Stratigraphic controls on vertical fracture patterns in Silurian dolomite, northeastern Wisconsin

Chad A. Underwood, Michele L. Cooke, J. A. Simo, and Maureen A. Muldoon

ABSTRACT

Vertical opening-mode fractures are mapped on quarry walls to assess the stratigraphic controls on fracture patterns in the relatively undeformed Silurian dolomite of northeastern Wisconsin. Our two-stage study uses maps of vertical fractures to assess the effectiveness of various types of stratigraphic horizons (e.g., organic partings or cycle-bounding mud horizons) in terminating opening-mode fractures. First, the mechanical stratigraphy of the exposures is interpreted from the observed fracture pattern. Both visual inspection and a newly developed quantitative method are employed to identify effective mechanical interfaces. The two methods show similar results, confirming the validity of qualitative visual inspection. The second stage of our study stochastically predicts mechanical stratigraphy and subsequent fracture pattern from empirical relationships between the observed sedimentary stratigraphy and the interpreted mechanical stratigraphy. For example, 63% of cycle-bounding mud horizons within the inner-middle and middle shelf facies associations serve as mechanical interfaces. These empirical percentages are input to a Monte Carlo analysis of 50 stochastic realizations of mechanical stratigraphy. Comparisons of the stochastically predicted and interpreted mechanical stratigraphy yield errors ranging from 13 to 33%. This method yields far better results than assuming that all stratigraphic horizons act as mechanical interfaces. The methodology presented in this article demonstrates an improved prediction of fracture pattern within relatively undeformed strata from both complete characterization of sedimentary stratigraphy and understanding mechanical controls on fracturing.

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INTRODUCTION

Fracture patterns exposed on both horizontal surfaces (e.g., Dyer, 1988) and vertical outcrops (e.g., Gross et al., 1995; Bahat, 1999) have been used to infer paleostress orientations and, thus, give evidence of the tectonic history of a region. Interpreting the geologic history from vertical outcrop patterns of fractures requires consideration of both tectonics and stratigraphy, which can both produce variations in the fracture pattern (see Dholakia et al., 1988; Gross et al., 1995). Furthermore, determining the stratigraphic controls on opening-mode fracture patterns helps us better predict the subsurface flow paths of fluids such as ground water (e.g., Muldoon and Bradbury, 1998) and hydrocarbons (e.g., Nelson, 1982). Understanding the development of fracture networks within aquifers and reservoirs can improve fluid-flow prediction by constraining some of the uncertainty in fracture characteristics, such as fracture length, aperture, and connectivity.

In relatively undeformed sedimentary rocks, the density and height of opening-mode fractures (joints) are typically controlled by stratigraphy rather than faulting or folding (e.g., Becker and Gross, 1996; Hanks et al., 1997). Under these conditions, fracture density typically depends on the material properties and bed thickness of stratigraphic units (e.g., Huang and Angelier, 1989), because fractures commonly terminate at specific stratigraphic horizons (e.g., Gross et al., 1995). However, the pattern of fracturing is directly controlled by mechanical stratigraphy, which does not necessarily correspond to the sedimentary stratigraphy (e.g., Corbett et al., 1987; Gross et al., 1995; Hanks et al., 1997). A mechanical unit represents one or more stratigraphic units that fracture independently of other units (Figure 1). Fractures typically span the thickness of the mechanical unit and commonly abut the bounding stratigraphic horizons. Such stratigraphic horizons along which many fractures abut are termed "mechanical interfaces" (Figure 1) (Gross et al., 1995).

Consequently, the stratigraphic features that comprise the mechanical stratigraphy of a sequence are those that control fracture initiation and termination in rock strata (e.g., Gross, 1993). Vertical opening-mode fractures (joints) commonly initiate from flaws somewhere within a mechanical unit and terminate at mechanical interfaces (Gross, 1993). In layered formations consisting of interbedded brittle/ductile rocks, fractures typically initiate in the brittle layer and terminate at the contact with ductile layers (e.g., Cook and Erdogan, 1972; Erdogan and Biricikoglu, 1973; Helgeson and Aydin, 1991; Rijken and Cooke, 2001). Within relatively homogeneous layered formations, fractures may terminate at mechanical interfaces because of interface slip (e.g., Teufel and Clark, 1984; Renshaw and Pollard, 1995) and/or local debonding along interfaces that are weak in tension (Cooke and Underwood, 2001).

Whereas interface properties control fracture termination, mechanical unit thickness, or spacing of mechanical interfaces, controls fracture density. Predicting fracture density therefore requires

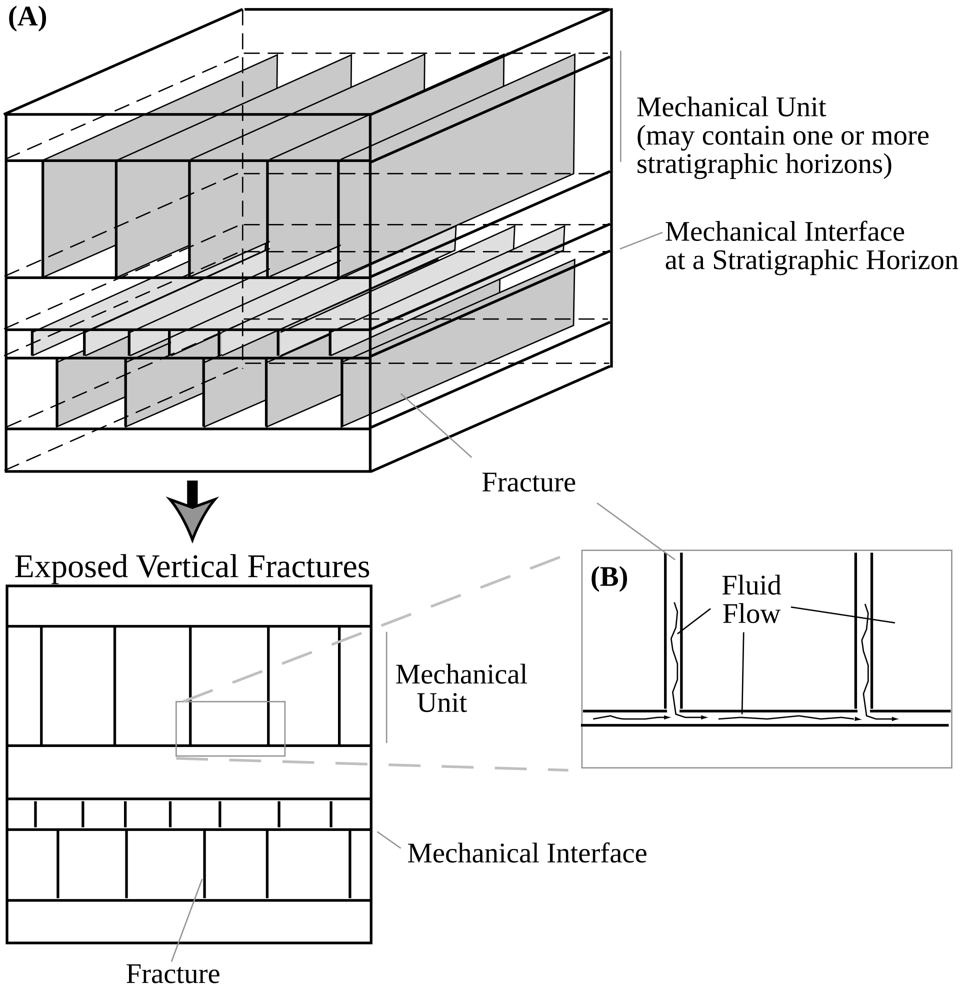


Figure 1. (A) Stratigraphic controls on fracture patterns. Fractures develop within mechanical units and abut mechanical interfaces (modified from Gross et al., 1995). Increased fracture density directly correlates with increased fracture porosity. Both effective porosity and effective permeability are highly dependent on the connectivity of the fracture network; therefore, increased fracture density does not necessarily lead to increased permeability. (B) Termination of vertical fractures can redirect the vertical component of flow to horizontal features, such as dissolutionally enlarged bedding planes. Laterally extensive horizontal high-permeability features are continuous up to 14 km (9 mi) based on hydrogeologic studies of the Silurian dolomite (Muldoon et al., 2001).

knowledge of the distribution of mechanical interfaces. Field investigations indicate that in many relatively thinly bedded rock types, the product of fracture density and bed thickness is approximately 1.0 (Price, 1966; Hobbs, 1967; McQuillan, 1973; Huang and Angelier, 1989; Narr and Suppe, 1991; Gross, 1993; Gross et al., 1995; Wu and Pollard, 1995; Becker and Gross, 1996; Bai and Pollard, 2000). One explanation for this relationship relies on the concept of a stress shadow (Lachenbruch, 1961; Nur, 1982; Pollard and Segall, 1987; Gross et al., 1995) where new fracture growth is inhibited within a zone of decreased stress adjacent to an open fracture (Pollard and Segall, 1987). The size of the stress shadow is directly proportional to the height of the fracture, so that thicker mechanical units have longer and more widely spaced fractures than do thinner units (Pollard and Segall, 1987; Gross, 1993).

This article seeks to describe the relationship between sedimentary stratigraphy and mechanical stratigraphy, within a relatively undeformed setting, to test predictions of fracture pattern from stratigraphic information. We interpret the mechanical stratigraphy of a section of the shallow dipping (<2°) Silurian dolomite of northeastern Wisconsin (Figure 2) from careful fracture mapping along two quarry exposures. This article assesses the effectiveness of different types of stratigraphic horizons as mechanical interfaces that arrest fractures by correlating stratigraphic horizons (characterized by Simo et al. [1998] and Harris and Waldhuetter [1996]) with interpreted mechanical interfaces. The resulting empirical relationships between sedimentary stratigraphy and mechanical stratigraphy are used to predict vertical fracture pattern. We compare the stochastic predictions of mechanical stratigraphy and fracture pattern with our observations and interpretations to test the application of such empirical relationships toward fracture pattern prediction. The methodology used in this article can be employed to predict subsurface opening-mode fracture networks,

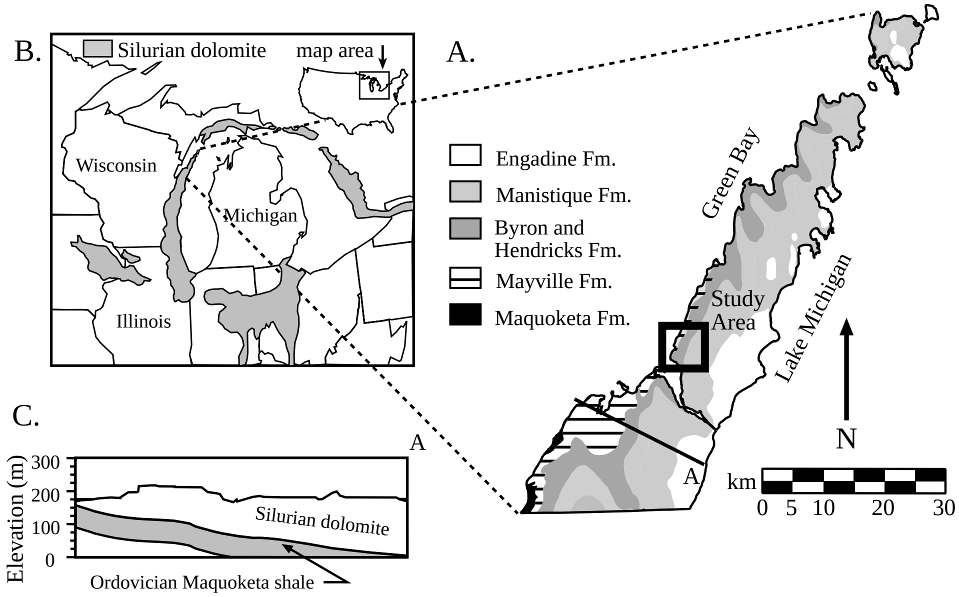


Figure 2. (A) Location of Door County, Wisconsin (Muldoon et al., 2001). (B) Bedrock geology of Door County, Wisconsin (Roffers, 1996). (C) Cross section through Door County, Wisconsin (Muldoon et al., 2001).

which are poorly sampled by vertical boreholes, from available observations of sedimentary stratigraphy. Such an approach enhances prediction of subsurface fluid flow through better characterization of potential flow paths. The key to this approach is accurate description of the relations between sedimentary stratigraphy and mechanical stratigraphy.

REGIONAL GEOLOGY, STRATIGRAPHY, AND FRACTURE PATTERN

Door County, Wisconsin occupies much of a peninsula that lies between Lake Michigan and Green Bay in northeastern Wisconsin (Figure 2). It is underlain by approximately 160 m (525 ft) of Lower Silurian (Hegrenes, 1996) or Llandovery (Watkins and Kuglitsch, 1997) dolomite. The Silurian strata were deposited in the western margin of the Michigan basin, a relatively undeformed cratonic structural basin (Sleep and Sloss, 1978; Howell and van der Pluijm, 1990, 1999). Aside from early Paleozoic subsidence in the Michigan basin, the mid-continent region has been relatively free of tectonic activity since the Precambrian (Howell and van der Pluijm, 1990). Consequently, opening-mode fractures (joints) are one of the few structural features present in this part of the continent. Relatively undeformed sedimentary rocks (i.e., neither faulted nor folded), such as those at Door County, may develop opening-mode fractures due to regional extension, thermoelastic contraction, and/or unloading associated with uplift and erosion (e.g., Price, 1966; Voight and St. Pierre, 1974; Lajtai, 1977; Narr and Currie, 1982; Lacazette and Engelder, 1992) and/or increased pore fluid pressure at depth (e.g., Secor, 1967; Ladiera and Price, 1981; Magara, 1981; Engelder, 1985; Lorenz et al., 1991).

Stratigraphy

Chamberlain (1877) first mapped and subdivided the Silurian strata of the Door Peninsula into stratigraphic units (Figure 2), and, later, Waldhuetter (1994), Harris and Waldhuetter (1996), Hegrenes (1996), and Watkins and Kuglitsch (1997) provided a sequence stratigraphic framework. Geophysical logs from 19 wells and core descriptions provided regional subsurface correlation of stratigraphic units (Gianniny et al., 1996).

Silurian lithologies of the Door Peninsula are grouped into one of three facies associations: inner, inner-middle, and middle shelf facies association (Simo et al., 1998). The Mayville Dolomite, Manistique Formation (Cordell and Schoolcraft members), and Engadine Dolomite mostly contain middle shelf facies associations (Figure 2). The Byron Dolomite is characterized by inner shelf facies association, and the Hendricks Dolomite corresponds to alternating inner-middle and inner shelf facies associations (Figure 2). Overall, the stratigraphic succession shows a shallowing from the Mayville to the Byron followed by a deepening through the Engadine.

The inner shelf facies association is interpreted as having been deposited in a shallow, restricted-marine, low-energy, tidal-flat environment. Subaerial exposure surfaces, some with decimeter-scale depositional relief, are common and bound thin (~0.3–0.9 m [1–3 ft]) depositional cycles. Complete cycles contain a lower part characterized by bioturbated, fenestral mudstone-packstone with intraclasts. The upper part of a typical cycle consists of domal stromatolites or peloidal-ostracod mudstone-packstone at the base and mudcracked, thin and crinkly laminites at the top of the cycle. Cycle tops are affected by intense diagenesis, are very well cemented and massive, and contain occasional microkarst features (Figure 3). Cycle boundaries separate the very well cemented laminite/diagenetic cap and the overlying, less-cemented fenestral mudstone-packstone (Figure 3). At these contacts, thin and discontinuous organic-rich mudstones may occur. All the lithologies in the inner shelf facies association are dolomitized by fine-crystalline, micritic dolomite.

The inner-middle shelf facies association is interpreted to represent slightly deeper depositional conditions and is a transition between inner and middle shelf deposition. This facies association predominantly consists of thin-bedded, fine-crystalline, peloidal-skeletal rocks and mat- and fenestral-laminated mudstone-packstones. These two lithologies alternate and define medium-bedded depositional cycles. Organic-rich laminae at cycle boundaries are less common than in the inner shelf facies association.

The middle shelf facies association consists of coarse-crystalline, bioturbated and massive skeletal (brachiopods, corals, and stromatoporoids) wackestone and bioturbated cherty mudstone-wackestones. Bedding planes are discontinuous, and organic-rich laminae are not present. Depositional cycles are thickly bedded (>5 m [16 ft]) (Waldhuetter, 1994) and defined by an upward decrease in mud and an increase in grain size (Hegrenes, 1996).

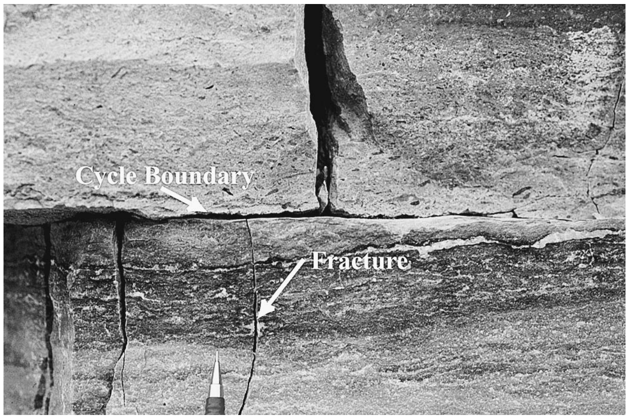


Figure 3. Fracture termination at the top of a shallowing-upward cycle boundary in the inner shelf facies association. Sheet cracks below the cycle boundary are indicative of a supratidal setting. The intraclastic conglomerate above the cycle boundary was deposited in a deeper environment. Staining along the fracture indicates fluid flow through this fracture network that may have been enhanced by blasting of the outcrop.

Fractures

Fracture orientations in the Door Peninsula resemble those in other parts of the Michigan basin (Holst and Foote, 1981; Holst, 1982; La Pointe and Hudson, 1985; Roffers, 1996). These fracture orientations are likely controlled by the present-day stress field (~50°) (Haimson, 1978) or past stress fields associated with the Appalachian and Ouachita orogenies (134° and 001°, respectively) (Craddock and van der Pluijm, 1989). Roffers's (1996) multiscale analysis identified four major fracture sets (069°, 152°, 046°, and 135°) and four minor fracture sets (088°, 165°, 030°, and 118°) in Door County. These fracture orientations are consistent at different scales (from outcrop to lineament scale) and in different facies associations (Roffers, 1996). Our fracture mapping at a quarry in Door County indicated dominant fracture orientations of 040° and 160°, which are consistent with an independent investigation of the same quarry by Rock Products Consultants (1999). Joint surface textures, including hackle marks and fringe joints, observed along many fracture surfaces demonstrate that the fractures investigated in our study are joints, which form by opening-mode failure of the rock (e.g., Pollard and Aydin, 1988). For consistency with the hydrogeologic literature of the region, we refer to these features as fractures in this article.

METHODS

Mapping methods are used to describe the fracture pattern and density within stratigraphic layers of the Silurian dolomite, and in-situ testing is used to determine relative dolomite stiffness. The mapped fracture patterns are then used to infer the mechanical stratigraphy of the Silurian sequence in Door County, whereas variations in rock stiffness are used to assess lithologic contrasts as factors in fracture termination.

Vertical fractures were mapped along quarry walls exposing different facies associations (see Figures 4C, 5C). The orientation of the quarry walls is controlled by the dominant fracture sets (040° and 160°) so that

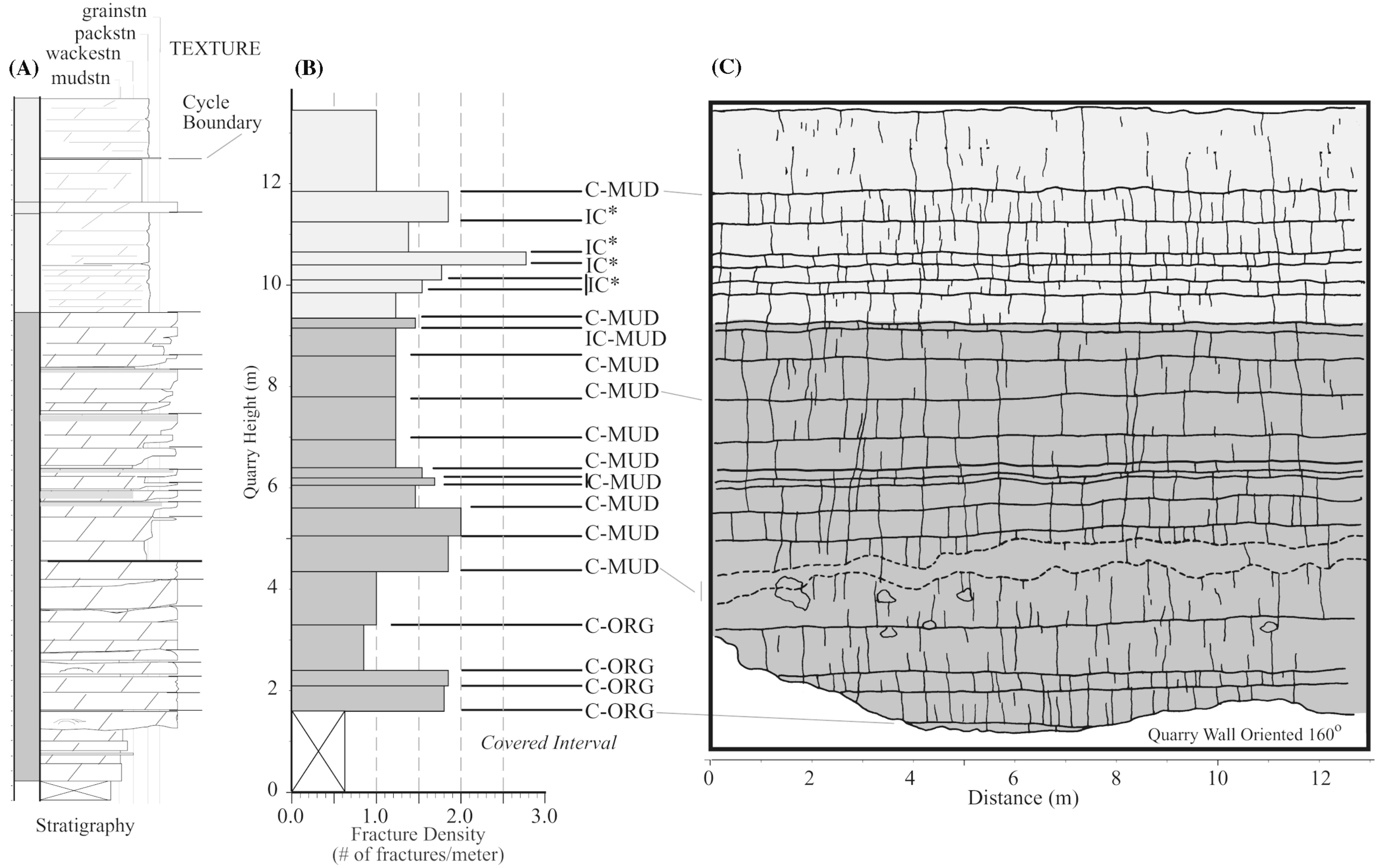


Figure 4. (A) Sedimentary stratigraphy developed from core and outcrop observations of Simo et al. (1998) and Harris and Waldhuetter (1996); (B) mechanical stratigraphy; and (C) fracture map for the lower quarry exposure. Whereas the horizontal axis of the stratigraphic section (A) describes the texture of the facies association, the horizontal axis of the mechanical stratigraphic section (B) shows the fracture density of the mechanical unit. Dark-gray layers represent inner shelf facies associations, whereas lighter gray layers represent inner-middle/middle shelf facies associations. Abbreviations for mechanical interfaces: C = cycle boundaries; IC = intracycle boundaries; ORG = organic horizons; MUD = mud horizons; * = no stratigraphic equivalent. Dashed lines indicate a major scour surface; irregular circles are weathered stromatoporoids.

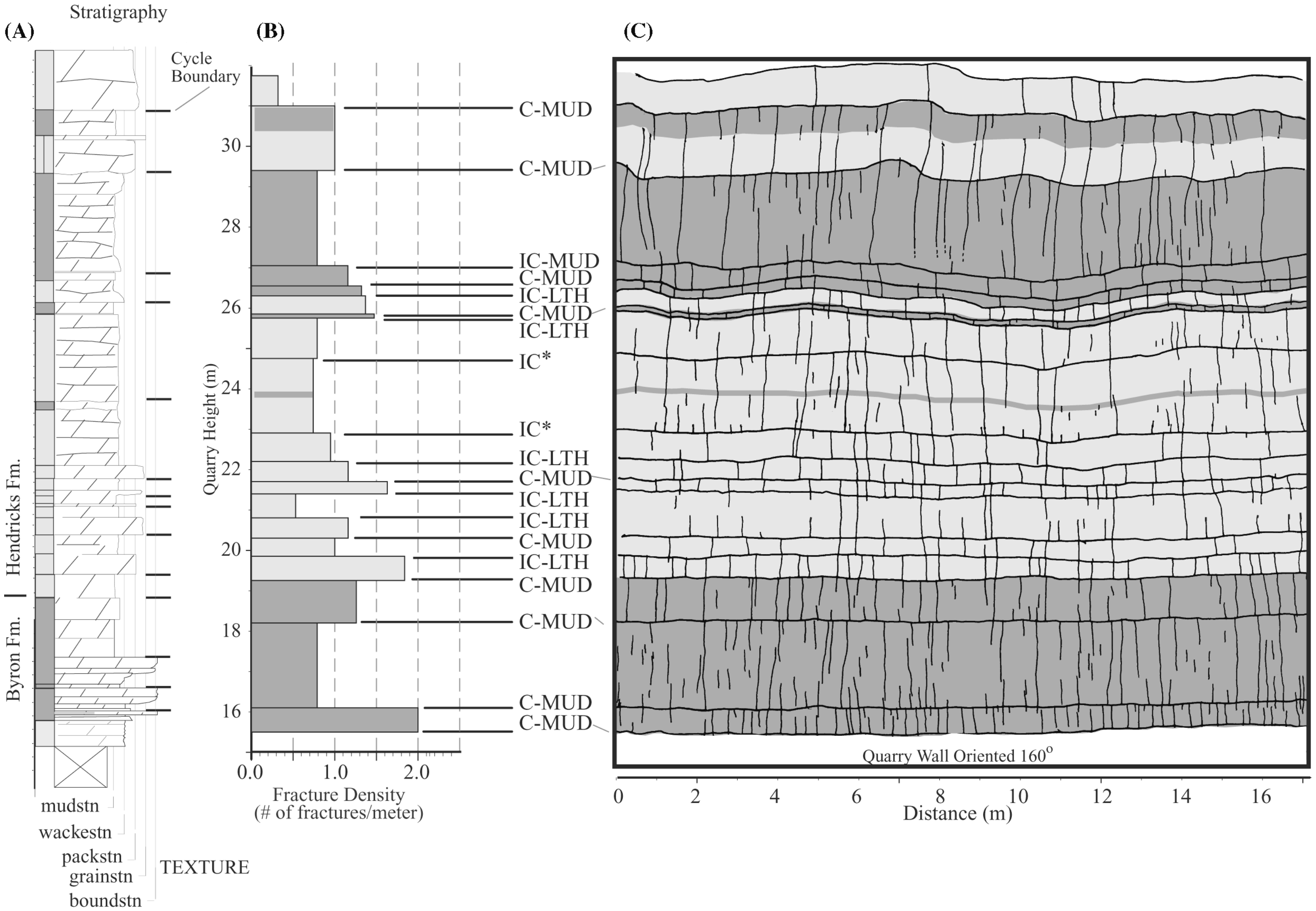


Figure 5. (A) Sedimentary stratigraphy, developed from core and outcrop observations of Simo et al. (1998) and Harris and Waldhuetter (1996); (B) mechanical stratigraphy; and (C) fracture map for the upper quarry exposure. Dark-gray layers represent inner shelf facies associations, whereas lighter gray layers represent inner-middle/middle shelf facies associations. Abbreviations for mechanical interfaces: C = cycle boundaries; IC = intracycle boundaries; ORG = organic horizons; MUD = mud horizons; * = no stratigraphic equivalent.

walls along one fracture set expose the other set of fractures. For our study, we mapped in detail the fracture set trending 040°; enlarged photographs of the outcrop (at a scale of 1 cm = 0.3 m) were used to aid the fracture-mapping process (see Figures 6, 7, 8). Comparison of fractures on differently oriented quarry walls, which expose the same strata, reveal little difference in fracture density and termination characteristics between the two dominant fracture sets (Underwood, 1999). Along both of these quarry walls, vertical fractures abut the same stratigraphic horizons (Underwood, 1999). The close correlation of fracture pattern between these two sets suggests that each fracture set developed similarly within each stratigraphic level of the Silurian dolomite.

Fracture density is a function of mechanical unit thickness (e.g., Huang and Angelier, 1989) and rock stiffness (e.g., Gross et al., 1995). The in-situ stiffness of stratigraphic units was measured using a Schmidt Hammer, a portable device that measures the rebound of a hammer impacting the rock (e.g., Poole and Farmer, 1980). The error in the stiffness values obtained from the Schmidt Hammer can be evaluated from the range in multiple readings at the same locality (Poole and Farmer, 1980). For the purpose of this article, the Schmidt Hammer results are not intended to indicate absolute stiffness values; instead, we use the results to determine the relative stiffness of each facies association within the Silurian dolomite. These results are then used to assess the influence of rock stiffness on observed fracture pattern.

Identification of Mechanical Interfaces

We use two methods to infer the location of mechanical interfaces. The first method employs visual identification of mechanical interfaces in the field where numerous vertical fractures abut distinct stratigraphic horizons (Figures 4C, 5C). Figure 3 shows an example of the fracture terminations used to visually identify mechanical interface locations in the field. This method, however, may involve visual bias, because the

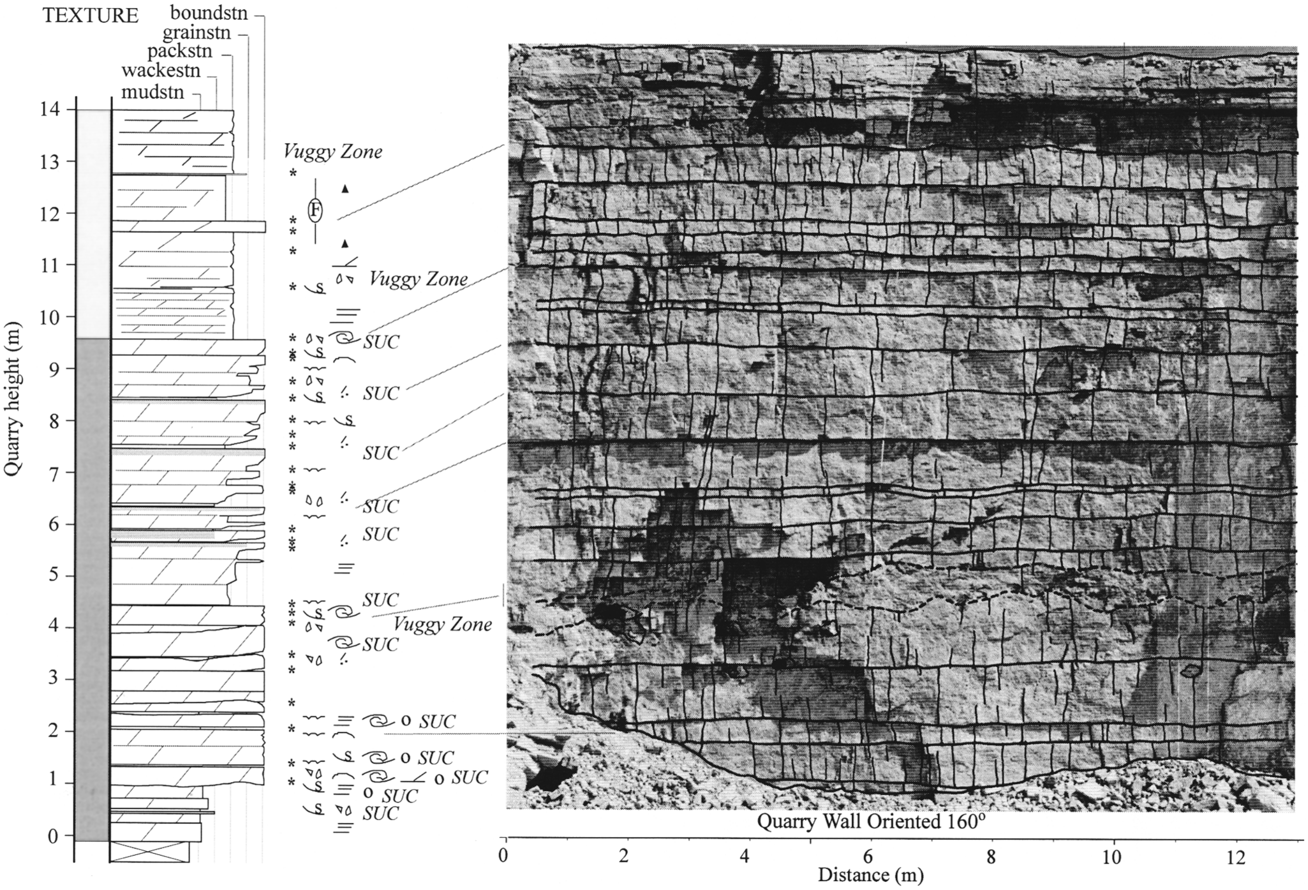


Figure 6. Photo/fracture map overlay for lower quarry exposure, accompanied by stratigraphic section (stratigraphy from Harris and Waldhuetter [1996] and Simo et al. [1998]). See Figure 8 for key to symbols. Refer to Figure 4 for inferred mechanical stratigraphy.

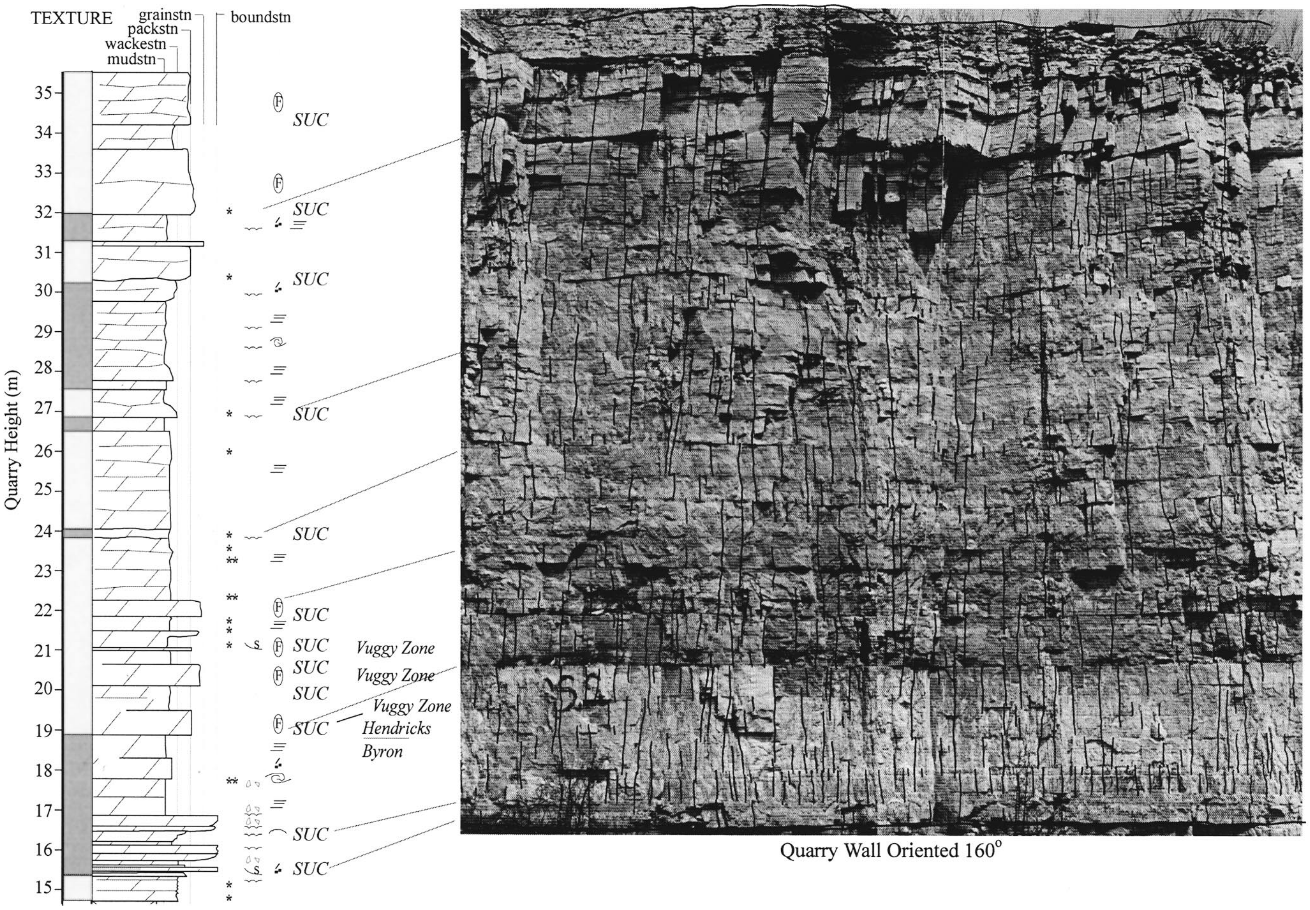


Figure 7. Photo/fracture map overlay for upper quarry exposure, accompanied by stratigraphic section (stratigraphy from Harris and Waldhuetter [1996] and Simo et al. [1998]). See Figure 8 for key to symbols. Refer to Figure 5 for inferred mechanical stratigraphy.

mapper's eye may be drawn to visually distinct horizons such as those with color contrasts or highly weathered horizons. Such visual bias may overemphasize visually distinctive horizons or neglect indistinct but significant horizons.

To minimize visual bias, we developed a second quantitative method to identify mechanical interfaces that examines both the percentage of fracture terminations and the number of fractures that terminate at successive stratigraphic horizons. With this method, a stratigraphic horizon is considered to act as a mechanical interface only if both (1) a small percentage of fractures propagate through the horizon and (2) a sufficient number of fractures terminate at the horizon. The amount of visual bias involved in mapping interfaces in the field can be determined by comparing the quantitatively identified interface distribution with qualitatively mapped interfaces. To our knowledge, ours is the first study to assess visual bias in characterizing mechanical stratigraphy and the first to propose an objective methodology for evaluating mechanical stratigraphy from mapped fracture patterns.

To quantitatively establish the locations of mechanical interfaces within the stratigraphic sequence, fracture maps are digitized, and we count the number of fracture tips (i.e., fracture terminations) within successive sampling intervals, as illustrated in Figure 9. Sample intervals containing a high number of fracture tips are likely to contain a mechanical interface that limits vertical propagation of fractures. This analysis of fracture pattern is sensitive to the thickness of the sampling interval (Figure 9). In the presence of undulating stratigraphic horizons, a thin sampling interval may result in fracture tips along one horizon counted within two adjacent intervals; this yields two interfaces where only one exists (Figure 9). In contrast, a thick sampling interval may group more than one horizon into a single interval; this yields one interface where more than one exists (Figure 9). Within the Silurian section, the minimum distance between two stratigraphic horizons is

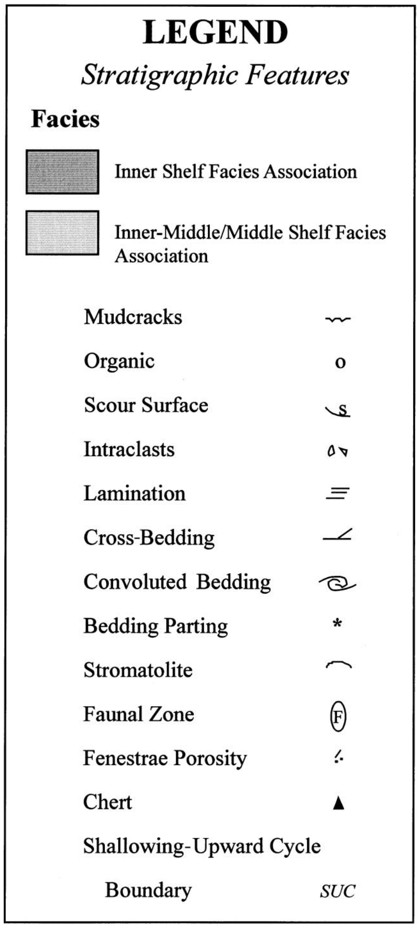


Figure 8. Key to stratigraphic sections. Stratigraphic symbols and nomenclature from Harris and Waldhuetter (1996) and Simo et al. (1998).

about 10 cm (3.9 in.), whereas typical surface undulations are less than 10 cm (3.9 in.). Consequently, a sampling interval thickness of 10 cm (3.9 in.) generally prevents the grouping of two adjacent interfaces and the splitting of a single undulating interface. Highly undulating surfaces require additional consideration in this analysis. This evaluation is stochastic because the number of fracture tips that fall within each sample interval may vary with position of the initial interval; decreasing sample interval thickness minimizes this variation.

In order for a stratigraphic interval to contain a mechanical interface, we require that the majority of the fractures that intersect the interval terminate within the interval rather than propagate through the interval:

$$\frac{\text{No. of Terminations}}{\text{No. of Terminations} + \text{No. of Crossings}} \times 100\% > 50\% \quad (1)$$

The majority criterion, on its own, is not robust unless we also observe a significant number of fracture terminations. For example, if only 3 fractures intersect a horizon along 13 m (43 ft) of exposure and 2 of the 3 fractures terminate at the horizon, the resulting percent termination is 66%. However, in the absence of units with anomalously low fracture density, this is not a significant horizon, because of the low number of fractures that intersect the horizon. We determine the critical number of fracture tips required for a sample interval to contain a mechanical interface by examining the frequency of fracture tips counted within each 10 cm (3.9 in.) sampling interval in our study area (Figure 10).

The nearly horizontal part of the data trend in Figure 10 indicates relatively infrequent stratigraphic horizons that contain many fracture tips, whereas the linearly sloping data trend indicates frequent horizons that contain fewer fracture tips. We interpret the horizontal data trend (Figure 10) to represent fracture termination at mechanical interfaces, whereas the sloping data trend represents relatively random termination of fractures within mechanical units (i.e., fracture termination is not constrained by sedimentary stratigraphy). It follows that the cutoff between these two data trends is the critical number of fractures within this outcrop required for an interval to contain a mechanical interface.

The placement of the frequency curve in Figure 10, and consequently the cutoff between stratigraphically controlled and random fracture terminations, varies with length of the mapped interval because longer exposures have more numerous fractures than shorter exposures. Therefore, the cutoff that we estimate, 15, is relevant for the 13 m (43 ft) of available exposure mapped in our study. Because the fracture density of most mapped layers in our study is approximately 1.5 fractures/m, an average layer exposes about 20 fractures, an adequate population size for assessing the percentage of fracture termination. This also suggests that the termination of 15 fractures within an average interval (of ~20 fractures) reflects the influence of stratigraphy on fracture termination.

If the cutoff value is too high (e.g., 20 fractures), this method may underestimate the number of mechanical interfaces. Similarly, a cutoff value that is too low (e.g., 10 fractures) may overestimate the number of mechanical interfaces. To be conservative, a lower cutoff should be used, because potential interfaces must also pass the majority termination criterion. Among all the horizons in our study area that termi-

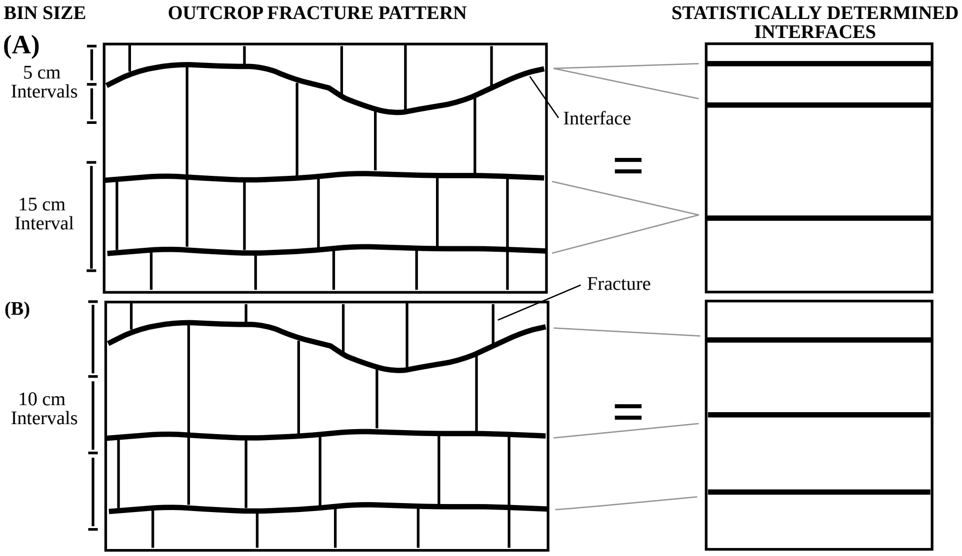


Figure 9. The sampling method used to quantitatively identify mechanical interfaces (from digitized fracture patterns) counts the number of fracture tips within each stratigraphic interval. (A) In the presence of undulating stratigraphic horizons, a thin sampling interval may result in fracture tips along one horizon counted within two adjacent intervals; this yields two interfaces where only one exists. In contrast, a thick sampling interval may group more than one horizon into a single interval; this yields one interface where more than one exists. (B) The optimum interval size correctly samples the number of fracture terminations at one interface.

nate more than 15 fractures, only five do not pass the majority test for fracture intersection (Figure 11). A 10 cm (3.9 in.)–thick sample interval could mislocate interfaces by up to 5 cm (2.0 in.); however, this relatively small error does not greatly influence the distribution of mechanical interfaces.

FRACTURE PATTERN AND MECHANICAL STRATIGRAPHY

In the outcrops studied, all fractures are vertical and perpendicular to bedding so that fracture length describes the vertical trace length observed on quarry walls. Several generalizations can be drawn from fracture maps in quarries representative of different facies associations within the Silurian dolomite. Fractures in the thinly bedded inner shelf facies association (Figure 4) are generally evenly distributed, densely spaced, and confined to distinct layers. Fractures in these units commonly abut shallowing-upward cycle boundaries, and, in some cases, fractures abut horizons within a shallowing-upward cycle. Organic horizons within this facies association appear weak and friable in outcrop, which may suggest that these layers are weak and

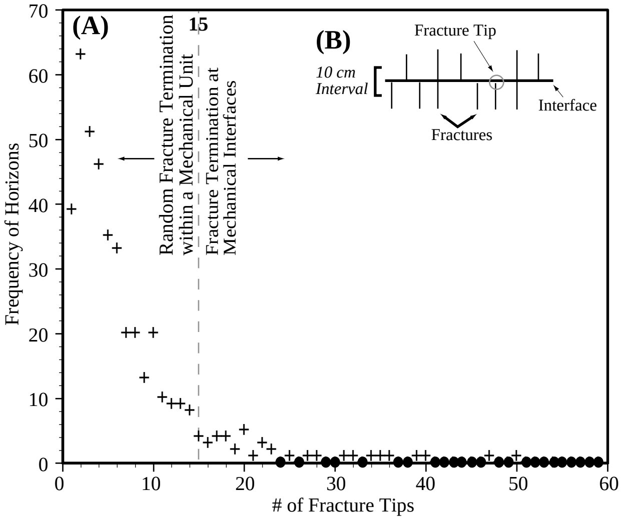
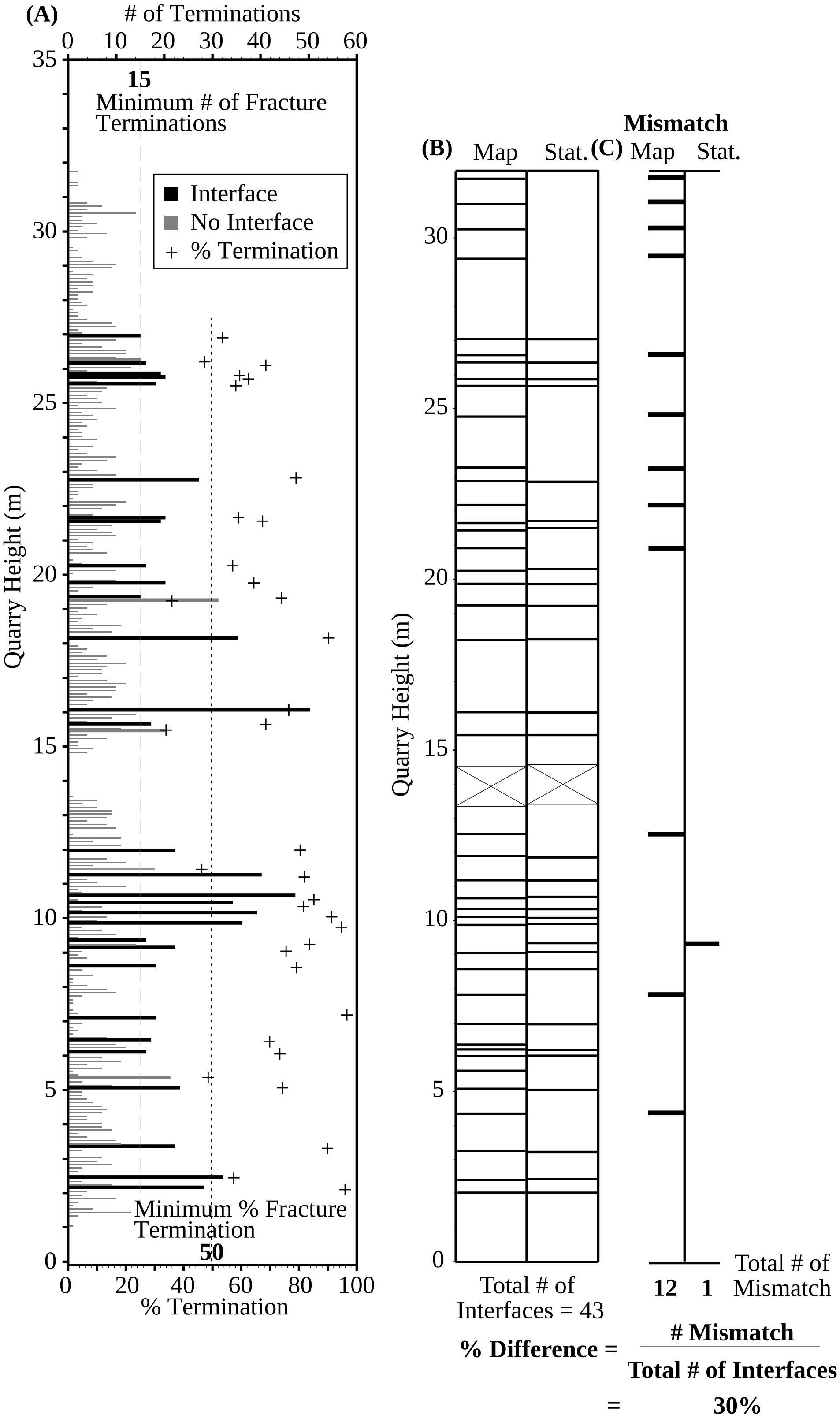


Figure 10. (A) The frequency of fracture tips within sampling intervals provides a method to determine which stratigraphic horizons have enough fracture tips to be considered mechanical interfaces. Many sample intervals contain less than 15 fracture tips, suggesting that fracture termination within these intervals is sparse because of relatively random fracture termination within mechanical units. Where fracture termination is stratigraphically controlled, the number of fracture tips within one interval should be greater than 15. (B) Determination of the number of fracture terminations at a stratigraphic horizon.

Figure 11. (A) Bold lines represent stratigraphic horizons that satisfy the mechanical interface criterion: greater than 15 fracture tips and greater than 50% termination within 10 cm (3.9 in.) interval spanning 13 m (43 ft) horizontal distance. (B) Comparison of visually mapped interfaces (left) with interfaces that meet our quantitative criterion (right) for the quarry exposure. (C) Differences between the two methods are highlighted by mismatches between mapped and statistically determined interfaces.



should arrest vertically propagating fractures (Cooke and Underwood, 2001). Although mud horizons do not appear as weak and friable as organic horizons, fractures also commonly abut these types of shallowing-upward cycle boundaries.

The fracture pattern differs in the transitional inner-middle shelf facies association (Figure 4). Vertical fractures in the inner-middle shelf facies association terminate both at mud cycle boundaries and at horizons within shallowing-upward cycles. The faunal-bearing bases of shallowing-upward cycles in this facies association commonly fracture independently from the thinner, laminated mudstone top of the shallowing-upward cycle; this results in abundant fracture tips within individual shallowing-upward cycles (e.g., 19.5 m in Figure 4). Fracture density within an individual shallowing-upward cycle is typically higher in the thinner, mudstone top than in the thicker faunal-bearing base. Although the inner-middle shelf facies association exhibits continuous and distinct bedding, in some cases, fractures span several shallowing-upward cycles.

The middle shelf facies association exposed within the quarry studied does not exhibit the massive bedding (>5 m [16 ft] thickness) documented elsewhere in Door County (Waldhuetter, 1994). Whereas those exposures display long (up to 8 m [26 ft]) and more widely spaced (5 to 7 m [16 to 23 ft]) fractures that may not be confined to distinct stratigraphic horizons (Underwood, 1999), fractures within the limited exposures of the middle facies association of this study area are similar to those observed in the inner-middle shelf facies association.

Stiffness Variations among Facies Associations

Our fracture maps of vertical outcrops suggest that sedimentary stratigraphy controls fracture patterns; fractures are largely contained within distinct stratigraphic units and abut stratigraphic horizons acting as mechanical interfaces (Figures 4, 5). Because either contrasts between layer stiffness or stratigraphic horizons can control fracture pattern (e.g., Cook and Erdogan, 1972; Huang and Angelier, 1989), we assess the variation of stiffness between facies associations of the Silurian dolomite by taking in-situ stiffness measurements at several locations within each facies association.

The in-situ stiffness tests yield average stiffness of 57.2 ± 5, 52.8 ± 5, and 60.9 ± 5 GPa for inner, inner-middle, and middle shelf facies associations, respectively. The stiffness variation between facies associations throughout the Silurian does not exceed the error of this testing method. We suspect that dolomitization may have contributed to present-day uniform strength properties and that fracturing likely occurred after dolomitization. Because stiffness changes are minimal throughout the Silurian dolomite, fracture termination is unlikely the result of material property differences between mechanical units, such as grain-size differences or cementation variations. Consequently, the termination of vertical fractures is likely controlled by the nature and distribution of stratigraphic horizons that act as weak mechanical interfaces.

Identification of Mechanical Interfaces

Interfaces inferred in the field are compared to quantitatively identified interface locations to assess visual bias. In general, interface locations determined from our quantitative method correspond well to those qualitatively assessed from fracture maps (Figure 11), suggesting that little visual bias occurred during the mapping process. Only one subtle interface that passed the quantitative criterion was missed in the visual identification (at 9.3 m in Figures 4, 11). Additionally, only one visually distinct mechanical interface delineated during fracture mapping in the field does not pass the quantitative definition of a mechanical interface (at 12.65 m in Figure 11). Interestingly, the visual identification approach was better suited for areas with highly undulating stratigraphic horizons or areas where the photographs used to aid in fracture mapping developed vertical distortion. The quantitative method failed to identify several horizons with greater than 10 cm (3.9 in.) undulations, such as the prominent exposure surface at 4.35 m (Figures 4, 11) and an interface at 7.8 m (Figures 4, 11). Because the photographs of regions high along the quarry walls (>20 m [66 ft]) developed vertical distortion, some apparent interface undulations are greater than the 10 cm (3.9 in.) sampling interval in the upper part of the mapped interval in Figure 5. Results from the two methods are merged by modifying the distribution of mechanical interfaces mapped in the field so that each interface conforms to the new quantitative definition with special consideration for undulating surfaces.

The close correlation between the visually and quantitatively identified nonundulating mechanical interfaces (Figure 11) suggests that the 15 fracture termination cutoff used to delineate the presence of a mechanical interface within a sample interval (Figure 10) does not greatly over- or underestimate mechanical interfaces. Although the two methods of identifying mechanical interfaces produced similar results, the application of quantitative criteria adds rigor to the analysis because we require that all interfaces pass the same objective definition of a mechanical interface.

Mechanical Interface Classification

Mapping mechanical interface distribution allows us to develop a mechanical stratigraphic section for mapped intervals (e.g., Figures 4B, 5B). We identify two groups of horizons that act as mechanical interfaces in the Silurian dolomite of Door County (cycle and intracycle interfaces). Cycle interfaces occur at the top of shallowing-upward cycles, whereas intracycle interfaces occur within an individual shallowing-upward cycle. Each group of interfaces includes distinct subcategories based on characteristics of stratigraphic horizons.

Cycle interfaces are most abundant in sections of the Silurian dolomite consisting of thinly bedded inner and inner-middle shelf facies associations. The shallowing-upward cycles may be separated by thin, weak deposits such as organic partings and mud layers that terminate fractures to differing degrees. Two subcategories of cycle-bounding interfaces were observed: organic partings and thin mud layers.

Organic cycle interfaces are generally characterized by the presence of brown, thinly laminated organic material; thickness generally ranges from 0 to 1 cm (0 to 0.4 in.) along any one interface. In outcrop, the organic interface is very friable, poorly cemented, and commonly iron stained. Organic cycle interfaces are less abundant than other interface types and are observed only within the inner shelf facies association (Figure 4).

Mud cycle interfaces range in thickness from less than 0.5 to 4 cm (0.2 to 1.6 in.); thickness is relatively uniform along individual horizons, but larger variations occur between horizons. These interfaces are generally platy and commonly mudcracked or are associated with storm deposits. Mud interfaces associated with storm deposits commonly undulate with amplitudes ranging from 1 to 10 cm (0.4 to 3.9 in.) and are commonly visually distinct and easily identifiable in the field.

Intracycle interfaces separate parts of individual shallowing-upward cycles that fracture independently of one another. As with cycle interfaces, different types of intracycle interfaces terminate fractures to differing degrees. Two subcategories of intracycle interfaces were observed: thin mud layers and contacts between layers of contrasting lithology.

Mud intracycle interfaces resemble muds of the cycle interface group but are generally thinner and more planar than cycle muds. Like cycle muds, intracycle muds may also exhibit mudcracks or may be associated with storm deposits (e.g., at 6.4 m in Figure 4). This interface type is observed in both the inner and inner-middle shelf facies associations.

Lithologic intracycle interfaces typically separate coarse-grained, faunal-bearing lithologies, which are deposited in a more open-marine environment, from fine-grained, thinly laminated lithologies deposited in a more restricted-marine environment. This interface type is observed only in the inner-middle shelf facies association (e.g., at 19.8 m in Figure 5).

In places, we identified a mechanical interface within a shallowing-upward cycle that did not correlate to any specific stratigraphic horizon noted in previous stratigraphic studies; we denoted such interfaces by the symbol IC* on Figures 4 and 5 (e.g., at 5.6 m in Figure 4). More detailed stratigraphic description is required to classify these interfaces.

Note that although mechanical interfaces correlate well with sedimentary stratigraphy, not all stratigraphic horizons contribute to fracture pattern. For example, some fractures propagate across mud horizons that, in the field, appear no different from nearby horizons along which the fractures terminate. This suggests that visually similar stratigraphic horizons may not have the same mechanical properties. Laboratory testing of interface mechanical properties may provide further insight into stratigraphic controls on fracture termination; however, such laboratory analysis is beyond the scope of our study.

Observed Fracture Density

Fracture density within our study area is measured as the number of vertical fractures per meter along bed-parallel transects across the vertical quarry exposures (approximately 13 m [43 ft] in length). Fracture density is measured in each interpreted mechanical unit within the study outcrops. To determine the influence of mechanical interface distribution on fracture density, we only report the number of fractures that, at a minimum, span the entire thickness of each mechanical unit. Fracture terminations within interpreted mechanical units do not meet our criterion for expression of a mechanical interface and seem to have a random distribution (Figure 10). Furthermore, fractures that span entire mechanical units may more effectively conduct fluids than fractures that terminate within units, because they enhance the overall connectivity of the fracture network.

Fracture density in the inner, inner-middle, and middle shelf facies associations in the quarry exposures decreases with increasing bed thickness but does not follow the expected density (*D*) times thickness (*T*) equals 1.0 curve based on numerous field observations (e.g., Price, 1966; Hobbs, 1967; McQuillan, 1973; Huang and Angelier, 1989; Narr and Suppe, 1991; Gross, 1993; Gross et al., 1995; Wu and Pollard, 1995; Becker and Gross, 1996; Bai and Pollard, 2000) (see Figure 12). If fracture density conforms to the relationship, $DT = 1$, then the beds are considered to be fracture-saturated (Bai and Pollard, 2000). However, over- or undersaturation may be the result of either sequential infilling of fractures in highly strained beds (e.g., Wu and Pollard, 1995; Becker and Gross, 1996) or low levels of tectonic strain, respectively. Ladeira and Price (1981) note that thicker beds have lower than expected fracture density and that fracture density becomes nearly constant with beds thicker than 1.5 m (4.9 ft) (Ladeira and Price, 1981) (e.g., Figure 12). As a result, the $DT = 1$ relationship may not be an appropriate method to predict fracture density in thick (>1.5 to 2.0 m [4.9 to 6.6 ft]) mechanical units.

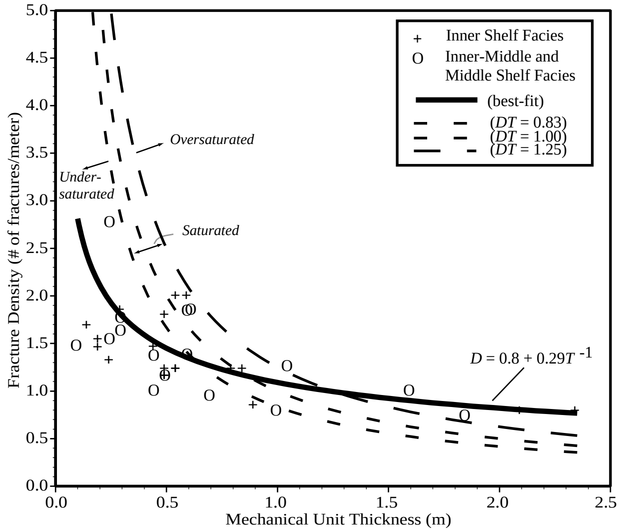


Figure 12. Fracture density vs. mechanical unit thickness for units in the quarry exposures. Fracture density is calculated from fracture maps (Figures 4, 5). The bold line represents the best-fit line though all of the data. Dashed curves represent density times mechanical unit thickness (*DT*) of 0.83, 1.00, and 1.25. Bai and Pollard (2000) suggest cutoff values for undersaturation ($DT = 0.83$) and oversaturation ($DT = 1.25$) based on layer-parallel stresses between adjacent fractures.

Fracture density data (Figure 12) indicate that mechanical units are generally undersaturated with respect to fracturing; this is expected because of the low-strain tectonic environment. As mechanical unit thickness increases, fracturing tends toward oversaturation; however, very few data points define this part of Figure 12. Fractures observed in core were not used in the density analysis, but these observations also suggest increased density with thinner beds (Underwood, 1999).

Fracture density also has been shown to correlate with the stiffness of mechanical units (e.g., Huang and Angelier, 1989; Gross, 1993). Although in-situ measurements did not detect systematic stiffness differences between facies associations, some variation was detected within each facies association. The observed scatter of data in Figure 12 may be due to stiffness variation within each facies association, which was not rigorously assessed by our study. Furthermore, little distinction could be made between the trend of fracture density for the inner and inner-middle/middle shelf facies associations.

PREDICTING MECHANICAL STRATIGRAPHY AND FRACTURE DENSITY

Fracture mapping and analysis indicates that the length (vertically) and density of fractures in the Silurian dolomite are primarily controlled by the distribution of mechanically weak interfaces. Therefore, determining the distribution of these interfaces is a requirement for predicting fracture patterns at depth. If the distribution of subsurface mechanical interfaces can be determined (i.e., using sedimentary stratigraphy from rock core), fracture patterns at depth may be inferred by relationships developed from outcrop observations. To test this methodology, we develop empirical relationships between sedimentary stratigraphy and mechanical stratigraphy, which we use to predict the distribution of mechanical interfaces and subsequent fracture patterns. In this section, we establish empirical relationships between sedimentary and mechanical stratigraphy based on field observations. In the next section, we use these empirical relations to stochastically predict mechanical stratigraphy and compare one stochastic realization to the mechanical stratigraphy inferred from outcrop fracture pattern to assess the errors in this methodology. Then we use quantitative relationships between mechanical stratigraphy and fracture density to predict fracture pattern.

The quantitative relationships between sedimentary and mechanical stratigraphy are derived by comparing characterizations of sedimentary stratigraphy and mechanical stratigraphy determined from outcrop observation (Figure 13). This comparison reveals that not all stratigraphic horizons effectively terminate fractures (Figure 13). If we assume that each stratigraphic horizon acts as a mechanical interface (i.e., each recognized horizon is abutted by many fractures), we would predict many more closely spaced mechanical interfaces (Figure 13). This would yield shorter and more densely spaced fractures than those observed and mapped (Figures 4, 5). Because this method greatly overpredicts the distribution of mechanical interfaces, sedimentary stratigraphy should not be directly used to determine fracture patterns. Instead, statistically developed empirical relations can guide prediction of mechanical stratigraphy from sedimentary stratigraphy.

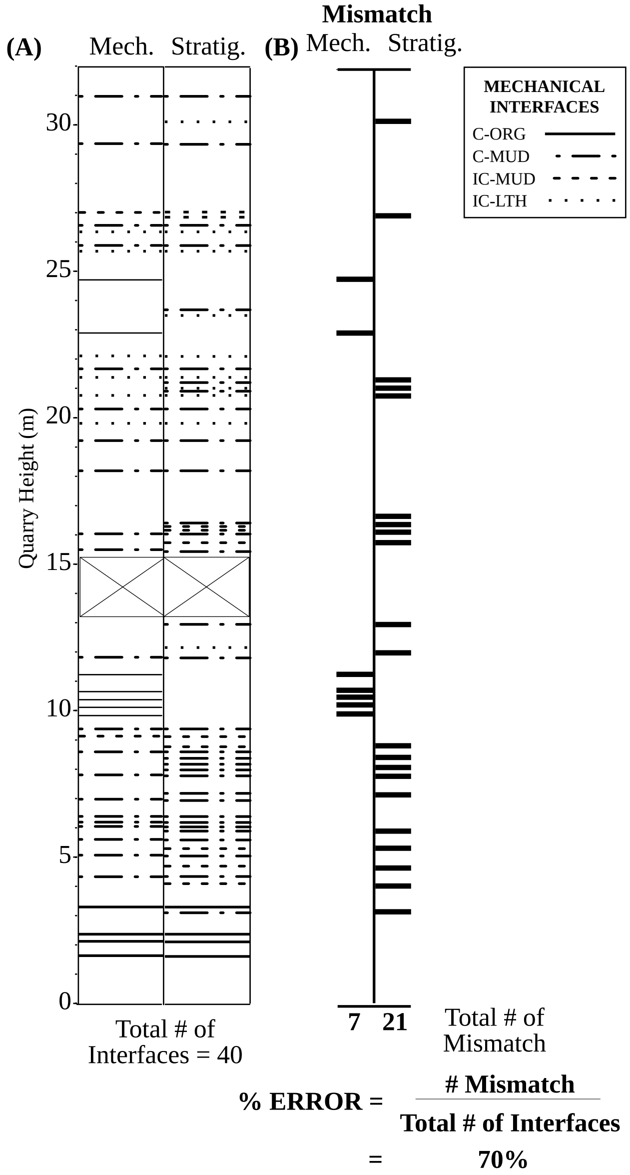


Figure 13. (A) Comparison of interpreted mechanical interface distribution (left) with all noted sedimentary stratigraphic horizons (right) within the quarry exposures. Mechanical interfaces are identified from both visual inspection and from our quantitative criterion. (B) Not all stratigraphic horizons act as mechanical interfaces. Some mechanical interfaces occur where no sedimentary stratigraphic horizons had been noted. Abbreviations for mechanical interfaces: C = cycle boundaries; IC = intracycle boundaries; ORG = organic horizons; MUD = mud horizons; LTH = lithologic contact.

We evaluate the probability that each type of stratigraphic horizon acts as a mechanical interface (Figure 14). In addition to investigating the types of stratigraphic horizons, we assess whether facies association influences the degree of fracture termination at the stratigraphic horizon. Within the inner shelf and inner-middle/middle shelf facies associations, shallowing-upward cycle boundaries, both mud and organic, commonly act as mechanical interfaces, whereas intracycle mud horizons are less effective (Figure 14). Be-

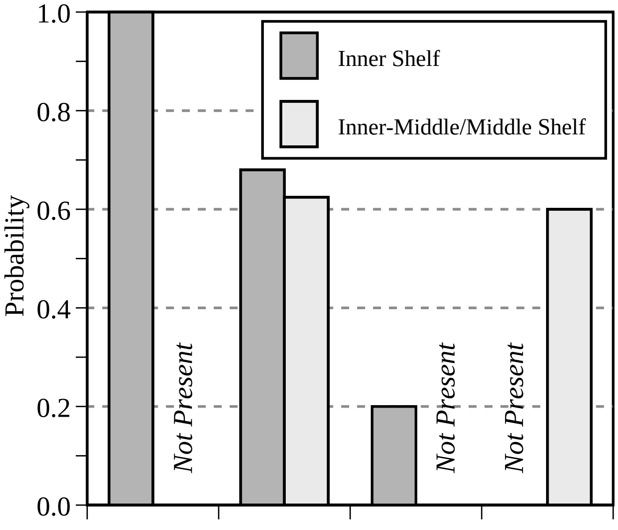


Figure 14. Probability of a stratigraphic horizon acting as a mechanical interface. Probability for each horizon is calculated as the number of stratigraphic horizons in the study outcrops that act as mechanical interfaces divided by the total number of that stratigraphic horizon type. Abbreviations for mechanical interfaces: C = cycle boundaries; IC = intracycle boundaries; ORG = organic horizons; MUD = mud horizons; LTH = lithologic contact.

cause the middle shelf facies association is not abundantly exposed within the quarry exposures used for our study, our statistical analyses group middle shelf and inner-middle shelf facies associations to create larger sample populations. Intracycle horizons between contrasting lithologies occur mostly within the inner-middle/middle shelf facies associations and arrest fractures as effectively as cycle-bounding muds in both facies associations (Figure 14).

We use the probabilities developed for each type of mechanical interface in each facies association to stochastically predict the distribution of mechanical interfaces from only descriptions of sedimentary stratigraphy. To illustrate our predictive method, a cycle-bounding mud horizon within the inner-middle/middle shelf facies associations has a 63% chance of acting as a mechanical interface that effectively terminates fractures. Among all of the observed stratigraphic horizons that are cycle-bounding mud layers, only 63% are randomly chosen to act as mechanical interfaces (Figure 14). This process is repeated for each type of mechanical interface.

Some intracycle interfaces do not correlate to specific stratigraphic features. Because there is no correlation with sedimentary stratigraphy, the location of these interfaces can not be predicted using the approach outlined in the preceding paragraph. For the purpose of testing our model predictions against interpreted mechanical interfaces, those interfaces that do not correlate to distinct stratigraphic horizons are not considered. Because these horizons are relatively infrequent (Figures 4, 5), the mislocation of these mechanical interfaces does not greatly influence the overall predicted fracture pattern.

Testing Mechanical Stratigraphy Predictions

We test our method for predicting mechanical interface distribution by comparing the predictions, based on sedimentary stratigraphy mapped in the field (Waldhuetter, 1994; Simo et al., 1998), to the mechanical stratigraphy inferred from the mapped fracture pattern of the same stratigraphic interval. By testing our predictive tool on the same stratigraphic section that was used to develop the empirical relationships, we can assess the error in predicted fracture pattern. This predictive model is stochastic because each realization, based on random assignment of mechanical interfaces, can produce different interface distributions.

To assess the error of our model predictions, we run a Monte Carlo simulation using 50 realizations (e.g., Harbaugh et al., 1977). This predictive method has a 0.32 probability of having the average error within the 50 model realizations (23 ± 4% in Figure 15). Although significant error (13–33%) occurs in predicting the exact location of mechanical interfaces, an example realization demonstrates important similarities between predicted and fracture-inferred mechanical stratigraphy (Figure 16). Correlation between interpreted and predicted mechanical interface distribution is best for the lower part of the quarry exposure where the dominant interface types are mud and organic, which have higher probabilities of acting as mechanical interfaces (Figures 14, 16). The degree of correlation decreases higher in the quarry exposure where intracycle interfaces, which have lower probabilities of acting as mechanical interfaces, are more prevalent (Figures 14, 16). Overall, the empirically predicted mechanical interface distribution equally overpredicts and underpredicts the location of mechanical interfaces (Figure 16). The error of our stochastic method for predicting mechanical stratigraphy from sedimentary stratigraphy is less than the error incurred if we assume that every stratigraphic horizon acts as a mechanical interface (25% < 70%) (see Figures 13, 16).

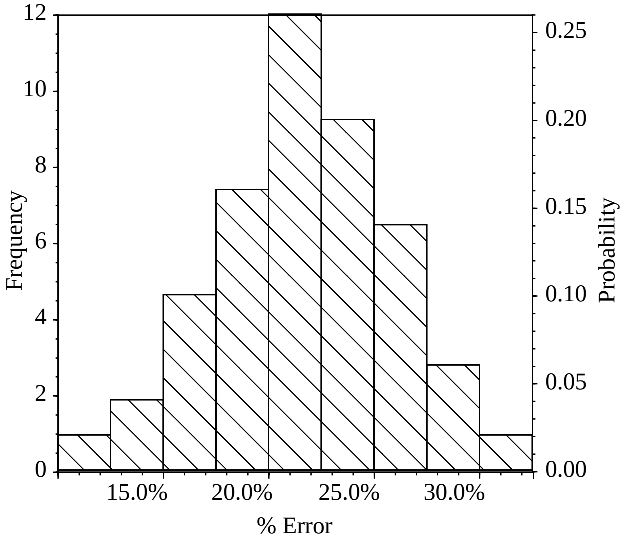


Figure 15. The average percent error for 50 realizations is 23 ± 4%. The probability of encountering a given error value is computed by dividing the error frequency (left vertical axis) by the total number of realizations used in the analysis (50). The probability of extreme minimum and maximum error of 13 and 33%, respectively, is only 0.02. We are 96% certain that the percent error in any model run will fall within the range of 13–33%; this certainty is based on integrating the area under the probability curve.

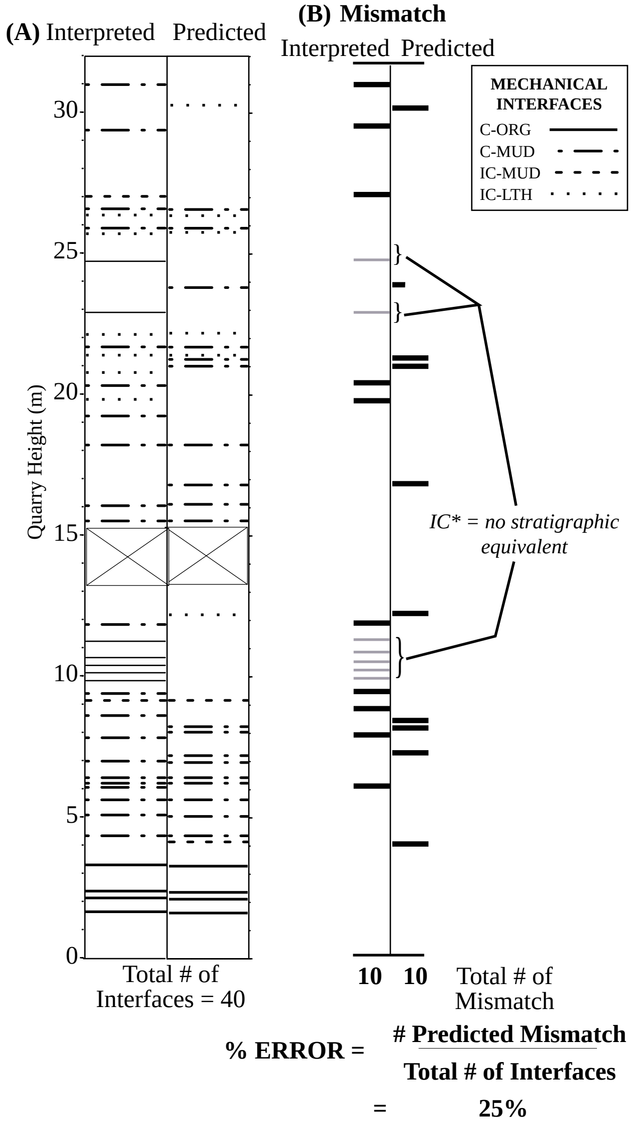


Figure 16. (A) One realization of predicted mechanical stratigraphy (right) vs. interpreted mechanical interface distribution (left) for the quarry exposures. (B) The percent error of 25% is evaluated from mismatches between predicted and interpreted mechanical interface distribution. Abbreviations for mechanical interfaces: C = cycle boundaries; IC = intracycle boundaries; ORG = organic horizons; MUD = mud horizons; LTH = lithologic contact. Interfaces with no stratigraphic correlation are not included in this analysis.

Testing Fracture Density Predictions

Once the distribution of mechanical interfaces is predicted, fracture density can be estimated from mechanical unit thickness, defined as the distance between mechanical interfaces. We use a best-fit linear-inverse function through the density-thickness data collected at the study site (bold curve in Figure 12; $D = 0.8 + 0.29/T$) to predict fracture density. This function is similar in form to the $DT = 1$ relationship described by Bai and Pollard (2000) and commonly observed in outcrop (e.g., Huang and Angelier, 1989).

A comparison between the predicted and interpreted fracture density is provided in Figure 17. Generally, the predicted fracture density exceeds observed density within beds thinner than about 0.3 m (12 in.) (Figure 17). This is a consequence of the overestimation of fracture density in thin beds by the best-fit linear-inverse function (Figure 12). Within the lower quarry section, clusters of high- and moderate-density beds were observed, whereas the stochastic realization predicts less clustering of high-density beds and some alternating high- and moderate-density beds. Within the upper section, both interpreted and predicted sequences have clusters of high-fracture-density beds. Furthermore, both sections have repeated sequences of decreasing fracture density upsection (~22 and ~26 m in Figure 17).

This predictive realization does not accurately reproduce the distribution of fracture density everywhere in the sequence; however, the correlation is better than a prediction of fracture density based solely on stratigraphic unit thickness that does not consider mechanical units. Because a mechanical unit may consist of one or more stratigraphic units, the thinner units predicted by stratigraphic inference of mechanical stratigraphy (e.g., Figure 13) would yield much greater fracture density throughout the sequence.

The method used in our study of identifying and using empirical relationships between fracture pattern and stratigraphy to predict fracture pattern captures some of the overall trends in observed fracture pattern. For example, variations in predicted fracture density within the upper section on Figure 17 closely match interpreted variations. Because our method reasonably predicts the mechanical stratigraphy and first-order fracture density for the mapped intervals, this predictive method provides valuable inferences regarding fracture pattern at depth using detailed stratigraphic descriptions of available core. This method may also provide a useful tool in predicting fracture pattern in similar stratigraphic environments and a wide range of tectonic environments.

IMPLICATIONS FOR FLUID FLOW

Because many carbonate reservoirs are fractured, prediction of flow characteristics requires an understand-

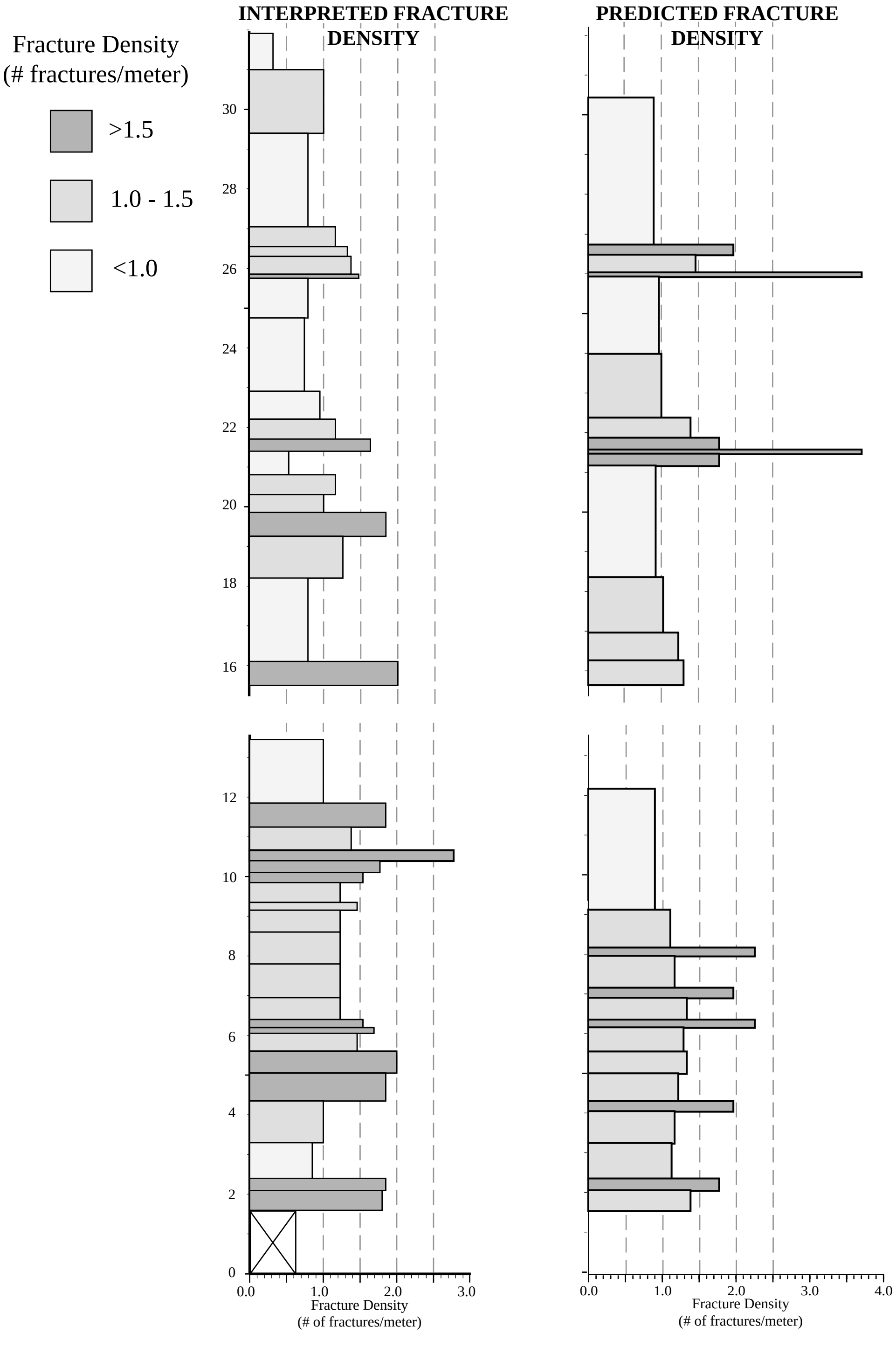


Figure 17. Interpreted and predicted fracture density for the quarry exposure. Mechanical interfaces in the predicted sequence represent the same realization shown in Figure 16. Fracture density predictions use empirical relationships with mechanical unit thickness (Figure 12). Gray shading indicates relative fracture density of units.

ing of the surface and subsurface fracture pattern. Developing a method for predicting vertical fracture patterns at depth is an important step toward characterizing flow processes. In our case study, the predictive model could allow us to compare expected fracture patterns with hydrogeologic data for the corresponding depth interval. Additionally, predicted fracture density could provide storage estimates for the aquifer or reservoir.

The positions of horizontal high-flow features in Door County generally correlate with changes in sedimentary stratigraphy, such as cycle boundaries or other lithologic changes (Sherrill, 1978; Bradbury and Muldoon, 1992; Gianniny et al., 1996; Muldoon et al., 2001). Variations in vertical fracture patterns may contribute to the development of these hydrogeologic features. For example, horizontal high-flow features may develop at mechanical interfaces where abundant vertical fractures terminate. The termination of many vertical fractures at a stratigraphic horizon could redirect vertical flow horizontally along the bedding interface (Figure 1). In addition, a decrease in fracture density below an interface reduces the number of vertical flow paths and can increase the tortuosity of vertical flow paths; both effects impede vertical flow and may promote horizontal flow. Within carbonate strata, such as the Silurian dolomite, increased groundwater flow enhances dissolution and enlarges flow features such as bedding planes. Continued dissolution may promote the development of regionally extensive high-permeability features that are observed throughout Door County (Muldoon et al., 2001).

Using mechanical stratigraphy to better understand fracture patterns is important not only in aquifer characterization but also in petroleum reservoir studies. Recent work on the Austin Chalk in Texas (Corbett et al., 1987; Rijken and Cooke, 2001) and the Lisburne carbonate group in Alaska (Hanks et al., 1997) has emphasized the importance of mechanical stratigraphy in understanding and predicting fracture patterns in petroleum reservoirs.

CONCLUSIONS

Our study introduces an innovative technique to quantitatively identify mechanical interfaces from fracture patterns. The identification of mechanical interfaces through such quantitative means can minimize the visual bias involved in conventional identification. Stratigraphic horizons that both have a majority of abutting fractures and exceed a cutoff number of abutting fractures are considered to act as mechanical interfaces. However, this method is sensitive to undulation of surfaces and underidentifies mechanical interfaces where stratigraphic horizons undulate excessively. Visual estimates of mechanical stratigraphy performed in the field compare well with the quantitatively determined mechanical stratigraphy, indicating that our estimations incurred little visual bias.

Through correlation of mapped vertical opening-mode fractures with sedimentary stratigraphy, we have identified several stratigraphic controls on fracture patterns within two exposed intervals of the Silurian dolomite in Door County, Wisconsin. First, mechanical interfaces correspond to many, but not all, distinct stratigraphic horizons (Figures 4, 5). Consequently, predictions of mechanical stratigraphy should not use each observed stratigraphic horizon. Second, the type of stratigraphic horizon is a greater factor in the termination of fractures than the facies association (Figure 14). Cycle-bounding organic partings and mud horizons are more effective at terminating fractures than intracycle mud horizons or horizons between contrasting lithologies.

The probability of a stratigraphic horizon acting as a mechanical interface can be used to stochastically predict mechanical stratigraphy from sedimentary stratigraphy. Because all stratigraphic horizons do not act as mechanical interfaces, interface locations are chosen stochastically, based on the empirically developed relationships for each interface type. A Monte Carlo analysis indicates that this predictive method yields much lower error than that incurred by using every distinct stratigraphic horizon as a mechanical interface (Figure 13 vs. Figure 16). Once the distribution of mechanical interfaces is developed, we can predict fracture density from mechanical unit thickness. The best linear-inverse fit between the fracture density and mechanical unit thickness of the outcrops studied produces fracture pattern similar to the interpreted distribution (Figure 17).

The methods presented in this article allow the prediction of opening-mode fracture patterns using only sedimentary stratigraphic data. This is of particular interest where dealing with unexposed parts of a stratigraphic sequence. This study provides the foundation for groundwater and hydrocarbon flow studies that use fracture data, such as fracture density and length, as input parameters into flow models. Flow models that incorporate vertical fracture data based on the stratigraphic controls on fracturing within an aquifer/reservoir are likely to better represent flow conditions.

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