistributed by basinal processes” (Elliott, 1986). They are therefore by definition progradational features. Deltas are typically further divided on the basis of the dominant physical process (Coleman and Wright, 1975; Galloway, 1975), with the division into river-, wave- or tidal-dominated (Galloway, 1975) remaining the most common classification. Orton and Reading (1993) stressed the role of varying grain size in controlling delta form and shape, and Dalrymple (1992) extended the ternary classification scheme to include change of relative sea level. It is recognised that there is a gradual transition between the different end members, and recent workers (e.g. Fielding et al., 2005; Gani and Bhattacharya, 2007) have stressed that present morphology and process may be a poor indicator of facies complexity due to overprinting.

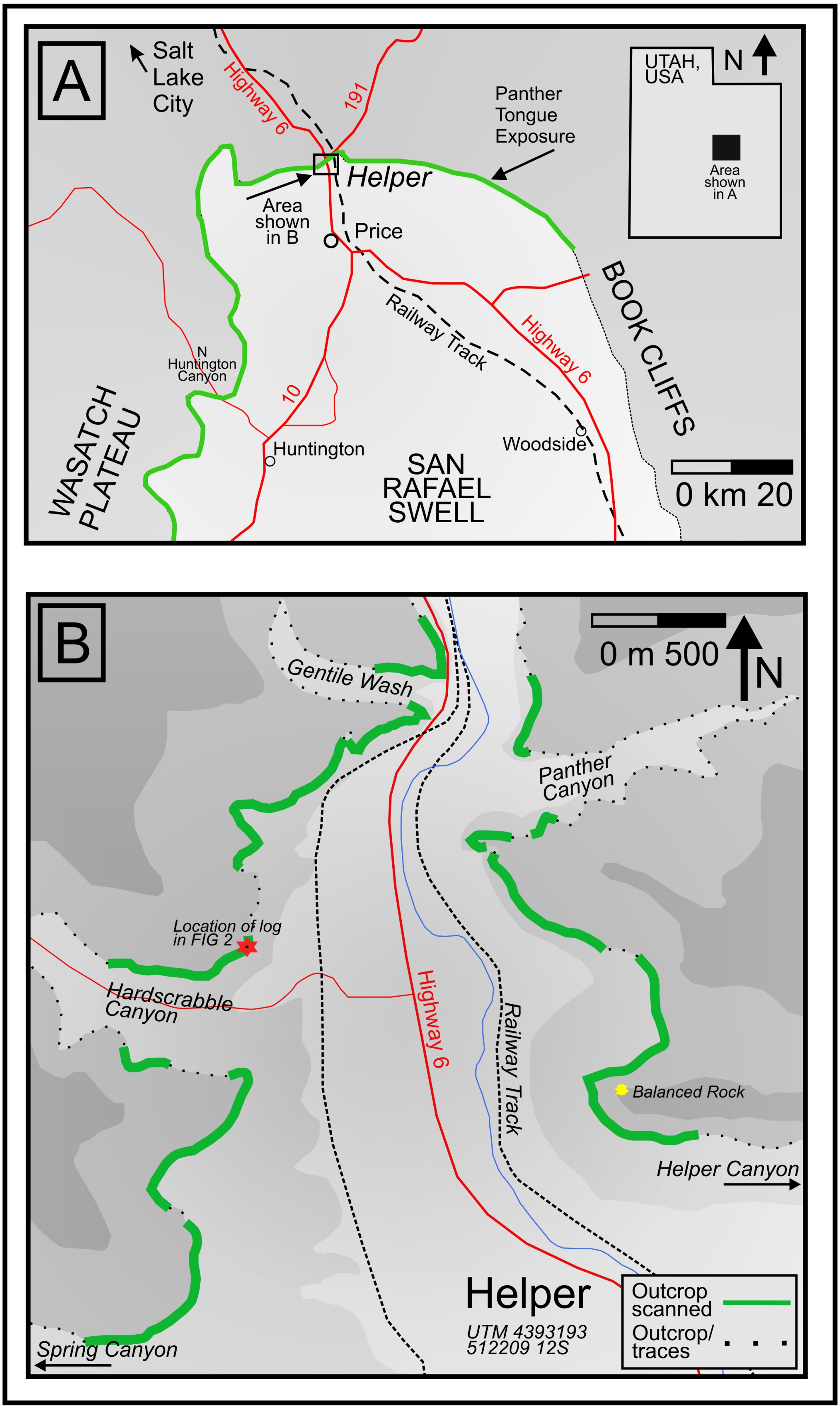


Fig. 1. Study area. **(A)** Map of the central-east Utah, USA, with location of Helper study area. **(B)** Study area around and north of Helper. Outcrops are located both east and west of Highway 6.

Modern studies of deltas date back to Gilbert (1885) and Barrell (1912), who introduced the basic tripartite division of deltaic facies into topsets, foresets and bottomset beds. This concept was extended by Rich (1951) who termed the surfaces associated with these beds undaform, clinoform and fondoform, respectively. Rich (1951) used the term clinoform specifically to describe the seaward dipping, topographic landform produced in association with foreset beds. Rich (1951) also used the term clinothem to describe the body of rock bounded by individual clinoforms. Vail (1977) extended the usage and scale of the term clinoform to describe inclined seismic reflectors that owe their inclination to the primary depositional dip. Mitchum (1977) described the geometry of seismically-defined clinoforms as sigmoid, oblique or shingled. Today the term clinoform is most commonly used to describe the seaward sloping depositional surface of a morphological feature and within a wide variety of sub-aqueous depositional systems (e.g. Hampson, 2000; Gani and Bhattacharya, 2005; Bhattacharya, 2006).

Clastic clinoforms cover a wide range of scales from 10^1 – 10^5 m in length to 1 – 10^3 m in height (e.g. Helland-Hansen, 1992; Anderson et al., 2004). Clinothems may contain a variety of interfingering facies from the bottom set, through the foreset to the top set beds (e.g. Gani and Bhattacharya, 2005). Mapping of the shoreline or shelf edge break at the top of successive clinoforms has been used to plot the shoreline and shelf edge trajectory through time (Posamentier et al., 1992; Helland-Hansen and Gjelberg, 1994).

River dominated deltas

In river dominated deltas sediment is transported across the delta top to the shoreline by a network of terminal distributary channels that spread out from a main trunk channel (Olariu and Bhattacharya, 2006). Sediment is deposited at the mouth of these channels in mouthbars. Autocyclic shifting of the distributary channels results in abandonment of older mouthbars and deposition in former interdistributary areas (Elliott, 1986; Olariu and Bhattacharya, 2006) leading to a radiating pattern of deposits (Willis et al., 1999). The lithological expression of overlapping lobes that results may be subtle and difficult to identify in limited outcrop of subsurface datasets (Bhattacharya and Willis, 2001). Autocyclic switching is expected to be less prominent in forced regressive system-tract-deltas than for deltas in other systems tract due to the incision and subsequent confinement of the main trunk channel in an incised valley (Posamentier and Morris, 2000).

The nature of deposition within the mouth bar and the clinoform geometry is controlled by the relative density of the incoming and ambient fluids, the grain size, and the role of other, basinal processes (Bates, 1953; Wright, 1977; Orton and Reading, 1993; Gani, 2004; Bhattacharya, 2006). In sand-dominated, shallow water systems such as the study interval, turbidity currents play a key role in the deposition of the clinothems. Turbidity flows may be triggered by sandy sediments accumulated in the proximal part of the mouth bars reaching a threshold slope angle and collapsing (Bates, 1953; Bhattacharya, 2006) or they may evolve directly from rapid sedimentation at the delta front (Wright et al., 1986; Mulder and Syvitski, 1995). In the former case rapidly-deposited sands with burrowed tops are expected to be interbedded with mud that are deposited slowly from suspension in between "events" (MacEachern et al., 2005), whereas in the latter sedimentation from gravity flow is more continuous, resulting in a lower degree of bioturbation (Bhattacharya, 2006).

During progradation of a sand-dominated delta the clinothems thin and fine in a seaward direction in an en-echelon pattern as they build basinwards. Sand dominated beds are interbedded with muds and finer material deposited during quieter periods (Posamentier and Morris, 2000; Bhattacharya and Willis, 2001; Anderson et al., 2004). In outcrop, the finer siltstone occurs as slightly more recessive breaks in the cliff face. An idealised depositional strike view of the clinothems will show bidirectional downlap, forming a lens-shaped geometry (Berg, 1982; Willis et al., 1999; Bhattacharya, 2006). A plan view will show the seaward dipping lenses of sediment that define the individual lobes and the radiating pattern and minor changes in dip direction of successive lobes (Anderson et al., 2004).

Within the delta front clinoforms generally approximate time lines (Miall, 1985) which may be difficult to distinguish in distal portions of the deltas where the predominantly finer grained deposits are subhorizontal. Packages of sediment with genetically related clinothems are termed bedsets, which for the purpose of this study equate to the individual autocyclically derived delta lobes. The term parasequence is reserved for larger scale packages that have an allocyclic origin. It is recognised that these definitions are not universally accepted, however this is a pragmatic approach and a full discussion of this subject matter is beyond the scope of this paper.

The maximum dip of the clinoforms with respect to a palaeo-horizontal datum is highly variable. Seaward dips of 5 – 15° are common (e.g. Anderson et al., 2004; Olariu and

Bhattacharya, 2006). In fine to medium grained clastic systems, maximum dip in a depositional direction can vary from almost zero to as high as 27 ° (e.g. Posamentier and Morris, 2000). Variations in the dip are related to grain size and process but at outcrop are further complicated by variations in orientation with respect to depositional dip which differs from bedset to bedset. The aim of this study is to systematically measure clinothem, thickness and dip and to look for patterns within the packages

The Panther Tongue Member

The Cretaceous-aged Panther Tongue Member of the Star Point Formation, Mesaverde Group, is well exposed along the eastern flank of the Wasatch Plateau and in the western part of the Book Cliffs, around the town of Helper in central Utah, USA (Young, 1955; Howard, 1966) (Fig. 1). Young (1955) defined the upper Cretaceous Star Point Formation as being comprised of two sandy wedges which sit within the Mancos Shale, namely the Panther Tongue and the overlying Storrs Tongue. A thick interval of Mancos Shale overlies the Emery Sandstone Member beneath the Panther Tongue and a thin interval of Mancos Shale separates the top of the Storrs from the overlying Blackhawk Formation (Newman and Chan, 1991). The thickness of the Star Point Formation varies between 7 m and 100 m (Hintze, 1988). All of these deposits were laid down on the western edge of the Cretaceous interior seaway that developed as a foreland basin as a result of flexural down warping of the lithosphere due to the rise of the Sevier Orogenic belt in the west. The formation of the basin and its subsequent filling were controlled by a complex interplay between tectonic activity and variations and changes in eustatic sea level (Jordan, 1981; Fouch et al., 1983; Kauffman, 1984; Cross, 1986).

In his overview-paper, Young (1955) described the Panther Tongue as a longshore bar oriented northeast-southwest interfingering with the Mancos Shale. Howard (1966) interpreted it as nearshore deposits. Newman and Chan (1991) expressly placed the deposits of the Panther Tongue in a prograding fluvial dominated deltaic environment topped by a transgressive lag. Olariu et al. (2005), Posamentier and Morris (2000), and Howell and Flint (2004) and Howell et al. (2008) supported this interpretation and proposed a lowstand to falling stage setting for the development of the deltaic system.

The proximal part of the Panther Tongue Member crops out in the area around the town of Helper where it forms vertical sandstone cliffs at various orientations with a maximum thickness of 25 m (Figs. 1 and 2). The overlying Storrs Member is of distal shoreface origin (Howell and Flint, 2004) and assumed to have been deposited close to horizontal. Beds within the Storrs Member have a tectonic dip of 3.9°, measured from the virtual outcrop. The ravinement surface at the top of the Panther Tongue dips has a comparable strike and dips north at 3.8°. This small difference may reflct a 0.1° dip of the ravinement surface or is simply related to uncertainties in data collection. Around Helper the deposits include heterolithic clinothem packages that thin towards the south-southwest and are interpreted as delta front mouth bars (Posamentier and Morris, 2000; Olariu et al., 2005). A large (20 m deep, 200 m wide) trunk channel is exposed west of Helper in Spring Canyon (Olariu et al., 2005). In the same area, Olariu et al. (2005) and Olariu and Bhattacharya (2006) also identify terminal distributary channels in outcrop and ground penetrating radar (GPR) profiles. The top of the succession is marked by a medium to coarse grained, heavily bioturbated interval interpreted as a transgressive lag (Hwang and Heller, 2002).

The Panther Tongue extends southward for between 52 and 100 km along the eastern margin of the Wasatch Plateau (Newman and Chan, 1991; Posamentier and Morris, 2000).The system progrades towards the SSW which is parallel to the regional palaeo-shoreline (Howard, 1966; Williams and Stelck, 1975; Olariu et al., 2005). This is in contrast with overlying and underlying shoreface deposits that mainly prograded towards the east. Olariu et al. (2005) advocated that the oblique orientation of the shoreline may have been controlled by structural topography and limited accommodation during falling relative sea-level.

Sedimentology and Sequence Stratigraphy

Four facies associations have been described from the proximal Panther Tongue Member (Fig. 2), namely pro-delta, lower and upper delta front, and transgressive lag. The lower and upper delta front constitute the greater part of the mouth bar-deposits. No delta-plain facies have been observed. Mouth bar-deposits, trunk channels, “terminal” distributary channels, and up-stream-accreting mouth bars have been described by Olariu and Bhattacharya (2005), Olariu et al. (2005) and Howell et al. (2008).

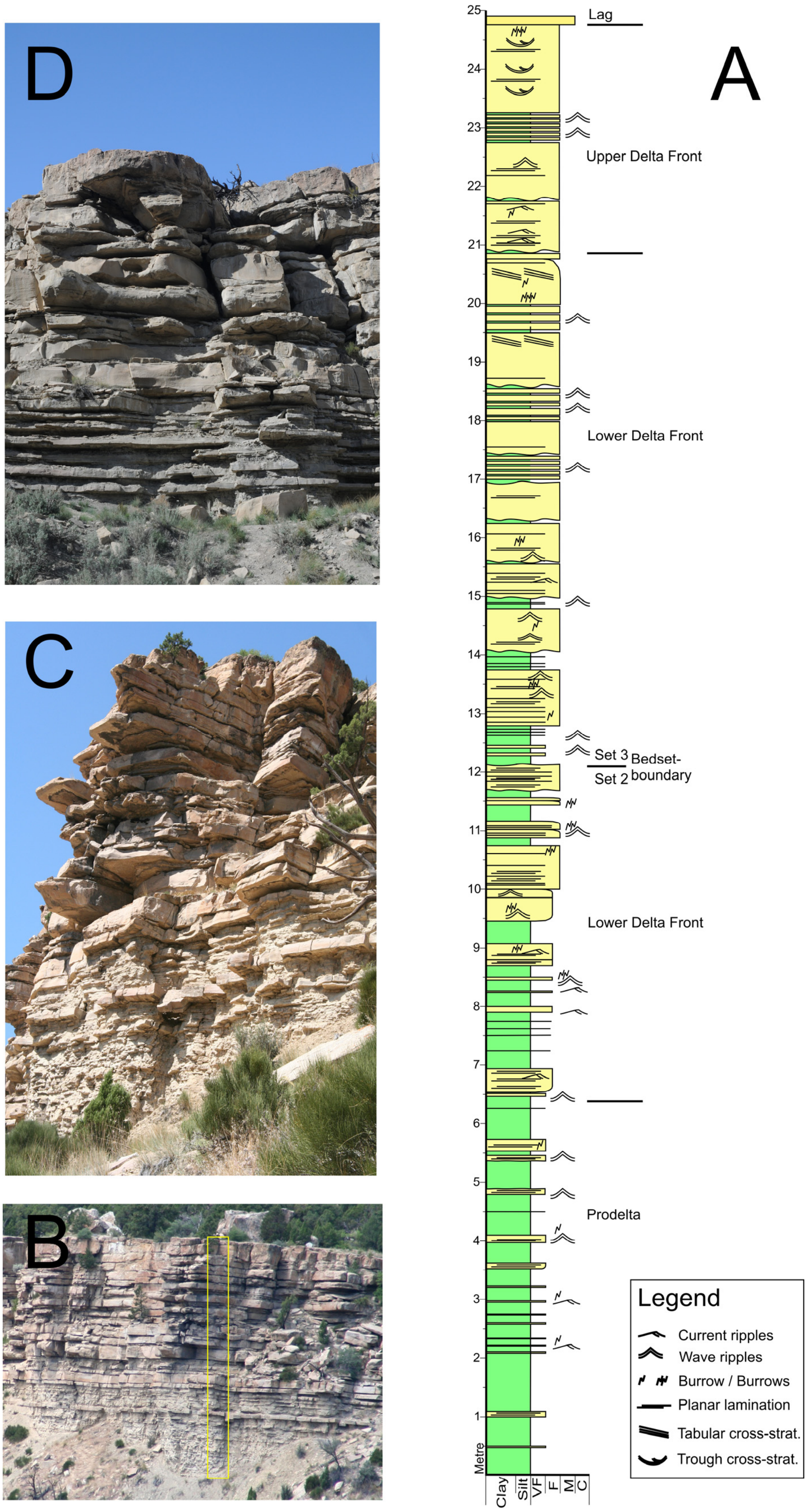


Fig. 2. **(A)** Stratigraphic log summarising main features of the clinothems. Location indicated in figure 1B. **(B)** Photo with log-position outlined. **(C)** Close up of (B). **(D)** Photo from Gentile Wash, proximal to log-area, illustrating upward-coarsening trend that characterises the Panther Tongue.

The clinothems comprise both the upper and lower delta front with thin pro-delta siltstone layers sandwiched in between (Fig. 2). The clinothems record mostly very fine to medium coarse grain size, occasionally also up to coarse grained, dip palaeo-seawards, are thickest in the proximal parts and become thinner palaeo-seawards before they eventually pinch out in the Mancos shale in an offlapping manner (Newman and Chan, 1991; Catuneanu, 2006). There is an overall upwards-coarsening of the sandstone beds from very fine to medium grained. Locally the upper most bed is medium coarse grained. Individual beds have a sharp, locally erosive base with occasional sole marks, bioturbation is rare and beds show grading from massive to planar laminated to rippled with wave ripples on top (Fig. 2). Liquefaction and soft sediment deformation structures have been observed in some of the massive layers. Tabular cross-stratified and trough cross-stratified sandstones also occur. Prodelta shales bound the delta front deposits and the basal bounding surface is gradationally based (Posamentier and Morris, 2000; Catuneanu, 2006). In a depositional strike direction, the clinoforms are more horizontally continuous and dip more shallowly than in the dip direction. Catuneanu (2006) separates the delta front clinoforms of the Panther Tongue into steep clinoforms (maximum approximately 27°) associated with grain flow deposits, and finer grained and lower angled (maximum approximately 10°) clinoforms associated with turbidity flows. The steeper clinoforms are not seen in the current study area.

Sequence stratigraphically, the Panther Tongue has been interpreted as a falling to lowstand delta formed during a forced regression on the basis of an apparently falling trajectory associated with a lack of time equivalent coastal plain deposits (top-truncated delta) (Posamentier and Morris, 2000; Olariu et al., 2005; Catuneanu, 2006; Howell et al., 2008). No evidence of lowstand deposits offshore of the Panther Tongue Member indicates that it is formed by a single fall in relative sea level (Posamentier and Morris, 2000). Hwang and Heller (2002) mapped a regional transgressive lag formed during the subsequent transgression. The overlying Storrs Member has been interpreted as a transgressive systems tract (Howell and Flint, 2004).

Study Area

The study area covers 5 km² around and slightly north of Helper, from Gentile Wash covering some 2850 and 1550 m of outcrop west and east of Highway 6, respectively (Fig. 1). The outcrop between Gentile Wash and Helper (along Highway 6) comprises a depositional dip section, while the sections on the west and east of the town are broadly parallel to strike. Using the Outcrop Area Ratio (OAR) of Enge et al. (2007) suggests a modest three-dimensionality of 1.2. The outcrops are highly suited to studying the depositional architecture of clinothems as the two key sections, on the east and west side of Highway 6 provide almost 1.5 and 3 km respectively of near continuous exposure that is directly parallel to depositional dip (Fig. 1).

Data processing and generation of virtual outcrop models (VOMs)

The capture and representation of the geological outcrop data for accurate quantitative analysis has been addressed by the collection of high-resolution three dimensionality, digital data from outcrops using a ground-based laser scanner (lidar) and the building of VOMs. The virtual outcrop has been supplemented by a series of traditional sedimentary logs.

Laser scanning and the creation of virtual geological outcrops provide a means for the rapid collection and interpretation of large volume of spatially accurate geometric data. It can give insight into both facies scale heterogeneities and large-scale body geometries (e.g. Bellian et al., 2005; Enge et al., 2007; Buckley et al., 2008). Since the pioneering work of Bellian et al. (2005), there has been a rapid increase in the application of lidar to the study and characterization of geological outcrops, and the use of laser-scanning as a method for ground based geological fieldwork is proven (Pringle et al., 2004; Bellian et al., 2005; Olariu et al., 2005; Buckley et al., 2006; Pringle et al., 2006; Enge et al., 2007; Redfern et al., 2007; Buckley et al., 2008; Jones et al., 2008).

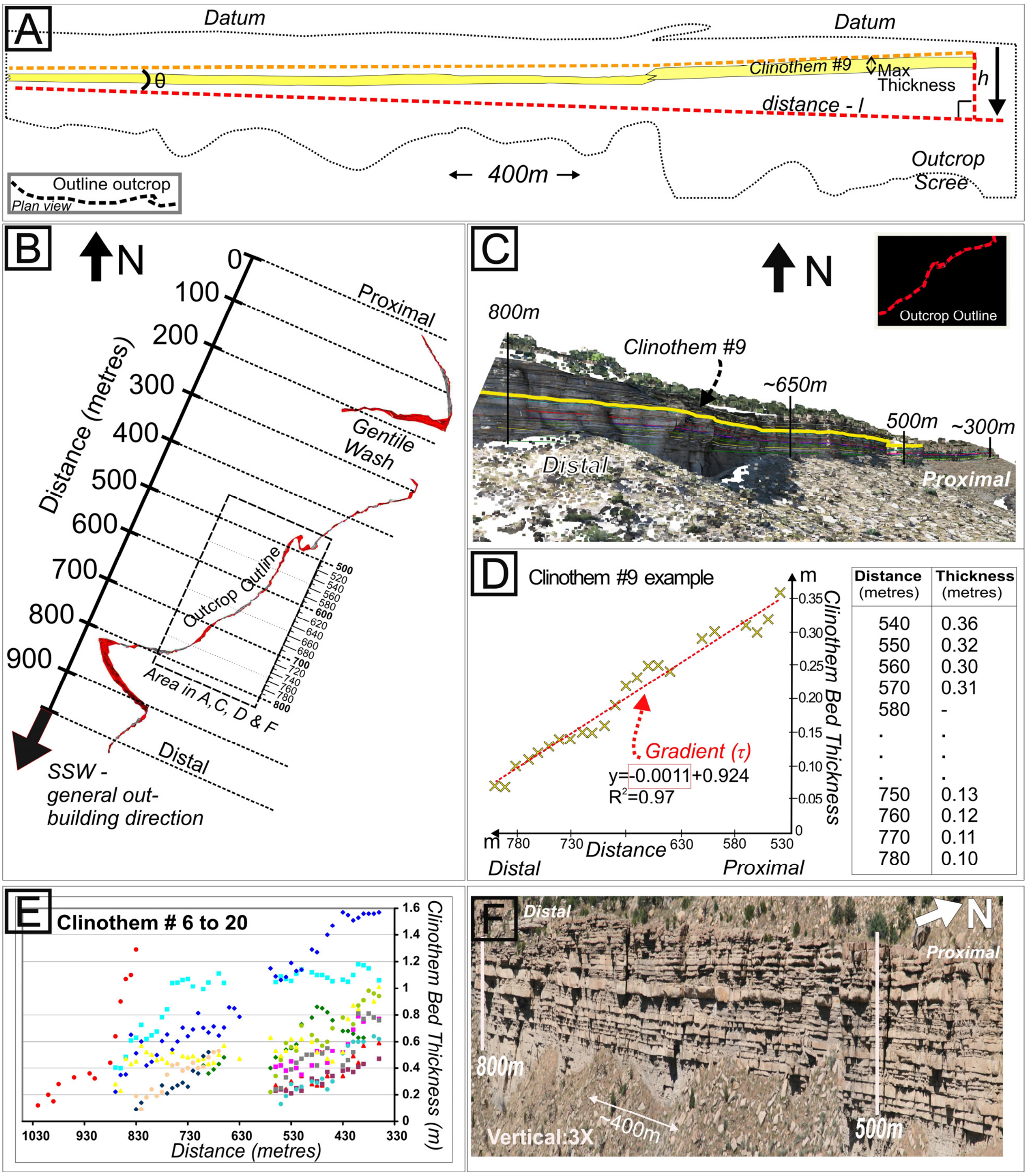
Key issues with the utilization of outcrop data have been: (1) the collection of sufficient volumes of spatially accurate data; (2) correlation of surfaces over long distances and between individual outcrops; (3) the recognition of subtle dip and strike changes in the field; and (4) safe access to vertical and sub-vertical portions of the outcrop. Generation of a VOM involves several steps, from collection of data to post-processing and assembling of the model, as described in Enge et al. (2007) and Buckley et al. (2008). The virtual outcrop model captures the outcrop morphology in detail. As each pixel in the VOM has an XYZ position, measurements can be made and surfaces and features can be traced and digitized and interrogated statistically.

Methodology, parameters and dataset

The combination of traditional field techniques and the VOMs has made it possible to record large volumes of spatially-constrained quantitative measurements from the outcrops and to build a substantial database of these parameters. Methods for collection of the different parameters and the different parameters themselves are discussed in the following sections.

Bed-thickness, bed length and dip angle were recorded at regularly spaced positions for 50 separate clinothem beds in the proximal part of the Panther Tongue. Clinoform surfaces occur in both the upper and lower delta front deposits and extend seaward into the more horizontally stratified prodelta deposits. Outcrop observations indicate that as the dip angle decreases so does the grain size. The grain size at the sub-horizontal, distal end of the clinothems is typically very-fine sand to silt. Bed thickness and other measurements from the VOM have been confined to the more sand-rich, dipping portion of the beds and have typically not been taken from the finer grained portion of the beds.

A key advantage of working from the VOM over traditional photomontages is the possibility to orientate the measurements with respect to the mean palaeo-flow direction. Measurement locations were selected so that each measurement was c. 10 m down depositional dip from the previous one, i.e. they were projected orthogonally on to a plane orientated at 210° which is interpreted from measured palaeo-current reading to be the mean transport direction for this part of the delta system (Howard, 1966; Williams and Stelck, 1975; Newman and Chan, 1991; Olariu et al., 2005) (Fig. 3). Reference to this azimuth was used as basis for all subsequent calculations. The result is measured positions (sections) that are spaced 10 m apart were the outcrop is orientated at 210°. Where the outcrop is locally very oblique to palaeo-flow direction, such as around the entrance to Hardscrabble canyon, readings were taken with a wider spacing (Figs. 1 and 3). This approach is similar to the one used by Hampson and Storms (2003) when reconstructing true spatial relationships of shoreface clinoform geometries.



Distance (metres)	Thickness (metres)
540	0.36
550	0.32
560	0.30
570	0.31
580	-
.	.
.	.
.	.
750	0.13
760	0.12
770	0.11
780	0.10

Fig. 3. Data collection methods and gradient parameter example. **(A)** Outline of single clinothem (#9), shown together with key elements measured. **(B)** Successive measurements were done 10 m down depositional dip from the previous one, i.e. they were projected orthogonally on to a plane orientated parallel palaeo-current. **(C)** Clinothem from (A) outlined on the virtual outcrop model. Area overlaps with small box in (B). **(D)** For each clinothem, a decay gradient-parameter was calculated. Note that distance from origin (y-axis) *increase* towards the *left* in fig. (to facilitate comparison with pictures). **(E)** Thickness /distance plot of selected clinothems from distance 330 to 1030m shown in (B). Distance from origin (y-axis) *increase* towards the *left*. **(F)** Exaggerated outcrop view (3X) of clinothems from ~500 to 800 m shown in square area in (B). See text for details.

In the study area the total distance on the west side of Highway 6, from the north face of Gentile Wash to the entrance to Spring Canyon where a railway track starts to run approximately east-west, is 2850 m parallel to palaeo-flow. The east side of the highway from just north of Panther Canyon to the entrance of Helper Canyon in the area of "Balanced Rock" is 1550 m parallel to palaeo-flow (Fig. 1). Making measurements every tenth meter, implies 285 and 155 measuring positions on the west and east side, respectively. Oblique orientation of the outcrop relative to mean palaeo-flow direction, major irregularities in the outcrop and some gaps lower the number of measurement positions to 220 and 100 positions (sections) on the west and east sides. A total of 2376 measurements were made from the 50 separate clinothems in the 320 different measurement positions within the VOM. Some minor variations in the vertical quality of the outcrop resulted in not all of the beds being visible at every position. Measurements were normally terminated at the point which the bed became too thin to measure in the virtual outcrop (at thickness < ~0.1 m) or occasionally at end of outcrop (at thickness between 0.1 - 0.45 m).

At each measurement position the location, the apparent thickness (vertical) and the vertical distance to the top of the Panther Tongue were noted for each of the studied clinothems (Fig. 3A). An origin was defined at the up-dip pinch-out of the most landward measured clinothem, and the clinothems were numbered 1 to 29 on the west side of the valley and 1 to 21 on the east side. In each case 1 is the oldest.

Most but not all of the clinothems were measured. In each position, an average of between half and three quarter of the beds that were present were analysed. For instance, for a position with 20 sandy clinothem beds separated by thin beds of finer material, on average data were recorded for between 10 and 15. Some beds, especially those that were above 1 m and clearly amalgamated and would skew the statistics were excluded, although it was not always possible to determine which beds were amalgamated on the VOM. Whilst this means that amalgamated beds thinner than 1 m were included and thicker non-amalgamated beds generally but not always were excluded, the results were preferable to including a lot of amalgamated beds. Beds typically thin down-dip, although there is some minor thinning in the up-dip portion, predominantly associated with the truncation by the transgressive surface.

Initial data analysis

The vertical measurements were corrected for structural dip and converted to true thickness and true distance from the flat transgressive top of the unit (Fig. 3A). The position was used to determine the distance from the origin and the clinothem (bed) length parallel to palaeo-current direction (Fig. 3B). The data were also used to calculate the depositional-dip angle. The average (not maximum) apparent dip was found by calculating the inverse tangent of height difference from minimum distance to maximum distance from datum, divided by total length of clinoform (Fig. 3A).

The data for each individual clinothem was plotted as true thickness against distance from the origin and also as distance from the up-dip pinch out (Fig. 3D and 3E). In both cases it can be seen that the beds predominantly thin down depositional dip. There is however occasionally an initial thickening that is associated with the wedge shape that occurs as a consequence of the transgressive ravinement that occurred across the top of the delta (Hwang and Heller, 2002) (Fig. 2). The down dip thinning can be described by a broadly linear trend. For each individual clinothem, the least squares regression line of the trend was calculated (Fig 3C and 3D). In the equation for that trend $y=ax+b$, b is proxy for the bed thickness at the thickest part and a describes the gradient of the decay i.e. how quickly the bed thins down-dip. This is termed the "decay gradient (τ)" (Fig. 3). The R-square index of the regression was also noted as a measure of how uniformly the bed thinned. In most cases R^2 was greater than 0.75 (80% of the cases). The decay gradient parameter τ is a key part of the data analysis as it allows the thinning of the clinothem to be described as a single number. The relationship between τ and clinothem dip is discussed below. The truncating nature of the top of the unit to some extent makes initial bed thickness, normally corresponding to maximum thickness, an ambiguous figure and a comparison between τ and initial thickness difficult. This fact however does not influence the averaged decay gradient.

The Panther Tongue Member Database

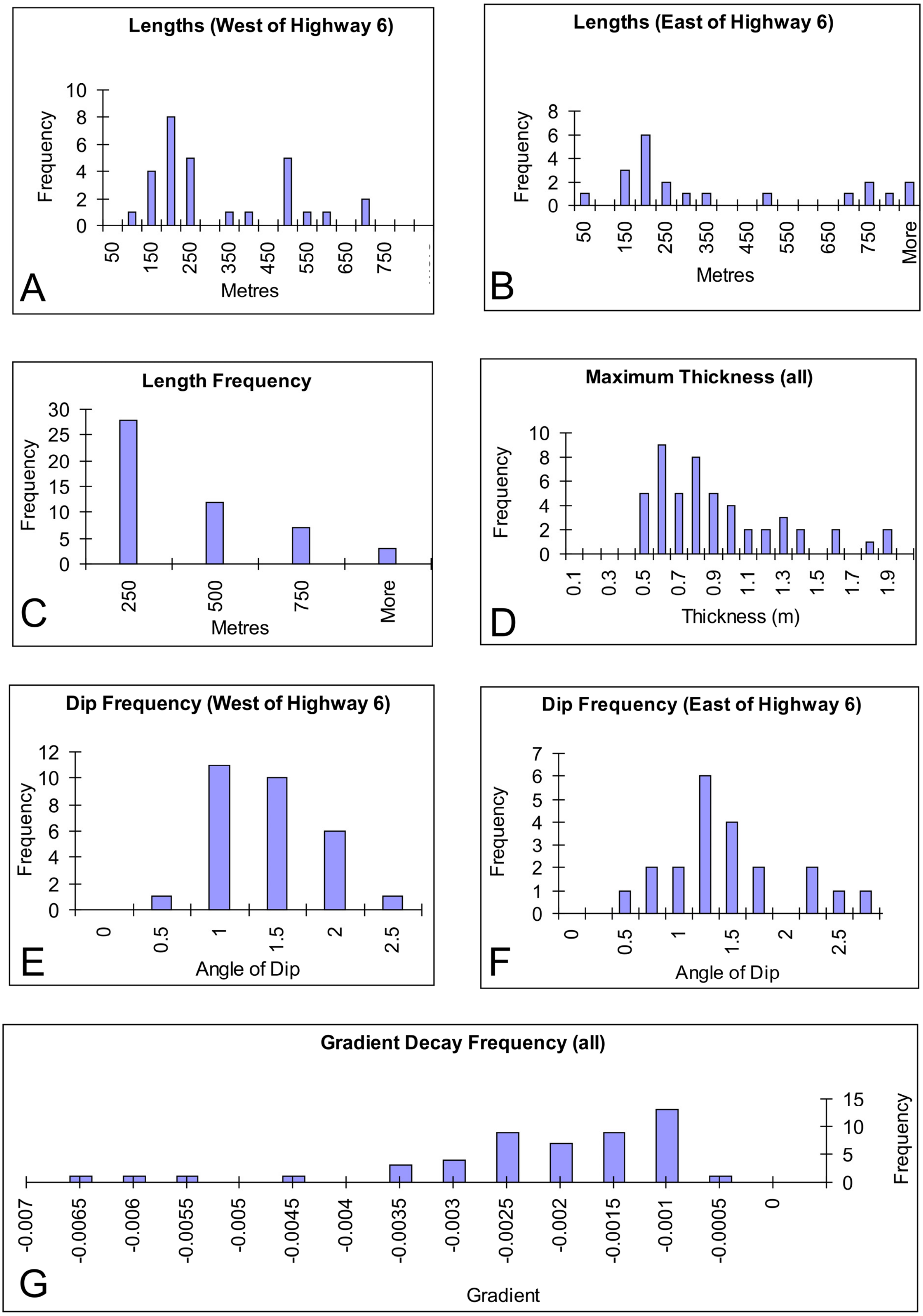
The results of the measurements and analysis are presented below and then discussed in the subsequent section (Figs. 4, 5 and 6). If not explicitly stated otherwise, results and discussion include data from the outcrops on both west and east side of Highway 6 (Fig. 1).

Thickness: The frequency distribution shows that 65% of the clinothems have a maximum recorded thickness clustering between 0.5 and 1.0 m (Fig. 4D). The most common thickness is between 0.5 and 0.6 m. Above 1 m there is marked decrease in the number of occurrences: 36 clinothems had a maximum thickness of less than 1 m and 51 (92%) are less than 2 m.

Length: 50% the clinothems have a recorded maximum length of 250 m or less and 82% have a maximum length of 500 m or less (Fig. 4A, 4B and 4C). As pointed out, the actual bed length is somewhat longer but the measurement is truncated at the point where the bed reaches a thickness of < 0.1m, and about one third of the lengths are also minimums, due to gaps in the outcrop (Fig. 1). However the distribution is strongly clustered and internally consistent and only two clinothems have a recorded maximum length of less than 100 m. The maximum documented length is 870 m. There is a very weak tendency for clinothems in the more distal portions of individual delta lobes to be shorter, as discussed below.

Angle of dip: Clinoforms dip in a basinward direction. The average dip angle, corrected for the later tectonic dip is distributed between 0.4 and 2.65° (Fig. 4E and 4F). 79% of the clinoform dip angles lie between 0.75 and 1.75°. Initial inspection of the data shows a cyclic pattern for successive clinothems (Fig. 6B and 6D). The data have been subdivided to illustrate the data from the west and east sides of the study area separately. The cyclic pattern shows a tendency for the dip angle to increase in successive beds (in a down-dip direction) and then declines suddenly before gradually increasing again. The cycles divide the beds into nine groups and are discussed further below. The outcrop on the west side of Highway 6, south of the entrance to Spring Canyon (Fig. 1) provides a transition from dip to strike orientated outcrop where the apparent dip of the beds reduces. A similar less defined pattern is observed south of the entrance to Panther Canyon (Fig. 1).

Fig. 4 (opposite). Clinothem bed frequency statistics. **(A)** Lengths west of Highway 6. **(B)** Lengths east of Highway 6. **(C)** Lengths, all areas. **(D)** Maximum thicknesses, all areas. **(E)** Dip values west of Highway 6. **(F)** Dip values east of Highway 6. **(G)** Gradient decay values, all areas. See text for details.


Lengths (West of Highway 6)
Frequency
10
8
6
4
2
0
50
150
250
350
450
550
650
750
Metres
A
Lengths (East of Highway 6)
Frequency
8
6
4
2
0
50
150
250
350
450
550
650
750
More
Metres
B
Length Frequency
Frequency
30
25
20
15
10
5
0
250
500
750
More
Metres
C
Maximum Thickness (all)
Frequency
10
8
6
4
2
0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Thickness (m)
D
Dip Frequency (West of Highway 6)
Frequency
12
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
Angle of Dip
E
Dip Frequency (East of Highway 6)
Frequency
7
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5
Angle of Dip
F
Gradient Decay Frequency (all)
-0.007
-0.0065
-0.006
-0.0055
-0.005
-0.0045
-0.004
-0.0035
-0.003
-0.0025
-0.002
-0.0015
-0.001
-0.0005
0
Gradient
15
10
5
0
Frequency
G

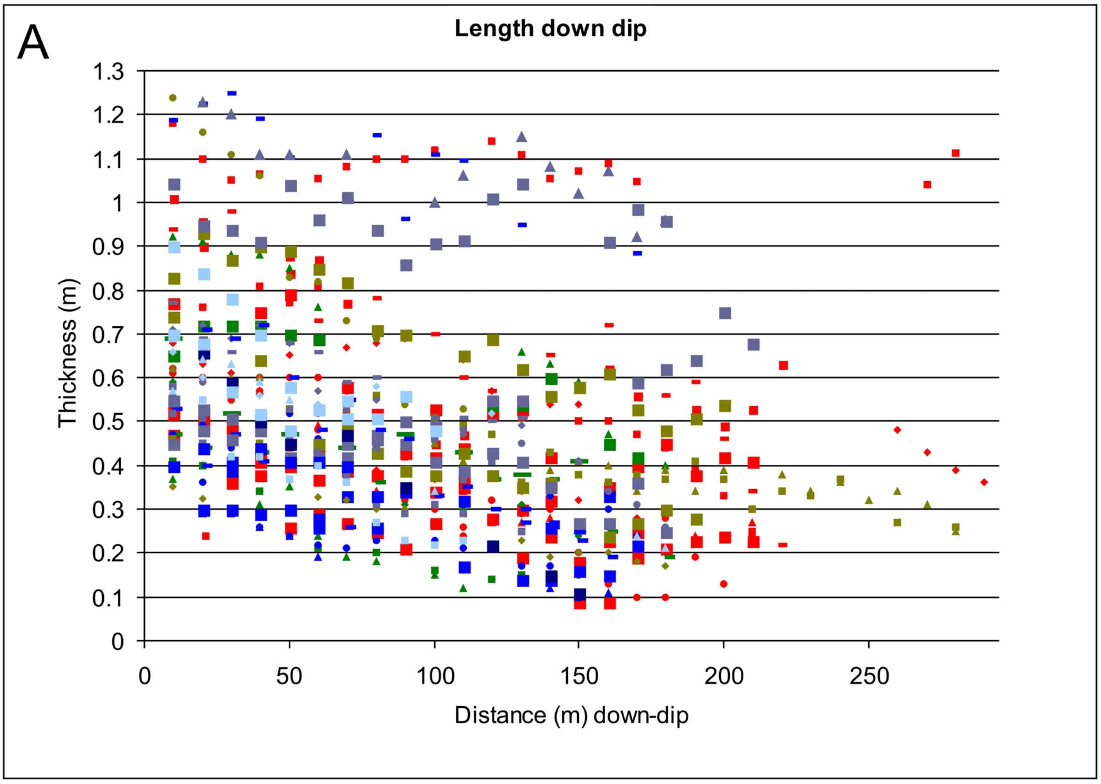
Data Analysis

Length / Thickness development: The thickness of a typical bed decreasees down-depositional dip away from the origin (Fig. 5A). Half of the clinothems have a maximum recorded thickness below 0.8m and maximum recorded depositional dip length (down to 0.1m thickness) of less than 250m (Fig. 4D). 82% of the clinothems have a maximum recorded depositional dip length (down to 0.1m thickness) of less than 500m (Fig. 4C). A thickness reduction from 0.8 to 0.1m over a distance of 250m gives a length-thickness relationship of about 1:350. An identical reduction over a distance of 500 m doubles the length-thickness relationship to about 1:700, and hence a gentler clinoform.

For analysis and discussion of length versus thickness development, a complementary plot of clinothem length value was produced with a common zero starting point rather than the ordinary position measured from the up-dip pinch-out origin. Figure 5A which includes length values from 0 to 300 m shows that at the origin, most of the clinothems are between 0.4 and 1.3 m thick, with some recorded thicknesses also above this. One hundred meters down-dip, these thicknesses have decreased to between 0.2 and 1.0 m and by 200 m down-dip to between 0.2 and 0.5. By 300 m down-dip the majority of the remaining clinothems are less than 0.4 m thick.

Bed thickness decay gradient (τ): For each of the clinothems it is possible to define a straight line through the thickness/distance from pinch-out plots (Fig. 3D). The gradient of this line (τ) provides information on how quickly the clinothem thins down-dip. The τ-value for 50 measure clinothems varies between -0.0007 and -0.0067, with the majority around -0.0020 (Fig. 4G.) A cross plot of gradient numbers and total length of individual clinothems shows how the steeper clinothems also have a tendency for being the shortest (Fig. 5B).

τ-value trends: Figure 6A and 6C shows a plot of the τ-value against the clinothem number. The two plots illustrate the data from the west and east sides of the study area separately and also show the identified groups discussed in the following. The plot with 29 clinothems from the western part of the study area, calculated from a total of ca. 1300 unique measurements, points to a cyclic pattern in which the data are divided into distinct groups each with an internal tendency for a decrease in the τ-value down-dip. The groups are separated from one



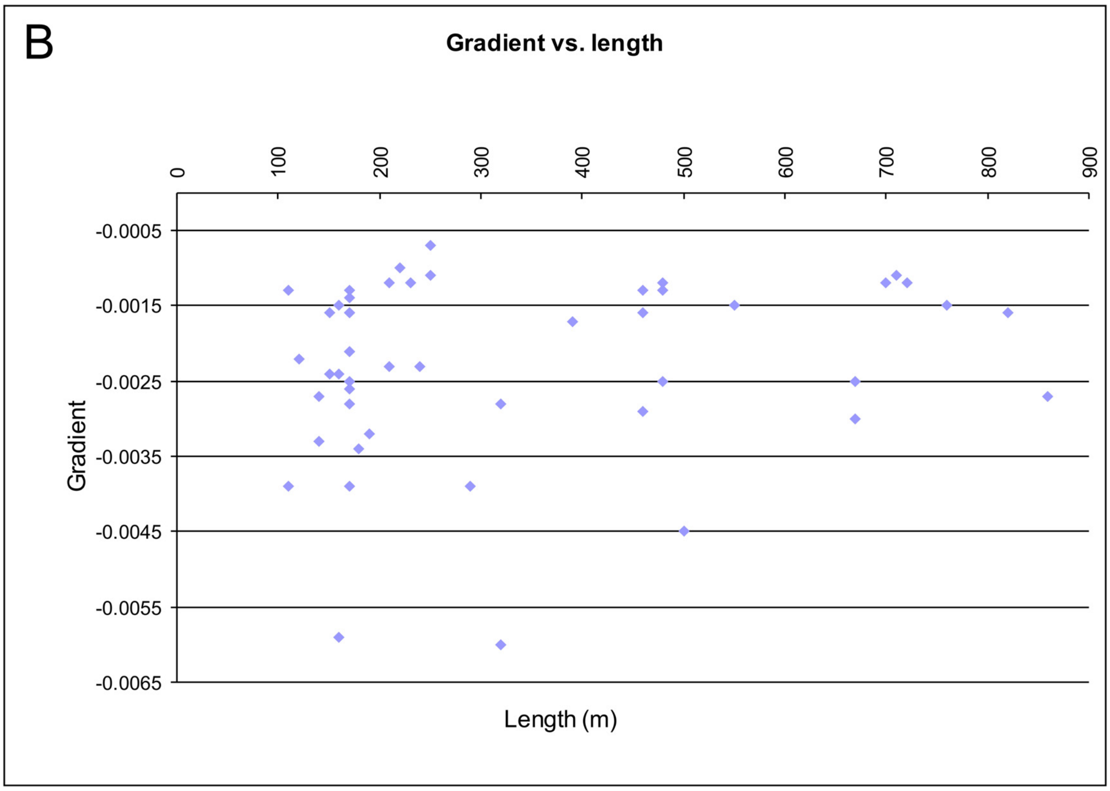


Fig. 5. **(A)** Clinothem length values with a plotted with common zero starting point and including length values from 0 to 300 m. At the origin, most of the clinothems are between 0.4 and 1.3 m thick and decreasing down-dip. By 200 meters down-dip, most thicknesses have decreased to between 0.2 and 0.5 m. **(B)** Plot of length and gradient values of individual clinothems. There is a tendency for the steeper clinothems to also be the shorter.

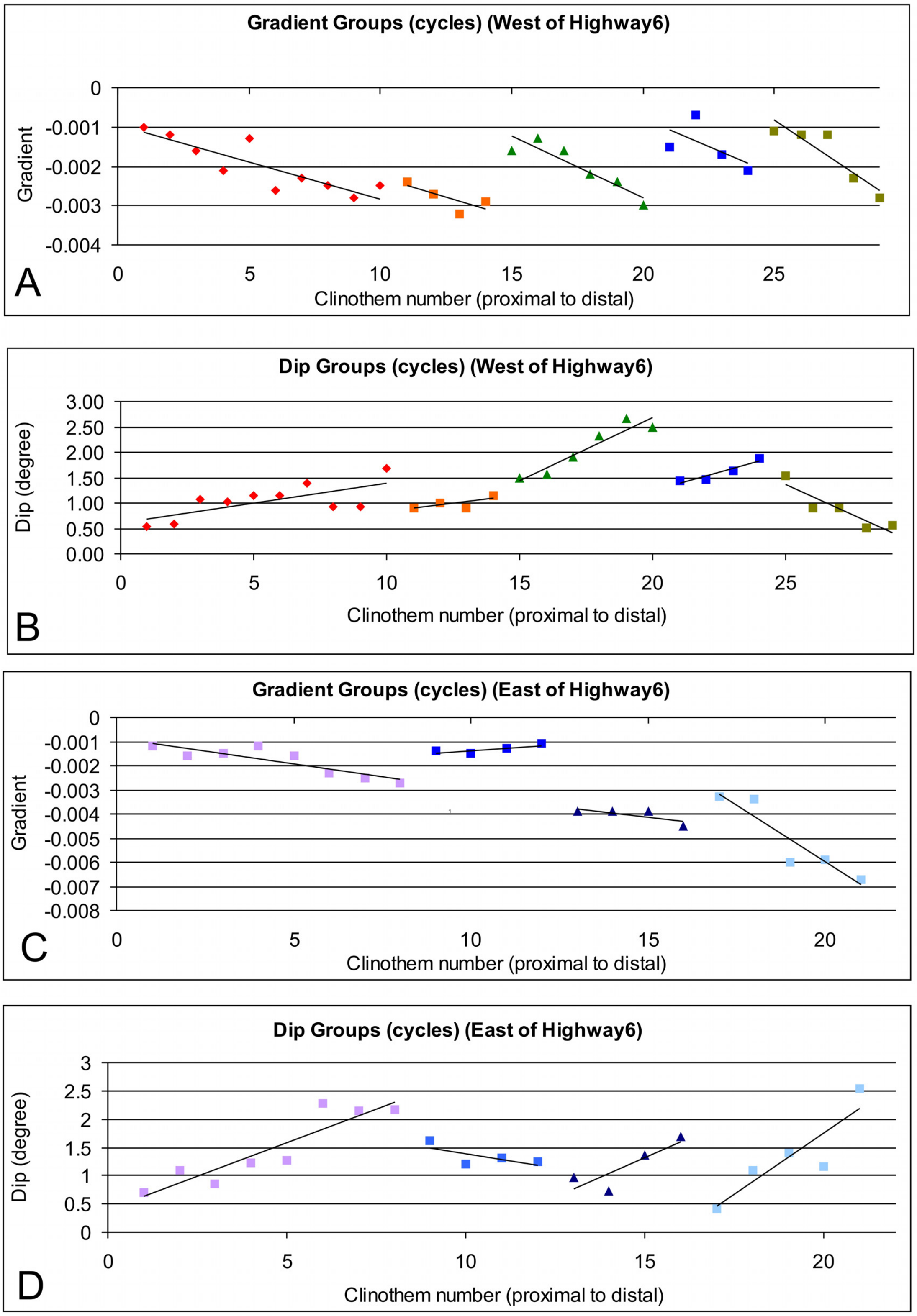


Fig. 6. Nine gradient and nine corresponding dip value-groups (cycles) have been identified, five from west and four from east of Highway 6, respectively. Interpreted corresponding gradient- and dip-groups are shown using the same colours. **(A)** Five gradient-groups from west Highway 6. **(B)** Five dip-groups from west of Highway 6. **(C)** Four gradient-groups from east of Highway 6. **(D)** Four dip-groups from east of Highway 6.

another by a sudden increase in the τ-value (Fig. 6A). The 21 clinothems from the eastern area, calculated from ca. 1000 unique measurements, also show signs of grouping with similar trends but the overall pattern here is a little more complex. One group from the area south of the entrance to Panther Canyon (Figs. 1 and 6C) deviates from the general pattern. Also, the lowest (most negative) τ-values are found around "Balanced Rock", furthest south in the eastern area (Figs. 1 and 6C).

On the basis of τ-values nine distinct groups of beds have been identified. A trend line and separate colours have been added to define the systematic change in τ-values within each of the groups (Fig. 6A and 6C). While it is recognised that the clinoform number is a simple discrete parameter and therefore the true gradient of these trend lines is not relevant, plotting the lines allows a valid comparison between successive groups. On the west side of the outcrop valley, the points within all of the five groups show similar negative gradients from proximal to more distally (Figs. 6A and 8). With minor discrepancy, the individual groups all start with τ-values around -0.0010 and end with values around -0.0030. Three of the four groups defined on the eastern side of the outcrop area also show a negative trend (Fig. 6C). However, the trends within the groups are not as uniform as those observed in the west and there is a tendency for more negative τ-values furthest south. The second group on the east side shows an opposite trend to the rest of the groups, with a small but successive increase in τ-value.

Within the population as a whole, there is no obvious relationship between τ and dip. However, a cross plot of τ against corrected dip angle for individual bedset shows a weak and inverse relationship for most groups (Fig. 7). This relationship can be interpreted to imply that there is a weak tendency for steeper dipping clinothems to thin more rapidly down dip.

Trends and bedsets

In all but one of the nine distinct groups of beds that have been identified on the basis of τ-values, beds within a single group show a tendency for a progressive decrease in the τ-value with a sudden increase at the boundary to the next group (Fig. 6A and 6C). Correspondingly, nine distinct groups of beds have also been identified on the basis of dip-values (Fig. 6B and 6D). In all but one group, beds within a single group show a tendency for progressive increase in the dip-value with a sudden decrease at the boundary to the next group. Individual τ-values and dip-values cannot be compared directly as they are both derived differently, but the boundaries delineating the groups of τ-values and the groups of dip-values are common. This pattern organises groups of τ-values and dip-values delineated by the same boundary into pairs. Each pair shows an inverse relationship between the τ-value and dip-value trends for all but one of the pair (Fig. 6). This relationship for paired groups is repeated throughout most of the study area in a cyclic manner.

These pairs of gradient and dip-groups are interpreted to represent beds with a linked depositional origin i.e. they are genetically related and are therefore termed bedsets (sensu Campbell, 1967; Van Wagoner et al., 1990). Within each bedset there is a decrease in τ-value and hence faster decline in clinoform thickness, and there is an equivalent tendency for the dip angle to increase. Successively steeper dipping clinothems are linked to a successively faster decline of clinothem-thickness.

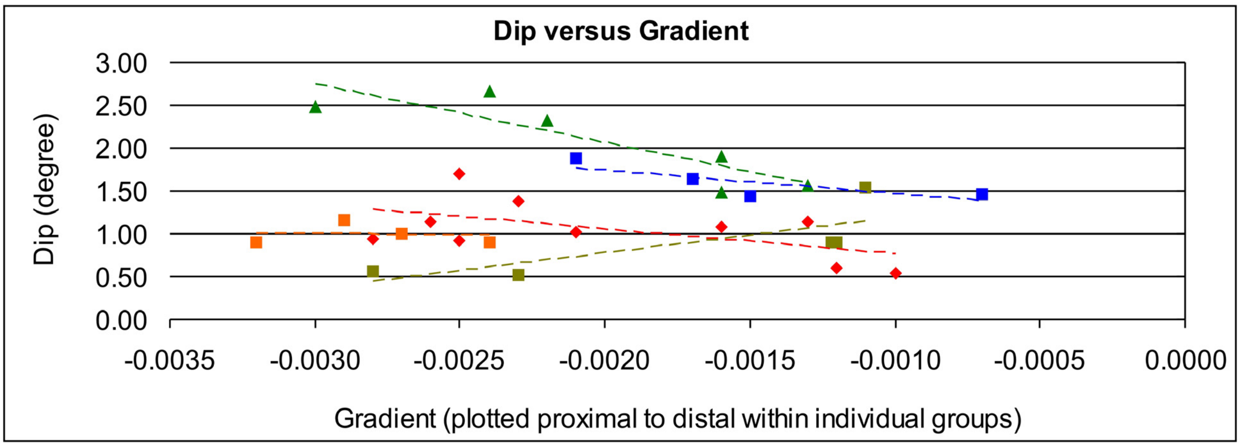


Fig. 7. Plot of dip against gradient (τ). For individual bedset there is a weak and inverse relationship between τ and corrected dip angle for most groups. This can be interpreted to imply that there is a weak tendency for steeper dipping clinothems to thin more rapidly down dip. Example is from west of Highway 6. See text for details.

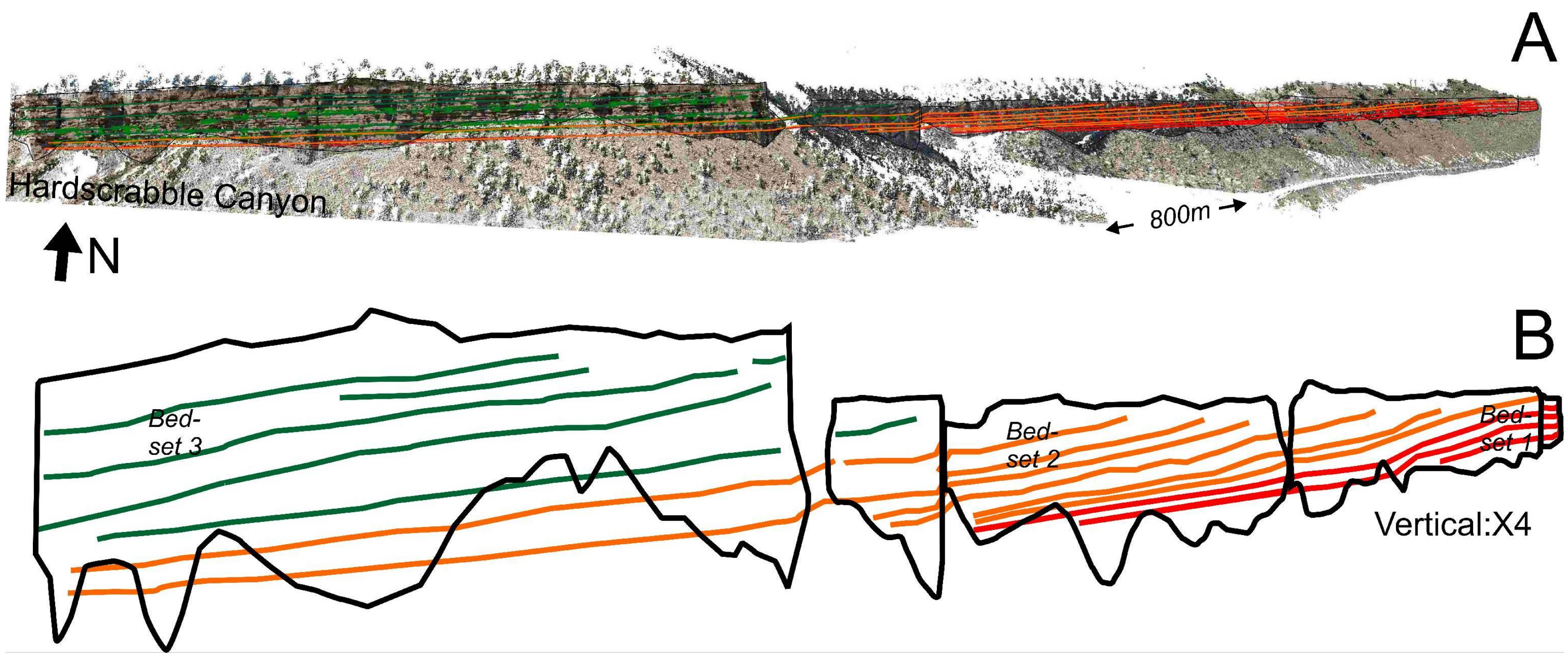


Fig. 8. Example of interpreted bedsets. **(A)** Line drawings on virtual outcrop model of selected clinoforms of the three northernmost bedsets identified (shown in different colours) west of Highway 6. These bedsets correspond to the three most proximal groups in fig. 6A. (**B)** 4X vertical exaggeration of line drawings from (B) shown with outcrop outline. Location is from Gentile Wash (right end of cartoon) to Hardscrabble Canyon (left side) nearly 1500 m roughly parallel to depositional dip.

The VOM and other outcrop data and field sedimentary logs were studied to characterise the nature of the surfaces which bound the bedsets. The bedset boundary in figure 8 and also shown in figure 9 described below is typical. A corresponding pair-boundary is identified around the 12 m level in figure 2, corresponding to the separation of the second and third group from the bottom at the entrance to Hardscrabble Canyon (Fig. 8).

In the 8 m below the boundary, ten thin (from 0 to 0.8 m) and quite uniform sandy beds are present. There are no exceptionally thick beds, but sandy beds are typically interbedded with thin siltstone beds or lamina covering the clinoform surface. The surface area itself is unremarkable but constitutes a 2 m interval with 5-6 thin sandstone beds (Fig. 9). Above this lies a 10 m interval that includes a mixture of thin and thick beds typically also interbedded with thin siltstone beds or lamina covering the clinoform surface and including a prominent 1 m thick sandstone bed at the base. There is a weak tendency for thinner beds upwards. Overall the surfaces that bound the bedsets are unremarkable and it is unlikely that significance (discussed below) would be recognised otherwise, especially in a single vertical succession.

Discussion

A series of quantitative data related to the delta clinothems of the Panther Tongue Member have been collected. These data describe bed length, thickness, dip and the basinward thinning of the clinothems. A systematic, sequential display of the data suggests that the clinothems occur in bedsets bounded by subtle surfaces. These observations have implications for understanding the evolution of the delta system and also for understanding hydrocarbon reservoir architecture in deltaic systems. In the following section three aspects are discussed: the application of the documented relationships to understanding the relationship between clinothem, length, thickness and dip angle; the origin of the bedsets and finally, the implications of the data for reservoir modelling.

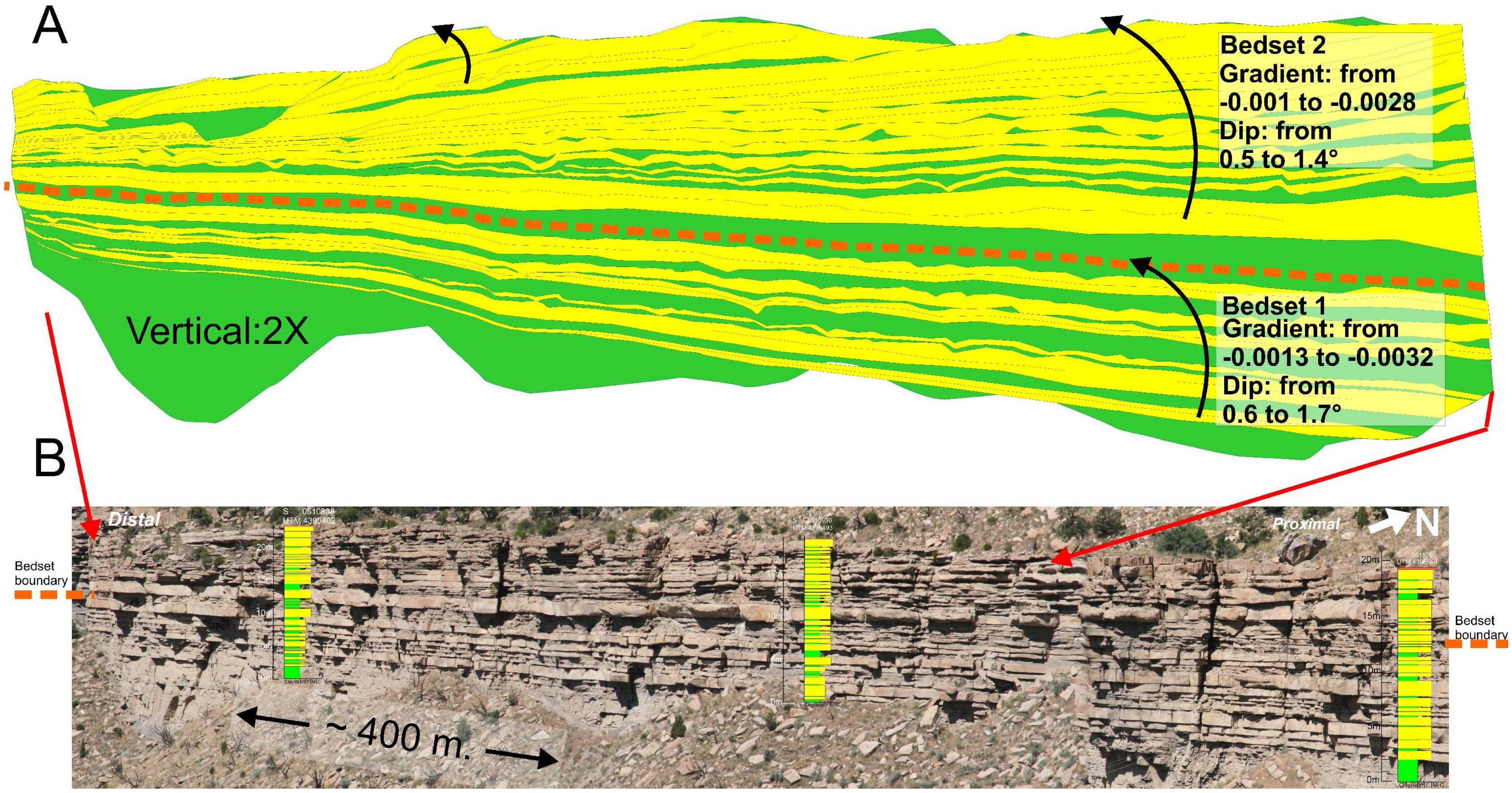


Fig. 9. Bedset boundary. **(A)** Line drawings of clinothems shown with 2X exaggeration. Bedset boundary is marked as dotted orange line, below thicker bed. The bedset boundary corresponds to the boundary between the two most proximal groups in Fig. 6A, and is also identical to the boundary between the two lowermost bedsets shown in Fig. 8. **(B)** Clinothems in proximal position shown with three stratigraphic logs. Depositional dip towards left. Note thicker bed in the middle of outcrop. Area shown corresponds to small box shown in Fig. 3B, from ~300 to 800 m.

Clinothem bed statistics

The properties of the measured clinothems have been documented above. Such bed statistics are a useful part of any reservoir modelling database (e.g. Howell and Mountney, 1997; Reynolds, 1999) and also have implications for understanding and reconstructing depositional systems from more limited datasets such as in the subsurface where a worker may be restricted to a few borehole logs and cores.

From the observations and relationships it is possible to determine that the beds have a mean thickness:length relationship of 1:525 m with the majority of beds having a ratio in the range of 1:350 to 1:700 m. The mean dip for almost 80% of the beds is 1.25°. In any given vertical section it is not possible to determine the lateral extent of any given bed because there is no guarantee that the log samples the maximum thickness. However, given a range of τ-values for the system (between -0.0007 and 0.0067, majority around -0.0020), the distance from the top of the deltaic package and the clinothem dip angle it is possible to predict a range of values that capture the maximum bed thickness and the lateral extent down depositional dip. From that point it is potentially possible to reconstruct the 2 and potential 3D architecture of the package. Further work is required to determine how applicable the τ-values documented from the Panther Tongue are to other similar delta systems (See Enge et al., Submitted).

Clinothem bedding- cycles and bedsets

Analysis of the vertical and lateral stacking of the clinothems has revealed a series of stratigraphic cycles which are termed bedsets. The internal architecture of a typical bedset is summarised in figures 8 and 9. Within a single bedset there is a tendency for successive clinothems to have progressively higher τ-values, i.e. a trend for the oldest beds to thin down dip less quickly than the younger beds, which are also steeper. A bedset boundary is defined by a sudden increase in τ-value and a sudden decrease in clinothem dip. These bedsets suggest that a portion of the depositional system built out with a successively increasing dip angle and deposited successively shorter clinothems up to some limit where it fell back approximately to the starting values and then repeated the same pattern over again. One single group of dip-values west of Highway 6 deviates from the pair-pattern by experiencing a *decrease* in dip values in spite of a *decrease* also in the corresponding group of gradient values (Fig. 6A and 6B). This atypical dip-value trend can be attributed to some depositional effect in this almost strike-oriented part of the outcrop, located south of the entrance to Spring Canyon (Fig.1). This is also the area closest to where Olariu (2005) and Olariu and Bhattacharya (2006) identify terminal distributary channels in outcrop, which may have influenced deposition in this area. East of the highway there is an *opposite* to normal relationship for one pair of groups where an identified *increase* in gradient values is corresponding to a *decrease* in dip values. Given the consistent but opposite to normal inverse relationship of the pair of groups, it is likely a true depositional effect, for example an outbuilding direction in this area deviating from the overall pattern.

The sandstone in the studied portion of the Panther Tongue contains a predominance of planer to massive, locally current rippled strata. This in conjunction with abundant flute casts and sole structures has been previously used to suggest that the Panther Tongue was primarily deposited from turbidity currents in the delta front (Posamentier and Morris, 2000; Olariu et al., 2005; Catuneanu, 2006). The heterolithic nature of succession suggests that the turbidite events that introduced the sand were episodic and may have either been related to the release of sand by the flood erosion of upstream fluvial point bars or they may have been caused by over-steepening and collapse of upper delta front mouth bars which have been subsequently removed by the transgressive erosion at the top of the Panther Tongue (Bates, 1953; Mulder and Syvitski, 1995; Fielding et al., 2005; Bhattacharya, 2006). Either way, the clinothems represent deposition on the dipping, seaward side of a mouth bar complex.

Olariu (2005) and Olariu and Bhattacharya (2006) have documented a system of terminal distributary channels in the Panther Tongue 6 km west of the study area. The individual channels typically have less than 4 m of relief, and are tens to hundreds of meters wide (Olariu and Bhattacharya, 2006) and fed an inter-fingering fringe of proximal, sand dominated mouth bar deposits. These authors also eloquently suggested that avulsion of both the channel and the mouth bar lobe occurred as the channel became choked with aggrading sediment.

The bedset packages identified in the study area are interpreted as the product of similar avulsions and the progradation of mouth bar successions into embayments between older delta lobes. Initially after the avulsion, the initial beds are shallowly dipping and have a low τ-value because they extend a long way basinward. As the mouth bar evolves the beds become steeper and the τ-value decreases as steeper, shorter beds are deposited. As the front of the mouth bar steepens it aggrades and the feeder channel becomes choked until avulsion occurs (Wright, 1977; Elliott, 1986; Willis et al., 1999; Fielding et al., 2005; Olariu and Bhattacharya, 2006). The cyclic pattern is repeated and the mouthbars amalgamate to form a delta lobe. Such a pattern is also reported from Quaternary deltas by Gani and Bhattacharya (2005), who interpret a cyclic pattern of coarsening upwards facies-succession bounded by minor flooding surfaces.

West of Highway 6, five such cycles can be identified over a distance of 2850 m parallel to palaeo-flow. On the east side of the highway, three or possibly four cycles can be identified over a distance 1550 parallel to palaeo-flow. The fourth cycles shows only a weak and atypical trend. The gap between the two sides of the valley is 300 m in the north and up to 1500 m as the valley widens to the south. Reynolds (1999) suggested a length-width relationship for mouth bars of 2:1. With some variability, this is supported by other observations of typical mouth bars from modern systems (e.g. Tye, 2004) Given that each of the mapped lobes extends in a basinward direction for between 350 to 700 m, a 1:2 relationship gives a likely width between 175 and 350 m. Therefore it is unlikely that the lobes on either side of the valley are the same ones, with the possible exception of the northern most. Hence it is likely that the whole study area of 5 km² consist of nine or ten bedsets, each of which represents a mouthbar complex (Figs. 4 and 7). It is also likely that there existed several mouthbar complexes in the area that now makes up the valley between the outcrops.

Implications for Reservoir Modelling

In common with other river dominated deltaic systems the sandstone clinothems of the Panther Tongue are interbedded with siltstone beds and lamina (Ainsworth et al., 1999; Howell et al., 2008) These siltstones produce dipping barriers and baffles to hydrocarbon fluid flow (Ainsworth et al., 1999; Chidsey Jr., 2004; Forster et al., 2004; Howell et al., 2008; Skorstad et al., 2008; Howell et al., in press). Dipping beds and bedsets have been shown explicitly to have an influence on simulated production (e.g. Forster et al., 2004). In log based subsurface datasets it is easy for these barriers to be over looked. Ainsworth et al. (1999) used the Panther Tongue as a template for modelling dipping clinothems of a producing subsurface oil field, but did not extract quantitative data from the outcrops. In contrast, Howell et al. (in press) performed regional quantitative analogue modelling including the Panther Tongue. Due to the small scale (typically the size of a single simulation-model grid cells), clinothems are not commonly recognized in subsurface datasets and are rarely included in reservoir models (Howell et al., 2008; Enge and Howell, Submitted).

The present study recognizes heterogeneities that represent potential barriers to fluid flow at two different scales: 1) bed / clinothem, 2) bedsets (mouth bars) / lobe. Whereas the first relates to draping of clinoforms, the latter also implies a major change of outbuilding direction and the possibility for reservoir to be juxtaposed with non-reservoir. The database of clinothem thicknesses, length, dip, decay and trends can be used as an input in analogue simulation of flow simulation of hydrocarbon subsurface reservoirs. The results of such dynamic investigations have implications for sweep efficiency, well planning, enhanced production planning and reservoir estimates.

A 2:1 relationship corresponds to a length-width ratio from minimum 350 x 175 m to maximum 700 x 350 m. In the 25 m high outcrop, around 30 clinothem beds implies 30 potential barriers or baffles to flow, depending on the extent of the silt draping. This can be incorporated in a model either as objects or as transmissibility multipliers (Enge and Howell, Submitted). The one anticipated transformation related to the lobe switch expected is the most prominent and widespread low-permeability zone, in addition to represent a risk of juxtaposition and compartmentalisation. The most proximal areas within the individual interpreted lobes are the sandiest, and hence the areas with best reservoirs, fewest barriers (more amalgamated sands) and are expected to have the best communication.

The length-width ratio is a guide for the optimal placement of wells. As the most significant potential barrier is the bedset surface, vertical well spacing of less than 700 m is required to penetrate both the proximal and distal parts of the individual mouthbar complexes. For angular to horizontal wells, it would be optimal to plan the well path so that all clinothems within the individual lobes are penetrated, i.e. to go from upper to lower reservoir unit within a dip-distance of less than 700 m.

Conclusions

This study is based upon a high resolution, virtual outcrop dataset from the Panther Tongue Member near the town of Helper, Utah. A series of parameters has been used to quantify aspects of clinothems and lobe switching in the distal mouth bar. The bed parameterisation and data analysis was based heavily on three dimensional virtual outcrop models generated by ground-based laser scanning (lidar), which allowed the accurate, spatial constrained measurement of individual bed thickness measurements. Mapped length/thickness trends constrain the spread of these variables, and can be used as a reservoir analogue. The sandy fraction of individual clinothems was constrained to a width:length dimension of 175 x 350 to maximum 350 x 700 m on average.

The presented dataset points towards cyclic depositional patterns in the Panther Tongue that can be related to mouth bar complexes and lobe evolution and switching. A trend for a decrease in the decay τ-value and increase in the dip angle of the clinothems are interpreted to quantify this progradation, as groups of clinothems are taken as the seawards accretion of a proximal mouth bars complex (assemblages). The threshold limit and sudden increase in the τ-value recorded are interpreted to represent an autogenic incident causing switching of the depositional system. Given that each of the mapped lobes extends in a basinward direction, a 1:2 width:length relationship gives a likely width:length ratio for between 175:350 m and 350:700 m for the mouthbar complexes constituting individual lobes.

The statistical data provide insight into the evolution of deltaic systems. The data also have important implications for the correlation and computer-based modelling of subsurface hydrocarbon reservoirs, where dipping mudstones associated with clinoforms generate important barriers and baffles to fluid flow

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