Evaluating Validity and Reliability in High-resolution Stratigraphic Analysis

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Abstract

The analysis of stratigraphic sections has always been conducted through an integration of quantitative and qualitative observations. Recently techniques have been put forward as mechanisms for extracting high-resolution quantitative data from outcrops for the purpose of assessing controls on accommodation space change. Evaluation of the validity and reliability of analytical techniques provides an important framework for future implementation. First, the discrete facies rank technique is employed by stratigraphers as a mechanism for the construction of a proxy sea-level curve. Exclusion of highly diagnostic but thin or infrequently occurring facies, as driven by sampling interval size, will potentially impact the results of analysis of stratigraphic organization. The probability of inclusion of a facies in a dataset of equally spaced lithologic observations is controlled by the thicknesses of the occurrences of the lithology as well as its recurrence frequency in the section. Second, the gray-scale analysis of outcrop photographs is used as a quantitative proxy for lithologic variation. Evaluation of this technique indicates it is highly dependent upon the geometric relationships between the outcrop and the focal plane of the camera. Geometric foreshortening can result in quantitative distortion of the gray-scale series, and thus impacts interpretations drawn from the analysis of the data series. Additionally, scale-dependent averaging of gray-scale values across a row of pixels can result in quantifiable distortion in the spectral characteristics of the data series. While both the discrete facies rank technique and gray-scale analysis of outcrop photographs can provide useful mechanisms for the collection of uniformly spaced stratigraphic data, great care must be taken in how these techniques are used and how results from the analysis of resultant data are interpreted.
Introduction

The analysis of stratigraphic successions has typically been achieved through application of an array of quantitative and qualitative techniques. Bed thickness, grain size, dip direction of crossbedding and many other types of stratigraphic and sedimentologic observations are intrinsically quantitative in their character. Measurements are made within the limitations of accuracy and precision and the resultant data are evaluated using a wide range of numerical techniques. Conversely, selection of the number and type of lithostratigraphic elements observed in a succession and their paleoenvironmental relationships are subjective and qualitative measures of the nature of the stratigraphic record. Taken together, qualitative and quantitative analyses have been utilized in a variety of ways to evaluate spatio-temporal variation in depths, durations and modes of deposition. Stratigraphic analysis has likewise been complicated by the several orders of magnitude difference between the scales and resolutions of outcrop and subsurface observations. Subsurface methods return continuous records of geophysical parameters that are readily evaluated by a wide range of statistical methods. Conversely, field-based observations are commonly more discrete and more qualitative in their character. Recently, several techniques for converting some of the complex qualitative aspects of outcrop observation into a continuous data series suitable for spectral analysis have been advanced. It is the purpose of the following to describe and evaluate two analytical techniques that have received use in the quantitative stratigraphic literature with specific attention to the validity and reliability of analytical results derived from them.
Discrete Facies Rank Technique

One of the central objectives of stratigraphy is the analysis of lithologically complex stratigraphic successions. The selection of an appropriate and representative suite of lithofacies, the parsing of the section according to occurrences of these lithofacies, and the ranking of the lithofacies by depth or some other paleoenvironmentally significant characteristic requires a comprehensive synthesis of all the observable sedimentological and stratigraphic characteristics possessed by the succession. Of the many and varied depositional environments recognized in sedimentary rocks, shallow water and peritidal carbonate settings present perhaps the greatest degree of textural and compositional variability and complexity. From the Proterozoic to the modern, sediments deposited in temperate and tropical carbonate environments display an astonishing variety of sedimentary features. In some cases, individual facies can be tied directly to specific depth ranges or paleoenvironments. For instance, the framestone textures of reef environments are readily recognizable, as are the desiccation features of supratidal laminites. Difficulty arises, however, in distinguishing and ranking the depth or positional relationships between the large number of apparently substitutable subtidal facies that form across the range of depths affected by wave action. Such lagoonal, shallow shelf or ramp sediments make up significant percentages of ancient carbonate rocks and therefore have been the subject of extensive study and debate.

Ranking of sedimentary facies by depth is a common and well established practice in stratigraphic analysis (Fischer, 1964; Olsen, 1986; Bond et al., 1991). Qualitative and quantitative analysis of patterns of depth-dependent facies transitions have likewise been conducted in a wide range of carbonate settings and the analysis and interpretation of carbonate facies cyclicity has been the subject of debate for several decades (Schwarzacher, 1975; Schwarzacher, 1993). More recently, however, workers have begun to approach the quantitative analysis of depth-ranked successions in a new way. By converting a standard stratigraphic column into a lithofacies series,
where the depth-ranked value of the succession is established at a constant thickness interval $\Delta t$, the resultant series of stratigraphic data is readily evaluated for spectral characteristics (Figure 1). This technique has, for example, been used by Preto et al. (2001) to argue for the presence of Milankovitch forcing of eustatic sea-level recorded by shallow carbonate sediments of the middle Triassic Latemar platform. In that example, the classic bi-lithologic cycles of the Latemar platform were further subdivided into four depth-ranked sublithologies. The 160-m Cimon del Latemar section was parsed into 472 occurrences of four sublithofacies with an average thickness of 34 cm. This measured stratigraphic column was then sampled at 0.5 cm intervals to create a ranked lithofacies series of 32,000 equally spaced secondary observations. The resultant series was then taken as a proxy sea-level curve for the duration of the Cimon del Latemar deposition. After tuning the results of a spectral analysis of the lithofacies series to a precessional duration of 21.7 k.y., the Latemar carbonates are then interpreted to have formed under conditions of periodic low amplitude (2-3 m) sea-level oscillations driven at Milankovitch orbital frequencies.

While this approach has yielded compelling results in the case of the Latemar, there remain several important questions to be considered regarding the validity and reliability of the discrete facies rank technique and its results. The first and most obvious question relates to the selection of a vertical sampling interval $\Delta t$. In a study of the recurrence characteristics of peritidal carbonate facies in the Lower Ordovician Kindblade and West Spring Creek Formations, Wilkinson et al. (1997) carried out detailed section measuring along Interstate 35 in the Arbuckle mountains north of Ardmore, Oklahoma. In this study, 2,161 lithologically distinct beds were identified in 819 m of continuous section by standard section measuring procedures. Fourteen lithostratigraphic units were recognized in this succession. Subsequently, the outcrop was re-measured in the field utilizing a discrete sampling methodology where lithologic composition was determined by direct observation every 0.38 m up-section throughout the succession. This sampling interval was derived from the average thickness of the 2,161 beds measured using standard section measuring techniques. These two techniques produce similar, albeit not
identical, results (Figure 2). Using the discrete sampling method, the facies micrite and grainstone are slightly over-represented relative to their percentage of the total stratigraphic column thickness, while the facies packstone and wackestone are under-represented relative to their total thickness. It is expected, when utilizing the fixed-interval sampling technique, that lithofacies exhibiting average thicknesses at or less than the average for the entire succession to be under sampled and this is indeed found to be the case for both wackestone (0.39 m) and packstone (0.24 m) facies. Interestingly, however, the grainstone facies is also thinner than the outcrop average (0.22 m) but is actually over-represented relative to its total thickness. Two factors lead to this observation; first, grainstones make up over 20% of the total number of observed beds but only 9% of the total thickness and second, grainstones are texturally distinct on a weathered outcrop and are therefore less likely to be mis-identified. Thus, the probability of inclusion in a dataset composed of equally spaced samples of lithology is controlled by both the thicknesses of the occurrences of the lithology as well as its recurrence frequency in the section.

In the case of the Ordovician study (Wilkinson et al., 1997), the choice of the sampling interval size was driven by an observed stratigraphic characteristic, average bed thickness. Additionally, because the technique used was the direct re-sampling of the outcrop, there were limitations associated with the collection of this primary lithologic data. That is, re-sampling at shorter stratigraphic intervals, while possible, was impracticable given the vast thickness exposed at the Ardmore outcrop. Without question, this technique would not be considered ideal for quantitative analysis of spatio-temporal characteristics due to the relatively broad spacing between successive samples (0.38 m) but it does provide an interesting example of how interval sampling of an outcrop can result in a different understanding of the stratigraphy than does a traditional boundary measuring technique. Conversely, the analysis of the Latemar section (Preto et al., 2001) utilized a very small (0.5 cm) secondary re-sampling interval for the collection of a proxy data series.
Within the Cimon del Latemar section, 161 of the 472 recognized lithologic units are vadose altered dolostones and caliche soils, a facies that is equivalent to the vadose diagenetic cycle caps of Goldhammer et al. (1987, 1990). Representing intervals of platform exposure, this facies provides the most reliable measure of relative accommodation space of the four subfacies recognized by Petro et al. (2001). The stratigraphic distribution of Facies 1 throughout the Cimon del Latemar section is found to be fairly uniform, as might be expected for a facies that makes up over a third of the observed units (Figure 3). Interestingly, however, despite the very small scale re-sample spacing of 0.5 cm, nearly 15% of the 162 occurrences of the facies fall at or below the re-sampling size. Additionally, the stratigraphic distribution of these very thin caps is not uniform throughout the section. Rather, 20 of the first 82 and 4 of the last 10 occurrences are at or below the resolution of the discrete sampling technique (Figure 3). Clearly, the observation that very thin occurrences of Facies 1 are not uniformly distributed throughout the section is of interest when considering potential controls of variation in long-term rates of accommodation space creation across the Triassic platform.

As the facies most representative of sea-level low-stands, Facies 1 is critical to any reconstruction of the temporal record of accommodation space change across the Latemar platform. The fact that occurrences of this facies could be skipped by the resampling technique raises two important questions about the discreet sampling technique. First, and most obviously, is the choice of the re-sampling interval. Unlike the case of the Ardmore section where there were practical physical limitations to making discreet interval observations throughout an outcrop, when creating a secondary re-sampled dataset, the size of the re-sample interval need only be dependent on computational efficiency. Ideally, re-sampling should be done at or below the Nyquist rate, 0.05 cm in the case of the Cimon del Latemar section. Conversely, if computational limitations would make re-sampling at very high resolution problematic, an alternative solution is to adjust the offset, or phase of the re-sampling interval. In the example given above it would be possible to shift the re-sampling from 0.5, 1.0, 1.5 cm... to 0.4, 0.9, 1.4 cm.
By shifting the re-sampling in this way, it becomes possible to select an offset that maximizes inclusion of thin beds in the dataset. Likewise, each re-sampled dataset could be analyzed using any of a variety of statistical techniques to evaluate sensitivity to the chosen re-sampling interval. Obviously, if comparable results are obtained at all offsets, the impact of skipping a few beds would be minimal.

Unquestionably, selection of an appropriate sampling interval is critical to any quantitative analysis of a section sampled using the discrete facies rank technique. What impact has exclusion of some of the thinnest occurrences of Facies 1 had on interpretations of sea-level change over the Latemar platform? It is reasonable to suppose that at least some aspects of the power and line spectrogram would be impacted by changes in the size of the resample interval. While as many as 24 occurrences of facies 1 could be skipped by the technique used by Petro et al. (2001), in fact only 8 were with no appreciable change in the resulting power spectrum when re-analyzed at the Nyquist rate (L. Hinnov, personal communication 2007).

While the exclusion of some of the occurrences of supratidal caliche soils from Petro et al. (2001) numerical analysis apparently did not adversely effect their interpretations, the exclusion of any occurrence of a paleoenvironmentally significant subfacies such as the vadose cap and caliche soils of the Latemar has the potential to impact quantitative analysis. Because facies 1 can only be formed when sea-level drops below the platform margin, every occurrence, irrespective of thickness, is significant. That is, it is conceivable that sea-level dropped below the platform margin and failed to produce a supratidal record, but the facies cannot be formed without subareal exposure. Therefore, the observed number of occurrences of Facies 1 represents the minimum number of intervals of platform exposure. Given that 162 occurrences of Facies 1 were recognized in the Cimon del Latemar section, and the duration of accumulation for that succession has been interpreted to range from ~0.6 m.y. (Zuhke et al., 2003) to 3.1 m.y. (Petro et al., 2001) the most elementary calculation would indicate that the Latemar platform experienced subareal exposure at an average recurrence interval ranging from 3,700 years to some 19,100
years, values that are midway between the short and long precessional frequencies calculated by Petro et al. (2001). Exclusion from this calculation of the 8 occurrences not included in the Petro et al. analysis (2001) lengthens the recurrence estimate by 5%.

Because of the importance of Facies 1 in the interpretation of platform exposure and submergence, and because vadose diagenesis and caliche formation are not constrained to follow the law of superposition due to the fact that diagenetic alteration and soil formation occurs in a penetrative way as an alteration of existing sediments, establishing meaningful thickness-duration relationships for this facies is extremely difficult (Drummond, 2002). Therefore, the spatio-temporal occurrence of this facies is much more significant than the thickness of individual occurrences. Accounting for potential computational biases resulting from exclusion of very thin but paleoenvironmentally significant facies is a critical topic for future work. This could be especially critical in peritidal ramps exhibiting more lithologic complexity than the bilithologic cycles found at Cimon del Latemer.

Gray-scale Analysis of Outcrop Photographs

Recently stratigraphic analyses have been conducted using digital outcrop photos as a data source. In this technique, a field photograph of an outcrop is sampled along a continuous transect to create a series of gray-scale intensity value measurements. Since the data are generated from a pixilated image, the result is a uniformly sampled continuous series of data. Such a data series could, in the ideal, present a very useful foundation for quantitative analysis.

As field geologists, stratigraphers and sedimentologists are well-trained in the techniques of observation and interpretation of outcrops. One of the most important aspects of field geology is the ability to observe and understand the geological “signal” that is often overprinted by various forms of “noise” that can impede high quality interpretations (Fichter, 1987). Specifically, the effects of weathering, erosion, and cover by scree or vegetation can adversely impact the
quality of observation and interpretation in the field. These problems are compounded when the dataset is reduced from an integrated sedimentologic and stratigraphic analysis to a set of pixilated gray-scale data drawn from across an image of an outcrop.

The gray-scale technique assumes that there is a direct relationship between lithologic composition and gray-scale value. As discussed by Schwarzacher (2005), the shade of gray of any pixel in a photo is the result of a complex set of variables that include lithology, weathering and cover. Additionally, there are less obvious factors that influence grey-scale intensity that include sharpness of contrast due to ambient light conditions, angle of the sun and depth of shadows, as well as the effect of any ground or surface waters on the outcrop. Taken together, these factors make interpretation of a stratigraphic section by gray-scale analysis an extremely complex and potentially unreliable process.

In a study of the Upper Triassic Dachstein Limestone of Italy, Cozzi et al. (2005) conducted a spectral analysis of 830 gray-scale measurements from a field photograph. The three segments of the Picco di Carnizza outcrop included in the study cover approximately 270 m of section and are interpreted to be composed of 112 Lofer-type cycles with an average thickness of 2.41 m. Given the scale of the image and the resolution of the scan, each pixel is calculated to represent 0.135 m of section and thus, on average, a cycle is composed of 18 pixels or approximately 0.225 mm on the photograph (Figure 4). Thus, this technique creates over a 10,000-fold reduction in stratigraphic resolution, prior to the spectral analysis of the data. Variations in the gray-scale values of this record are interpreted by Cozzi et al. (2005) to be the product of differential weathering of the cycles, wherein lighter shades are taken to be resistant ledges of subtidal limestone and the darker shades are recessive weathered and vegetated portions of the outcrop.
Angle of Gray-scale Analysis

The analysis of gray-scale data taken from outcrop photos is open to several criticisms. First, the scale of field photographs (e.g., Figure 4) can result in an astonishingly large reduction in the resolution of data available for analysis. Second, variation in gray-scale value could be interpreted to be driven by differential weathering taken to be facies-specific in its character. Yet, establishing a correlation between gray-scale intensity and directly observed lithologic composition is difficult. That is, without a set of baseline data that ties composition directly to gray-scale intensity through field checking, the validity of any analysis drawn from the data is at best suspect.

The somewhat obvious drawbacks discussed above mask other flaws in the gray-scale approach. An essential requirement of the spectral analysis technique is that there be a clear understanding of the spatio-temporal spacing of the data in the series. Figure 4, however, illustrates several problems. First, the composite section used in the spectral analysis was created from three separate lines taken at different angles across the image. Apparently, this was done in an attempt to keep the line of analysis perpendicular to strike as it appears on different faces of the outcrop. The result, however, is that the sampling across the rectilinear grid of pixels results in different amounts of vertical section per pixel (Figure 5). As illustrated by the five arrows of equal length, the angle between the section and the grid controls how many pixels are represented in the section, and thus the average thickness represented by each pixel. In this simple example, the number of intersected pixels ranges from a maximum of 6 to a minimum of 3. In the actual scan of the Picco di Carnizza, the differences in angle between the three traces are not as large as illustrated in Figure 5, but the integrated effect over hundreds of pixels is significant even when dealing with small angular differences. As such, differences in the pixel-thickness relationship between outcrop segments introduce artificial trending to the dataset. The angle of section problem, while real, is perhaps minor in the Picco di Carnizza example.
remains, however, a second more significant problem associated with pixel scaling in the analysis.

**Angle of the Outcrop**

The use of field photography as a data source for quantitative analysis presents a number of complex problems, the most obvious and most vexing is the complex geometry of the outcrop surface. Natural outcrops like the Picco di Carnizza or artificially created outcrops such as road cuts are subjected to the effects of weathering and erosion. As a result, an outcrop surface nearly always steps back at an angle from the vertical. This recession of the face of the rocks away from an observer results in a foreshortening of rocks lower in the section relative to those in stratigraphically higher positions. In order to evaluate the effect of outcrop angle on gray-scale analysis of field photographs, a simple experiment was conducted. Modeling of different outcrop surface geometries was accomplished by photographs taken of a brick wall with the focal plane of the camera tilted at various angles relative to the vertical brick surface (Figure 6).

With the focal plane held parallel to the brick surface, the degree of vertical distortion of the image is minimized. As the angle is changed, and the camera tilted up, the upper portion of the image becomes compressed relative to the lower portion thus modeling the effect produced by the geometry of back-stepping outcrop surface photographed with a vertical focal plane (Figure 6). By changing the angle between the brick surface and the camera’s focal plane from 0° to 20° to 30°, it is possible to evaluate the role of outcrop surface geometry on the gray-scale technique. Photographs of the brick surface were scanned, cropped to a half-brick width, and then sampled following the process described by Cozzi *et al.* (2005) using the image analysis shareware Scion Image.

In all three trials, the gray-scale series clearly shows the presence of brick-mortar couplets (Figure 7a, 7d, 7g). Using the position of local minima in the gray-scale values of the data series allows for the thickness of each couplet to be calculated (average actual couplet thickness 6.8 cm,
5.5 cm brick, 1.3 cm mortar). When the photograph was taken with the focal plane perpendicular to the wall, the couplets were found to have an average thickness of 31 pixels, resulting in a resolution of approximately 2.2 millimeters of wall length per pixel. Importantly, because the focal plane is parallel to the wall surface, there is no trend in the thickness data (Figure 7b). Fourier power spectrum calculated using standard techniques (Davis, 1986) from gray-scale data derived from the parallel focal plane photo displays a prominent single peak at 31 pixels. Thus, when the “outcrop” is vertical and the focal plane is placed in a parallel orientation, the positional data contained within the gray-scale series is reliable. Unfortunately, this is not the case when there is an angle between the focal plane and the surface.

When the camera’s focal plane is turned 20° to the wall surface, as described in Figure 6, the foreshortening that is produced results in a strong linear trend of decreasing apparent brick-mortar couplet thickness up-section, as measured in pixels (Figure 7e). Interestingly, while the cyclic pattern of the brick-mortar couplets is still evident in the gray-scale series, the trending in the data produces a significant degradation in the spectral power of the couplet (Figure 7f). The single strong peak found in the parallel data is broken into a number of smaller peaks of much lower spectral power positioned from 33 to 26 pixels, the range of apparent couplet thicknesses found in the series (Figure 7e).

If the angle between the focal plane and the surface is increased to 30°, an angle of stepback from the vertical fairly common to natural outcrops such as the Picco di Carnizza, the validity of interpretations drawn from gray-scale analysis becomes even more questionable. With increasing angle, the slope of the thickness trend increases, resulting in a further degradation of the quality of the spectral power of the couplet (Figure 7i). Now, the known peak at 31 pixels is further reduced in power, with additional peaks down to a thickness of 20 pixels present. Obviously, in this simple example it would be possible to detrend the data so as to return a result similar to the parallel example (Figure 7a, 7b, 7c). In a natural setting, however, establishing the correct stretching factor for detrending would be extremely difficult.
Unquestionably, the analysis of gray-scale renderings of field photographs can only be considered valid when great care is taken in the selection of the geometry of the photographic angle relative to the stratigraphic section. As illustrated in the previous discussions, variation in the strike geometry across the outcrop as well as the degree of outcrop step-back can impact the reliability of the positional relationships within the gray-scale data and, as such, can impact the validity of any conclusions drawn from a quantitative analysis of gray-scale data. In fact, the spectrogram derived from the Picco di Carnizza section (Cozzie et al., 2005, Figure 3A) shows a frequency shift across the section. This shift in frequency is at least as likely to be driven by such a photographic artifact as it is to reflect any real long-term changes in the rate of accommodation space creation during deposition.

The Role of Lateral Variability in Gray-scale Data

One of the great strengths of traditional field observation is the way in which an experienced geologist is able to draw data from along a bed’s lateral exposure. Given the complexity of the stratal expression of peritidal carbonate successions, can the gray-scale technique be adapted to integrate lateral stratigraphic content and if so, what impact does such integration have on the analysis of the resultant data series? Interestingly, the image analysis shareware Scion Image will average gray-scale values across a row of pixels. As such, if the geometry of the image is carefully selected such that horizontal rows of pixels are parallel to bedding, then it is possible to evaluate the gray-scale character of the outcrop at different width scales.

In order to evaluate the effects of lateral averaging along beds, high-resolution field photographs of the Ordovician Kope and Bellview Formations of northern Kentucky were analyzed (Figures 8 and 9). Limestones of the Kope and Bellview Formations were deposited on a shallow storm-dominated mixed siliciclastic-carbonate ramp. These rocks are part of the well-known Cincinnatian Series and have been extensively studied by a number of workers (Tobin &
The Kope and Bellview Formations are well-suited for photographic analysis because outcrops along the Alexandria-Ashland highway present a series of horizontally bedded exposures that are readily measured and photographed at high resolution with minimal outcrop step-back. Additionally, the interbedded limestone-shale stratigraphy presents perhaps a less complex lithologic setting than other peritidal or subtidal carbonate sequences (Cozzi et al., 2005; Wilkinson et al., 1997) and, as such, is better suited to gray-scale analysis.

The Kope Formation consists of a series of fossil-rich beds ranging from pure grainstones to packstones and wackestones interbedded with fossiliferous shale. Drummond & Sheets (2001) identified the presence of stratigraphic organization within the Kope composite reference section of Holland et al. (1997) in the form of stratigraphic clustering of grainstone and packstone beds. As illustrated in Figure 8, the Kope Formation is relatively shale-rich with prominent ledge-forming grainstone beds and small local scree cones. A field photograph of the Kope Formation was cropped to two sizes; in the first example, the width of the field of view is approximately 1 m while the second consists of approximately 2 cm taken from the center of the 1 m image. Figure 8 illustrates 2.51 m of stratigraphic with a pixel scale of 0.71 mm. Using the shareware Scion Image, these cropped images were subjected to gray-scale analysis. Due to the averaging of pixel values across the wider row, the 1 m wide image produces a smoother gray-scale trace than does the 2 cm wide image. Both of the traces, however, display a great deal of similarity in their gross geometry (Figure 8). Specific variations between the shape of the traces is due to a combination of lateral lithologic variation and increased inclusion of stratigraphic “noise” in the form of differential weathering, scree cover and vegetation when wider images are used.

When evaluating the stratal characteristics of the Bellview Formation several observations are readily apparent. First, the Bellview consists of a succession of thinly bedded grainstones and packstones with significantly less interbedded shale than found in the Kope. Second, the ambient light conditions at the time the photograph was taken and the lack of shale
results in thinner and less pronounced shadows than in the case of the Kope. Following the procedure discussed above, two scans of the Bellview exposure were subjected to gray-scale analysis. The larger vertical extent of the Bellview outcrop coupled with the thin bedded nature of the grainstones results in a very complex gray-scale trace (Figure 9). This illustration displays 4.79 m of section with a pixel scale of 3.14 mm. When considering the traces from the 1m and 2 cm scans, the higher frequency variation in the grayscale values makes visual comparison between the two somewhat difficult. However, gross trends and sharp breaks in contrast are recognizable in both datasets.

In order to expand the analysis of these gray-scale datasets, Fourier power spectra were calculated for each of the four scans using the standard techniques of Davis (1986). All four examples describe a log-log linear decrease in spectral power with increased harmonic number (Figure 10). While the overall patterns of these spectra are similar, there are some striking differences. In the Kope example, there is a significant reduction in the slope of the log power-log harmonic number relationship wherein the slope changes from -2.05 to -1.47. This reduction in slope is a reflection of the greater degree of high-frequency variation in the 2 cm-wide scan. That is, there is more spectral power over higher frequencies than is observed in the smoother, low-frequency dominated, 1 m-wide scan (Figure 8).

The gray-scale values derived from the photograph of the Bellview Formation (Figure 9) display significantly greater degrees of high frequency variation than do those taken from the Kope Formation photographs (Figure 8). This difference is evident not only by visual inspection of the traces, but also is clearly expressed in the power spectral analyses of the series (Figure 10). In the case of the Bellview Formation, the slopes of the log power versus log harmonic number relationships are much shallower than the Kope Formation. Likewise, the difference in slope of the power-frequency relationship between the 1 m and 2 cm scans is much less in the case of the Bellview (-0.74 to -0.61) than in the Kope (-2.05 to -1.47) (Figure 10).
How, if at all, can the spectral analysis of these gray-scale traces be used to evaluate the stratigraphic character of the two outcrops? In a wide variety of natural systems, the spectral power of a data series is found to scale inversely with frequency. The relationship \( P(f) = \frac{1}{f^\beta} \), where \( P(f) \) is the spectral power, \( f \) is the frequency, and \( \beta \) is slope of the power-frequency relationship (e.g., Figure 10), is the mathematical description of these types of systems. Two well known signal types, white noise \( \beta = 0 \) and random walks or Brownian noise \( \beta = 2 \), define commonly occurring natural end member cases of the 1/f noise range. Lateral averaging of pixel gray-scale values tends to smooth the signal and thus increase the slope of the power frequency relationship. Clearly, the two outcrops considered in this study display significantly different spectral characteristics. The Kope Formation is dominated by low-frequency shale-limestone alternations (closer to Brownian noise) while the Bellview Formation is dominated by high-frequency shale-limestone alternations (closer to white noise). Thus, when used in this way, the gray-scale technique does hold some promise as a tool for recognizing and quantifying bed geometries.

**Future Directions**

Recently, workers have begun to apply advanced imaging techniques to the analysis of sedimentary outcrops. By combining traditional field observations conducted by standard section measuring techniques with positional data derived from GPS measurements and 3-D positional observations (Adams et al., 2004; Bellian et al., 2005, Redfern et al., 2007). These approaches allow for the creation of highly precise digital outcrop models that can then be the subject of high-resolution quantitative analysis. While still being refined, these techniques provide an exciting approach to creating digital datasets suitable for quantitative stratigraphic analysis.
Conclusions

What conclusions can be drawn from this evaluation of quantitative techniques of outcrop analysis? First, choice of scale of sample spacing can impact the proxy sea-level curve generated from the discrete facies sampling technique. Likewise exclusion of highly diagnostic but thin or infrequently occurring facies is of significant concern when drawing interpretations drawn from the proxy sea-level curve. Spatio-temporal variation in the recognition of thin facies can impact the reliability of time-series results drawn from incomplete records of relative accommodation space change. Second, geometric orientation of outcrop bedding relative to the rectilinear structure of a gray-scale pixilated image can control the absolute stratigraphic thickness represented by each pixel. If the apparent strike of the beds changes across the photo, then the angular relationship between up-section direction and the pixel geometry can result in artificial trending in the gray-scale data. Third, the angle of outcrop step-back can cause foreshortening of lower portions of the outcrop and result in pronounced spatio-temporal compression of the upper portions of the outcrop, thus introducing another type of artificial trending in the dataset. Finally, the analysis of gray-scale data can, in some cases, be used as tool for the interpretation of bedding geometry allowing for recognition of differences in bedding style within and among outcrops.

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On this occasion of celebration of Professor Robert Ginsburg and his contributions to the fields of carbonate sedimentology and stratigraphy, it is only fitting that we acknowledge the vast impact his work has had on the research community’s on-going dialog regarding the characteristics and origins of shallow water carbonate deposition. Bob’s consistent demand that we ask the hard
questions, not be satisfied with easy solutions, and that we base our conclusions on sound observations and legitimate quantitative analysis has served as a model and guide for carbonate research for over four decades. Personally, and as part of the larger community of carbonate geologists, we offer a sincere ‘thank you’ to Bob. The manuscript was greatly improved by the comments, suggestions, and criticisms of Linda Hinnov and the editors of the volume.

References


Figure Captions

Figure 1. Graphical example of the discrete facies rank technique where a stratigraphic column is parsed into five distinct facies types, ranked by depth or some other paleoenvironmentally significant parameter, and then sampled at a constant spacing $\Delta t$. This technique allows for the creation of a continuous proxy sea-level curve derived from standard stratigraphic data.

Figure 2. Distribution of relative abundance of the fourteen facies types identified by Wilkinson et al. (1997) in the Lower Ordovician Kindblade and West Spring Creek Formations along Interstate 35 in the Arbuckle mountains north of Ardmore, Oklahoma. The fraction of total thickness was determined using standard section measuring techniques by summing the thicknesses of all occurrences of a given facies. The frequency of occurrence was calculated as the number of times that facies was identified when the section was measured a second time using a fixed interval observation technique.

Figure 3. Stratigraphic distribution of occurrences of the vadose altered dolostone and caliche subfacies (Facies 1) in the Cimon del Latemar section (Preto et al., 2001). The left column illustrates the positions of occurrences of the facies, while the right column describes the position of those occurrences that are thinner than or equal to the scale of the secondarily re-sample spacing (0.5 cm). A total of 24 of the 162 occurrences of Facies 1 are at or below the spacing interval.

Figure 4. Field photograph of the Picco di Carnizza section illustrating the lines of gray-scale analysis used by Cozzi et al. (2005, Geological Society of America data repository item 2005157). The three lines of section (dark, sub-parallel lines) in this image were used as the basis for the spectral analysis of Milankovitch periodicities in the succession. Sampled at 2,000 dpi, the gray-
scale data series derived from this image is the product of over a 10,000-fold reduction in stratigraphic resolution.

Figure 5. Graphical representation of the significance of differences in the angle between a rectilinear pixel grid of a scanned image and the apparent up-section direction recognized on a field photograph. Five traces of equal length are positioned on the pixel grid where the number of cells intersected by those traces ranges from a minimum of three to a maximum of six. Such dependence upon angular position can have a major control on the interpretation of spatio-temporal characteristics interpreted from a gray-scale series.

Figure 6. Cartoon illustrating the modeling of outcrop step-back by changing the angle between a vertical brick face and the focal plane of the camera.

Figure 7. Results of the outcrop step-back experiment. When the camera’s focal plane is held parallel to the wall surface, the gray-scale series defining the brick-mortar couplets shows no spatial trend (A and B) and results in a strong periodic signal at a thickness of 31 pixels (C). As the angle between the camera and the wall is increased to 20 and 30 degrees, foreshortening of the lower portion of the photograph relative to the upper part results in compression of the thicknesses of the brick-mortar couplets (D, E, G, H). Additionally, as the section becomes compressed, there is a marked degradation of the periodic signal (F and I). Given the simplicity and constancy of the brick-mortar couplets in this model, and the degree of signal degradation observed, foreshortening of an outcrop driven by step-back can have a major impact on any quantitative analysis of gray-scale data series.

Figure 8. Cropped photographs and gray-scale traces of a portion of an outcrop of the Kope Formation, Ordovician, northern Kentucky. On the right is a 1 m wide scan of the outcrop. To the
left of the field photograph is the gray-scale trace averaged over each horizontal row of pixels. Furthest left is a composite of a 2 cm wide scan through the center of the 1 m wide photo and the gray-scale trace derived from that image. Note the significant degree of smoothing in the 1 m gray-scale relative to the 2 cm trace.

Figure 9. Cropped photographs and gray-scale traces of a portion of an outcrop of the Bellview Formation, Ordovician, northern Kentucky. On the right is a 1 m wide scan of the outcrop. To the left of the field photograph is the gray-scale trace averaged over each horizontal row of pixels. Furthest left is a composite of a 2 cm wide scan through the center of the 1 m wide photo and the gray-scale trace derived from that image. Note that the thinly bedded grainstones of the Bellview Formation produce a trace with much more high-frequency and high amplitude variation than exhibited by the shale-rich Kope Formation (Figure 9).

Figure 10. Power spectrograms of the four gray-scale traces illustrated in Figure 9 and 10. For the 1 m wide scan of the Kope Formation, the gray-scale pattern exhibits Brownian like shape, with log Power-log Harmonic Number slope of -2.05. The 2 cm wide scan of the Kope Formation, however, displays greater high-frequency variation and thus a shallower slope of -1.47. Conversely, the Bellview Formation gray-scale traces exhibit patterns much closer to a white noise spectrum (-0.74 and -0.61 log-log slopes). These traces are dominated by high-frequency variations associated with the thinly bedded grainstones typical of the Bellview. Also note there is significantly less impact on the slope of the log-log relationship when a narrower scan of the Bellview is measured.
Figure 1, Drummond & Marlow
Figure 2, Drummond & Marlow

Kindblade and West Spring Creek Formations, Ordovician, Oklahoma

- Frequency of Occurrence 2161 Observations
- Fraction of Total Thickness (819 m)
Figure 3, Drummond & Marlow

Occurrences of Facies 1

Very Thin Occurrences

Stratigraphic Position (Bed Number)

4 of 10

20 of 82
Picco di Carnizza

equivalent to the first ~60 measured cycles

Figure 4, Drummond & Marlow
Figure 6, Drummond & Marlow
Figure 7, Drummond & Marlow
Figure 8, Drummond & Marlow
Figure 10, Drummond & Marlow