Processes and facies relationships in a Lower(?) Devonian rocky shoreline depositional environment, East Lime Creek Conglomerate, south-western Colorado, USA

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Abstract
Rocky shorelines are relatively common features along modern coastlines, but few have been recognized in the geological record. The hard substrates of rocky shorelines telescope the width of offshore marine environments, thus the diagnostic deposits observed in such settings today have a low preservation potential due to small accommodation space and high-energy conditions. This study recognized previously overlooked, laterally extensive Lower(?) Devonian rocky shoreline deposits in the San Juan Mountains of south-western Colorado. The newly defined lithostratigraphic unit, the East Lime Creek Conglomerate (ELCC), is 0–23 m thick, unconformably overlying Proterozoic crystalline rocks and unconformably overlain by the Upper Devonian Ignacio Formation and/or Elbert Formation. The unit mostly consists of clast-supported cobble-boulder conglomerate with rounded quartzite clasts up to 1.4 m in length interbedded with thin sandstone layers and lenses. Sandstones in the ELCC are distinguished from unconformably overlying Upper Devonian sedimentary rocks because they have sericite cements. Most importantly, there are buttressing relationships between the ELCC and underlying Proterozoic crystalline rocks interpreted as palaeo-sea cliffs, palaeo-wave-cut platforms and palaeo-tombolos. A proposed rocky shoreline facies model includes headlands with upper shoreface-beachface tabular cobble-boulder gravels sourced from rock fall talus, nearshore subaqueous debris-flow deposits and intervening pocket beaches with imbricated, stratified pebble-cobble gravel sheets. Palaeocurrent data (n = 338) from clast long-axis orientations, imbrication and cross-bedding indicate south-to-north transport roughly onshore-offshore to a coastline consisting of alternating rocky headlands and pocket beaches. This Lower(?) Devonian unit documents a previously unrecognized episode in the geological history of south-western Colorado.

KEYWORDS
beachface conglomerates, Palaeozoic coastlines, rocky shorelines, shoreface
Coastal environments can be subdivided on the basis of important processes. The shoreface extends from fair-weather wavebase offshore to the seaward limit of the swash zone, whereas the beachface (foreshore) extends from the seaward limit of the swash zone to the beach, berms or other features transitional to the backbeach (Figure 1a). While this classification works well on sandy coastlines, it tends to break down on gravel shorelines which lack nearshore bedforms and have narrow or absent surf zones (Sherman, Orford, & Carter, 1993). In extreme cases, the beachface in rocky shorelines may be very narrow or even nonexistent (or else laterally restricted to pocket beaches), and the shoreface may be telescoped across a wave-cut platform directly into the rocky headlands, that is, the breaker zone might be directly at the foot of sea cliffs (Figure 1b). The deposits created along rocky shorelines tend to be relatively thin (shallow water deposits directly overlying bedrock wave-cut platforms), laterally discontinuous or restricted (i.e., having small accommodation space) by the telescoped shoreface and beachface zones, winnowed by high-energy conditions and/or partly to completely removed by wave erosion. Thus, although rocky shorelines constitute about 33% of modern coastlines (Johnson, 1988), the deposits of these relatively common modern environments have a very low preservation potential in the geological record (Johnson, 2006). Yet the importance of these deposits is clear, because rocky shoreline deposits indicate sea-level position, coastal geomorphology, sediment source-to-sink relationships and other parameters at a specific time in the geological history of the region.

Recognition of rocky shoreline depositional environments was pioneered by Johnson (1988). Diagnostic criteria include (1) a basal unconformity surface with evidence for subaerial weathering, (2) an overlying transgressive sequence including conglomerates that have a map distribution parallel to the strike of the unconformity, (3) clast lithologies in the overlying conglomerates strictly limited to the available lithologies in the underlying unit(s) which served as the sediment source areas (“parent body” of Johnson, 1988), (4) abutting relationships between the conglomerates and the underlying unit(s) which might be expressed as palaeotopographic features such as wave-cut platforms, tidal notches, sea stacks, sea caves, or sea arches, (5) joints, fissures and other openings in the underlying unit(s) that are infilled by finer-grained clasts from the overlying conglomerates, (6) textural trends in the conglomerates, such as clast-size fining size away from sediment source areas and (7) fossils that represent organisms specialized for life in high-energy environments (Johnson, 1988; Johnson, Ledesma-Vazquez, Mayall, & Minch, 1997). All of these features can be observed in the East Lime Creek Conglomerate (herein abbreviated as ELCC), except for an absence of fossil remains.

The high-energy deposits found in rocky shoreline environments can be confused with other depositional settings. Previous workers interpreted the ELCC as fault scarps and related depositional environments (Baars, 1965; Baars & See, 1968; Thomas, 2007) despite the fact these are not extensive talus deposits; there is an absence of syn-tectonic features such as liquefaction structures; there is an absence of fault-zone kinematic features such as fault gouge, slickensides, or mylonite; there is an absence of secondary faults or drag folds; and the deposits do not show direct facies relationships to the regional faults, which are either Proterozoic, late Palaeozoic (Ancestral Rocky Mountain uplift), or Cretaceous to Palaeocene (Laramide orogeny) in age. Other previous workers interpreted the ELCC as talus slope, colluvial fan and braided stream deposits (e.g., Wiggin, 1987). The talus slope-colluvial fan interpretation can be discounted because these deposits are not breccias, are not wedge-shaped in profile, do not show fan-like palaeocurrent dispersion, and do not include palaeosols.

The braided stream interpretation can be discounted because of the lack of channel-form bodies infilled with barforms showing bar-head to bar-tail successions, lack of fine-grained bar-top or bank materials, lack of proximal-distal grain-size trends, lack of sorting trends consistent with
 discharge variability, lack of inundites and lack of an overall fining-upward sequence (Miall, 2010). In addition, the contact relationships between the ELCC and underlying Proterozoic bedrock would suggest that, if these are fluvial deposits, they represent bedrock-confined river systems. Studies of modern bedrock-confined river systems have demonstrated the importance of fine-grained pool-fill sequences (Jansen & Brierley, 2004). The pools form at bedrock-forced bends during multi-decadal floods, and infill during intervening years. The pools have distinctive spatial relationships to bars and bedrock bench deposits. None of these distinctive bedrock pool-fill deposits have been observed in the ELCC.

The hypothesis of this study is that the facies relationships in this enigmatic geological unit will provide evidence for an Early(?) Devonian rocky shoreline depositional environment in the San Juan Mountains in south-western Colorado. This is a previously unrecognized geological episode in the history of the Southern Rocky Mountains, with implications for sea-level, tectonics and palaeoclimate. This study illuminates the importance of subtle features in conglomerates and the need for correlating the relatively thin and discontinuous deposits that preserve the record of these high-energy, rocky shoreline depositional settings.

1.1 | Geological background

This paper proposes a new lithostratigraphic unit in south-western Colorado (Figure 2). The ELCC unconformably overlies several Proterozoic igneous and metamorphic units, and is unconformably overlain by the Upper Devonian Ignacio Formation and/or the Upper Devonian Elbert Formation (Figure 3). Prior to defining the ELCC, there are several significant controversies in the geological literature that require explanation.

1.1.1 | Proterozoic units

The three major Proterozoic units are the Twilight Gneiss, the Uncompahgre Formation, and a series of granitic intrusions (e.g., Bakers Bridge Granite, Tennmile Granite and others). Collectively, the Proterozoic section exposed in the core of the San Juan Mountains is about 3 km thick.

The protolith of the Twilight Gneiss was bimodal dacitic-hypabyssal volcanic rocks and associated pelitic rocks that were deformed and metamorphosed to hornblende-plagioclase gneiss and amphibolite (Barker, 1969). The deformation and metamorphism has been interpreted as part of a regional collision event (Yavapai orogeny) between the Mojave and Yavapai terranes (Amato et al., 2008). Concurrent with terrane accretion, the Twilight Gneiss was intruded by a series of 1.72–1.68 Ga trondhjemite plutons (Baars, Ellingson, & Spoelhof, 1987; Barker, 1969; Hutchinson, 1976).

The protolith of the Uncompahgre Formation was quartz arenite with minor shale and conglomerate, having an aggregate thickness of about 2.5 km (Baars et al., 1987; Harris & Eriksson, 1990). The Uncompahgre Formation has been interpreted as a Proterozoic marine shelf clastic depositional system (Harris & Eriksson, 1990). The Uncompahgre Formation was folded multiple times, producing an initial generation of isoclinal folds subsequently refolded into a second generation of plunging folds (i.e., refolded folds), prior to being subjected to greenschist facies metamorphism to quartzite and argillite. When viewed in the field today, there is an almost 90° angular unconformity between the nearly vertically standing Uncompahgre Formation and the overlying Palaeozoic sedimentary rocks. The deformation and metamorphism of the Uncompahgre Formation has been linked to the collision of the Yavapai and Mazatzal terranes (Mazatzal orogeny) about 1.65 Ga (Amato et al., 2008; Shaw & Karlstrom, 1999). Subsequently, the Uncompahgre Formation was intruded by plutons associated with the Silver Plume batholith at 1.47–1.39 Ga (Bickford, Wetherill, Barker, & Lee-Hu, 1969; Hutchinson, 1976).

The contact between the Twilight Gneiss and Uncompahgre Formation is controversial. Interpretations are either a depositional contact between the Twilight Gneiss and overlying Uncompahgre Formation (Barker, 1969; Gibson & Harris, 1992; Harris, Gibson, Simpson, & Eriksson, 1987), or a high-angle fault contact (Baars et al., 1987), or different thrust fault models (Harris et al., 1987; Tewksbury, 1985). This paper will present new information about the basal contact of the ELCC.

1.1.2 | Devonian sedimentary units

One stratigraphic controversy involves recognition of the ELCC as a separate unit from the Ignacio Formation (this term is used instead of “Ignacio Quartzite” in accord with Howard, 2005 restrictions on the use of quartzite as a sedimentary rock term). The discontinuous outcrops of pebble-boulder quartzite conglomerate found above Proterozoic crystalline rocks were poorly documented until fairly recently, and were presumably considered part of the Ignacio Formation (Figure 3). Spoolhof (1976) mapped these deposits as “pre-Elbert conglomerate” and assigned an age of “Devonian-Cambrian.” Wiggin (1987) argued that conglomerates south of Coal Bank Pass and north of Molas Pass are Cambrian, while conglomerates between Coal Bank Pass and Molas Pass are Devonian. Campbell and Gonzales (1996) mapped the conglomerates in the southern part of the San Juan Mountains, and believed that these were either part of the Ignacio Formation or an older separate unit. They proposed that the conglomerates are overlain by the Ignacio Formation in the western San Juan.
Mountains, but are overlain by the Elbert Formation in the southern San Juan Mountains. Gonzales et al. (2004) stated that the conglomerates could be Neoproterozoic to Cambrian in age. All of these previous studies assigned an age to the conglomerates based upon the belief that the Ignacio Formation is Cambrian in age. Finally, Campbell and Gonzales (1996) assigned the conglomerate to the "Weasel Skin Member" of the Ignacio Formation (Figure 3), but the name has no stratigraphic validity because they did not define a type section (McBride, 2016). In contrast to previous workers, we find all exposures of these conglomerates represent a single stratigraphic unit, the ELCC, underlying the Upper Devonian Ignacio Formation and/or Upper Devonian Elbert Formation at different locations.

A second long-standing controversy is about the age of the Ignacio Formation, and was recently reviewed by McBride (2016). Previously, the unit was assigned a Cambrian age based on poorly preserved and sparse specimens of *Obolus sp.* (Cross, Howe, & Ransome, 1905; Cross, Howe, Irving, & Emmons, 1905; Rhodes & Fisher, 1957; Wiggan, 1987). The poor preservation of the fossils led to equivocal taxonomic determinations and age assignments. Other brachiopod fossils were similarly non-determinant (Baars, 1965). An additional argument for Cambrian age was lithocorrelation to other basal Palaeozoic sandstones in the western USA (Baars, 1965; McBride, 2016; Ross & Tweto, 1980; Tweto & Lovering, 1977; Wiggan, 1987). However, a major problem with the Cambrian age assignment is the absence of an unconformity between the Ignacio Formation and overlying Devonian Elbert Formation, which contains placoderm fish fossils of late Frasnian to Famennian age (Cross & Larsen, 1935; Eastman, 1904; Thomson & Thomas, 2001). Barnes (1954) argued that because the Ignacio Formation grades upward into the Elbert Formation, the unit must also be Devonian in age. In contrast, Wiggan (1987) argued that certain small-scale karst features (infilled fractures and pores in peritidal carbonates) between the units represent disconformities, although these can be explained as typical syndepositional features in carbonate beachrock. Wiggan (1987) also believed there was an angular discordance at one location, but upon inspection that is actually the contact between the ELCC-Ignacio Formation, not the contact between the Ignacio Formation-Elbert Formation. More recently, Maurer and Evans (2011, 2013) have argued the Ignacio and Elbert Formations formed a single depositional system of Devonian age. McBride (2016) concurred, finding that single beds in the Ignacio Formation contain both
Obolus sp.(?) brachiopods and Devonian placoderm fish fossils, and recovering Ordovician (460 Ma) detrital zircon grains from the Ignacio Formation.

The third controversy is whether or not the McCracken Sandstone Member of the Elbert Formation is exposed in the San Juan Mountains (Figure 3). The type section of the McCracken Sandstone Member is an exploration well in the Paradox basin (Baars & Knight, 1957; Cooper, 1955; Knight & Cooper, 1955). Baars (1965) argued that the unit did not extend far enough eastward to provide surface outcrops in the San Juan Mountains. This has not prevented several researchers from identifying the unit in the field, using the criteria it is generally whiter in colour, harder (due to silica cement), more quartzose-rich, better sorted and better rounded than the sandstones in the Ignacio Formation (McBride, 2016). Regrettably, none of these distinctions are statistically robust (this paper). McBride (2016) remapped the Ignacio Formation and McCracken Sandstone Member of the Elbert Formation, essentially arguing they were deposited adjacent to one another, while agreeing with Maurer and Evans (2011, 2013) that the units formed a single, integrated depositional system.

Stratigraphic nomenclature should differentiate units based upon lithology and age. In the San Juan Mountains, two fundamental lithologic differences should define the Lower Palaeozoic stratigraphy. First, sandstones in the ELCC have sericite cements (Figure 4), which are lacking in all of the other units (Evans, 2007). The sericite cements uniquely identify sandstones in the ELCC and represent significant differences in age and diagenesis from the overlying Devonian sandstones. Second, the upper member of the Elbert Formation consists of repetitive beds of calcareous shale and carbonate, which are distinctive from the predominantly sandstone successions below it. Accordingly, this report reassigns to the Ignacio Formation the strata in the San Juan Mountains previously classified as the McCracken Sandstone Member of the Elbert Formation by several workers (Baars & See, 1968; Campbell &
Gonzales, 1996; Knight & Cooper, 1955; McBride, 2016), because of: (1) absence of an unconformity between the units, (2) absence of statistically significant compositional differences between the units, (3) evidence from facies analysis and palaeocurrent analysis that the units formed a single depositional system and (4) geochronologic evidence the units are both Late Devonian in age.

2 | METHODS

Thirteen stratigraphic sections were measured in the field and locations recorded using GPS. Conglomerate grain-size analyses were conducted in the field by following random transects on bedding surfaces and measuring the intermediate axis lengths of at least 100 adjacent clasts. Grain-size statistics followed the methods of Folk and Ward (1957). Conglomerate composition was determined by identifying clast lithologies along bedding plane transects \((n = 837)\). Thin sections for sandstone petrography were prepared using standard methods from 112 samples, and composition was determined from point counting >300 grains per slide \((total \ n = 30,847)\) following the methods of Dickinson and Suczek (1979). Palaeocurrent interpretations were based upon 103 unidirectional measurements of cross-bedding and clast imbrication and from 235 bidirectional measurements of long-axis orientations of conglomerate clasts exposed on bedding surfaces. Vector means were calculated and plotted for each location, and composite rose diagrams for unidirectional and bidirectional data sets were created using a non-linear scale (Nemec, 1988), showing vector mean, circular standard deviation (Kraus & Geijer, 1987), and Rayleigh test of significance (Curay, 1956). The data sets are statistically significant \((p < .05)\).

Approximately, 2 kg of ELCC was collected from outcrop and prepared for U–Pb analysis using standard crushing and separation techniques, including heavy liquid and magnetic separation at the US Geological Survey in Denver, CO. Zircon grains were poured and mounted in epoxy and polished. Cathodoluminescence imaging of individual zircon grains was used to characterize zoning and presence of inclusions, and was performed on a JEOL 5800 scanning electron microscope at the USGS Microbeam Laboratory in Denver, CO. Analyses of zircon grains were conducted using a Nu Instruments AttoM™ LA-SC-ICPMS at the USGS Southwest Isotope Research Laboratory in Denver, CO. Zircon was ablated with a Photon Machines Excite™ 193 nm ArF excimer laser in spot mode (150 total bursts per grain) with a repetition rate of 5 Hz, laser energy of \(-3\) mJ, and an energy density of 4.11 J/cm². Pit depths are typically less than 20 µm. The rate of He carrier gas flow from the HelEx cell of the laser was \(-0.6\) L/min.

![Photomicrographs](image_url) FIGURE 4 Photomicrographs a–d are of sandstones in the ELCC. (a and b) Sandstones showing sericite \((S)\) cements \((scale\ bar\ 0.5\ mm)\). (c) Sandstone with quartzite \((foliated\ polycrystalline\ quartz)\ clast \((scale\ bar\ 1.0\ mm)\). (d) Sandstone with fresh perthite \((P)\) and degraded perthite \((dP)\) clasts \((scale\ bar\ 1.0\ mm)\). (e) Ignacio Formation sandstone \((scale\ bar\ 0.25\ mm)\) and (f) putative McCracken Sandstone Member with quartz overgrowths \((OG)\) \((scale\ bar\ 0.25\ mm)\).
The massive or crudely stratified cobble-boulder conglomerates contain appreciable amounts of infiltrated...
FIGURE 5  (a) Massive (Gm) and normally graded (Gmn) conglomerate with megaclasts in the ELCC (scale bar 1 m). (b) Three vertically stacked, inversely graded cobble-boulder conglomerates (Gmv) interpreted as subaqueous debrites. (c) Quartzite clast with weathering rind, or interpreted corestone origin (hammer 28 cm). (d) Quartzite clast demonstrating in situ shattering and infilled matrix (scale bar 15 cm). (e) Vertical view of multiple episodes of infiltrated matrix infill into pocket structures created between largest framework clasts (hammer 28 cm). (f) Bedding plane view of infilled pocket structure between megaclasts, showing very tightly packed infill including line contacts (arrow). This is interpreted as the results of strong wave reworking of the matrix between the larger framework clasts (scale bar 15 cm). (g) Stratified conglomerate (Gl) with imbrication (arrow). (h) Cross-bedded conglomerate (Gx) above scale bar (15 cm). (i) Massive, pebbly sandstone (Sm) between normally graded conglomerate beds (scale bar 15 cm). (j) Several examples of trough cross-bedded sandstones (St), each one co-set thick (scale bar 15 cm). (k) Laminated sandstone (Sl) between stratified gravel sheets. (l) Hummocky stratified sandstone (Sh) showing basal erosion into underlying stratified conglomerate (scale bar 15 cm). See text for Section 3.
of the framework clasts have a median grain size of \(-6.7\ \varphi\), a mean grain size of \(-6.7\ \varphi\), a SD of \(-1.2\ \varphi\) (poorly sorted), and a skewness of 0.0 (symmetrical).

### Table 1: Conglomerate clast counts

| Lithology                  | Per cent composition | Sub-total |
|----------------------------|----------------------|-----------|
| Purple quartzite           | 19                   |           |
| Red quartzite              | 42                   |           |
| Gray quartzite             | 28                   |           |
| TOTAL quartzite            | 89%                  |           |
| Vein quartz                | 10 \(\%\)           | 10%       |
| Metaconglomerate           | <1                   |           |
| Banded iron formation      | <1                   |           |
| Schist/gneiss              | <1                   |           |
| Granite                    | <1                   |           |

Based upon random transects on bedding surfaces \(n = 837\).

matrix and also pocket structures (local concentrations of matrix), which are typically pebble-granule conglomerate or pebbly coarse-grained sandstone. These features appear to originate at a bedding surface and extend downward into the deposit, infilling distinctive regions between framework clasts (Figure 5e). The distinctive feature of pocket structures are non-spherical clasts oriented parallel to the confining framework clasts, being vertically oriented in the “neck” part of the pocket structure, and nearly horizontally bedded in the pocket itself. These are similar to features observed in modern coastlines where constant wave swash reworks the matrix to fill and tightly conform to available spaces between the framework grains (Figure 5f). Pocket structures differ from the high-angle scours described from shoreface conglomerates elsewhere which refer to conglomerate infills of erosional features in sandstones (Bourgeois & Leithold, 1984; Hart & Plint, 1995).

Sandstone

The sandstones in the ELCC are sericite-cemented quartz arenites (Figure 4a,b) with the exception of a single location, where they are sericite-cemented feldspathic arenites (at this location, the ELCC directly overlies granite that has a weathered carapace of disaggregated granite or grus). Sericite refers to highly birefringent, fine-grained micas observed petrographically (Eberl, Srodon, Lee, Nadeau, & Northrup, 1987). Previous studies on sericite in the San Juan Mountains demonstrated that the protolith was mixed-layer illite/smectite which was altered to fine-grained muscovite or phengite during multiple hydrothermal events associated with Cenozoic ore mineralization (Eberl et al., 1987). The presence of sericite in the sandstones of the ELCC was first reported by Evans (2007). The contrast between sericite-cemented sandstones in the ELCC and the absence of sericite in the overlying Upper Devonian units is indicative of an interval of subaerial exposure and weathering of the ELCC prior to deposition of the overlying units.

Sandstone compositions and modal quartz-feldspar-lithics values overlap with sandstones in the Ignacio Formation and putative McCracken Sandstone Member within one standard deviation (Table 2), with the exception of cement types and abundance. Sandstones in the ELCC have about 10% more polycrystalline quartz \(Q_p\) and about 0.5% more quartzite metamorphic lithics \(L_m\) compared to the other Palaeozoic units (Table 2). Because the sandstones of the ELCC, Ignacio Formation, and putative McCracken Sandstone Member in the San Juan Mountains have modal compositions which overlap within one SD, any distinctions based upon petrofacies (McBride, 2016) are not statistically significant.

Sandstones in the ELCC are typically found in broadly lenticular beds up to 50 cm thick. The most common sandstones are massive, pebbly, very coarse-grained quartz arenite (Figure 5i). In addition to distinctive sandstone beds, sandstone and pebbly sandstone infill of pockets or lenses in the underlying conglomerate suggest that there is a fairly appreciable amount of sand infiltration into what must have been open-matrix gravel. Such situations are common in wave-washed gravels after the stabilization of the larger clasts creates an open-gravel framework for sand to settle out of suspension, infilling the pore spaces (Figure 5e,f). Less commonly, sandstones demonstrate cross-bedding, lamination and hummocky stratification. Cross-bedding includes trough, festoon and planar-tabular types. Cross-bed sets are typically <20-cm in set height, representing small dunes associated with gravel bars in the breaker zone or upper shoreface (Figure 5j). Ripples are absent, presumably due to the coarse-grained nature of the deposits. Thinly bedded laminated sandstones are minor constituents in conglomerate sequences (Figure 5k). Hummocky stratified sandstones are interbedded with thin...
gravel sheets (Figure 5l). Bioturbation is absent even in the finer-grained sandstones, presumably due to either high-energy conditions precluding organisms or poor preservation potential for biogenic structures. Fossils are also absent. This is similar to the Cambrian rocky coastlines of the Baraboo, Wisconsin, district where characteristic marine fossils only become common constituents in sandstones several kilometres seaward of the high-energy shorelines (Dott & Byers, 2016).

**Stratigraphy**

The type section for the newly proposed ELCC is on the steep hillside of an unnamed valley along the east side of Lime Creek (shown as location 6A in Figure 2 and the UTM coordinates are given in Table 3). A detailed stratigraphic section is given in Figure 7. In addition, a reference section is located about 100 m distant from location 6A (location 6B in Figure 8 and Table 3). The reference section is on the valley floor and easier to access, but the basal contact is not as well exposed. As shown in Figures 7 and 8, the ELCC ranges up to 23 m thick.

The basal contact is an unconformity, either nonconformities above the Twilight Gneiss and granites or an angular unconformity above the Uncompahgre Formation. Proterozoic units below the unconformity show evidence of subaerial erosion, based upon (1) field observations of granites that have an upper weathered carapace of grus about 50 cm thick, (2) quartzite clasts that show weathering rinds (corestone formation) around individual clasts (Figure 5c) and (3) observations of fractures in the underlying Proterozoic rocks that show weathering, reddening and infiltration of clasts from the overlying ELCC.

The spatial distribution of the Proterozoic units below the unconformity is explained by recent observations. Tewksbury (1985) argued that the Uncompahgre Formation was thrust southward above the Twilight Gneiss, while Harris et al. (1987) proposed that the Uncompahgre Formation, after being deposited above the Twilight Gneiss, was “decoupled” from basement and then thrust northward. In contrast to these previous interpretations, our field evidence shows that the Twilight Gneiss was thrust northward over the Uncompahgre Formation (Figure 9a). Along Three Lakes Creek (about 3 km due east of Coal Bank Pass), small klippens (erosional outliers of a thrust sheet) of Twilight Gneiss are observed sitting directly on the Uncompahgre Formation (Figure 9b,c). In addition, sheath folds in the gneiss formed where the allochthonous Twilight Gneiss ramped over resistant vertically bedded quartzite.

**TABLE 2 Sandstone petrography**

| Category               | East lime creek conglomerate | Ignacio formation | McCracken sandstone member |
|------------------------|------------------------------|------------------|----------------------------|
| Monocrystalline quartz | 48.0 ± 12.4                  | 39.6 ± 17.4      | 51.7 ± 10.1                |
| Polycrystalline quartz | 23.3 ± 12.9                  | 12.8 ± 8.4       | 10.8 ± 7.6                 |
| Chert                  | 0.1 ± 0.3                    | 0.1 ± 0.3        | 0.2 ± 0.6                  |
| Plagioclase feldspar    | 0.0 ± 0.0                    | 0.0 ± 0.0        | 0.0 ± 0.0                  |
| Potassium feldspar      | 2.1 ± 5.8                    | 1.7 ± 3.5        | 5.3 ± 8.1                  |
| Volcanic lithics        | 0.0 ± 0.0                    | 0.0 ± 0.0        | 0.0 ± 0.0                  |
| Metamorphic lithics     | 0.5 ± 0.7                    | 0.1 ± 0.3        | 0.1 ± 0.1                  |
| Sedimentary lithics     | 0.0 ± 0.2                    | 0.1 ± 0.1        | 0.1 ± 0.2                  |
| Micas                  | 0.3 ± 0.4                    | 0.3 ± 0.5        | 0.1 ± 0.2                  |
| Accessory minerals     | 0.7 ± 1.6                    | 0.6 ± 1.4        | 0.3 ± 0.4                  |
| Matrix                 | 7.1 ± 4.4                    | 5.1 ± 5.7        | 6.0 ± 6.5                  |
| Carbonate cements       | 0.2 ± 0.9                    | 23.0 ± 12.0      | 6.2 ± 14.8                 |
| Quartz overgrowths      | 2.6 ± 2.8                    | 6.0 ± 6.6        | 13.8 ± 12.1                |
| Sericite cement         | 10.2 ± 4.7                   | 0.0 ± 0.0        | 0.0 ± 0.0                  |
| Clay argillans          | 0.0 ± 0.0                    | 4.0 ± 5.0        | 1.8 ± 2.6                  |
| Fe-oxide cement         | 1.8 ± 2.6                    | 4.5 ± 5.4        | 2.3 ± 4.8                  |
| Porosity                | 3.0 ± 3.7                    | 2.7 ± 2.7        | 1.7 ± 3.3                  |
| Summary QFL            | 96.4–2.8–0.8                  | 96.5–3.1–0.4     | 91.9–7.8–0.4               |
| Summary QmFLt          | 64.9–2.8–32.3                | 72.8–3.1–24.1    | 75.8–7.8–16.5              |
| Number of samples      | 44                           | 40               | 28                         |
| Number of grains counted| 12,078                       | 10,966           | 7,803                      |
(Figure 9d). Finally, the position of the thrust fault itself can be marked by deformation of both the top of the lower plate (the upper carapace of the quartzite is shattered and the matrix infilled by vein quartz, Figure 9e) and by retrograde metamorphism of the bottom of the upper plate (the lower carapace of the Twilight Gneiss is more schistose, Figure 9c). Field mapping suggests that the exposure of the Uncompahgre Formation between Coal Bank Pass (location 3 in Figure 2) and Molas Creek (location 8 in Figure 2) is a fenster, exposing the lower plate (Uncompahgre Formation) through a window in the upper plate (Twilight Gneiss). Subsequent erosion produced a palaeotopography with up to 65-m relief, and the ELCC was deposited above this palaeotopographic surface.

Palaeo-relief on the basal contact can be observed at numerous locations (Figures 7, 8, and 10). At location 2, there is about 1.5 m relief on the Proterozoic surface, and sheets of conglomerate that surround, onlap and overtop the palaeotopography are suggestive of a palaeo-tombolo (Figure 10a). At location 5, about 7.5 m of relief on the Proterozoic surface shows a buttressing relationship. This is interpreted as a palaeo-sea cliff and adjacent palaeo-wave-cut platform based upon field relationships (Figure 10b). Smaller-scale buttressing relationships are also observed at locations 3, 6A, 7, 8A, and 9B (Figure 8). Similar palaeotopographic features have been described from rocky shoreline environments by other researchers (Dott, 1974; Dott & Byers, 2016; Felton, 2002; Johnson et al., 1997; Mikulic, Kluessendorf, Thomka, & Norby, 2012).

| Map no. | Location description               | UTM grid | Easting | Northing |
|---------|-----------------------------------|----------|---------|----------|
| 1       | Falls Creek                       | 13S      | 0274172 | 4153901  |
| 2       | Shalona Lake railroad outcrop     | 13S      | 0251992 | 4152178  |
| 3       | Coal Bank Pass (south side)       | 13S      | 0255091 | 4175796  |
| 4       | Meadow below Coal Bank Pass       | 13S      | 0256637 | 4176029  |
| 5       | West side Lime Creek              | 13S      | 0256722 | 4176937  |
| 6A      | East side Lime Creek (type section)| 13S      | 0258905 | 4176971  |
| 6B      | East side Lime Creek              | 13S      | 0258924 | 4176880  |
| 7       | Andrews lake trail                | 13S      | 0260761 | 4177433  |
| 8A      | Molas Creek canyon                | 13S      | 0264337 | 4180102  |
| 8B      | Molas Creek waterfall             | 13S      | 0263488 | 4180141  |
| 9A      | Sultan-Molas fault valley         | 13S      | 0264360 | 4182238  |
| 9B      | South side Sultan Creek           | 13S      | 0264376 | 4182517  |
| 9C      | North side Sultan Creek           | 13S      | 0264567 | 4183172  |

The upper contact of the ELCC is an unconformity with either the Devonian Ignacio Formation or the upper member of the Devonian Elbert Formation. The unconformity has typically $<10^0$ discordance and can be difficult to observe at some locations due to obscure bedding attitudes in the uppermost conglomerate beds (Figure 10a). At the proposed type section, the unconformity shows an average discordance of about $4^0$. Both the Ignacio Formation and Elbert Formation show evidence for erosional reworking of part of the ELCC, including incorporated quartzite clasts and rare sedimentary lithics (sandstone clasts derived from the ELCC).

FIGURE 7 Stratigraphic section of the type section of the ELCC on a hillside above a small valley near the junction with Lime Creek (location 6A in Figure 2). The scale bar is 10 m. This location is about 100 m from the reference section (location 6B in Figure 2 and in Figure 8), which is more easily accessible but does not show the basal contact as well. The coordinates are given in Table 3. Lithofacies codes given in Table 4.
Across the study area, the thickness and organization of the ELCC is highly variable. In Figure 8, sections are correlated using the basal contact of the upper member of the Elbert Formation. The coordinates are given in Table 3. The ELCC unconformably overlies Proterozoic basement with palaeotopography producing buttressing relationships interpreted as palaeo-sea cliffs and palaeo-tombolos. The ELCC is unconformably overlain by either the Ignacio Formation or upper member of the Elbert Formation.

**FIGURE 8** Stratigraphic relationships in the ELCC (location numbers correspond to Figure 2) leveled on the basal contact of the upper member of the Elbert Formation. The coordinates are given in Table 3. The ELCC unconformably overlies Proterozoic basement with palaeotopography producing buttressing relationships interpreted as palaeo-sea cliffs and palaeo-tombolos. The ELCC is unconformably overlain by either the Ignacio Formation or upper member of the Elbert Formation.

Across the study area, the thickness and organization of the ELCC is highly variable. In Figure 8, sections are correlated using the basal contact of the upper member of the Elbert Formation, which is interpreted as a Devonian flooding surface of presumably low-relief. In Figure 8, the Proterozoic surface shows 0–40 m of palaeo-relief below the upper member basal contact. Figure 8 is intended to show localities of the ELCC, but omits other localities where the ELCC is absent and the Ignacio Formation or upper member of the Elbert Formation directly overlies the Proterozoic crystalline rocks. Combining these data sets, there is 0–65 m of palaeo-relief on the Proterozoic surface (Evans, 2007).

Within that palaeo-landscape, the ELCC is 0–23 m thick, and the Ignacio Formation (including the reassigned McCracken Sandstone Member) is 0–40 m thick. Several trends are notable: (1) adjacent to palaeotopographic features such as palaeo-sea cliffs, the ELCC is typically thicker and coarser-grained and (2) where overlying a...
surface of low palaeo-relief (interpreted as a palaeo-wave-cut platform), the ELCC is thinner, finer-grained (pebble-cobble conglomerate) and better stratified. These trends are interpreted as lateral variations within the ELCC depositional environment between rocky headlands and intervening pocket beaches. In contrast, the thicker parts of the Ignacio Formation do not show consistent relationships to grain-size trends or to exposures of the Proterozoic bedrock. These thicker intervals of Ignacio Formation are interpreted as Devonian valley-fill sequences composed of fluvial, estuarine and marginal marine deposits (Maurer, 2012; Maurer & Evans, 2011, 2013). The differences in textural and stratigraphic trends in the ELCC versus the overlying Devonian Ignacio Formation highlight the lack of relationship between these two units.

**Age**

The precise age of the ELCC is not known due to an absence of datable materials such as tuffs or fossils. However, there are multiple lines of evidence to constrain the age. First, there is an angular unconformity separating Proterozoic crystalline rocks from the overlying ELCC. Second, there is a low-angle unconformity separating the ELCC from the overlying Upper Devonian (Frasnian–Famennian) Ignacio Formation. In addition, sandstones in the ELCC have sericite cements indicating weathering and diagenesis which is not present in the overlying units, and the ELCC and the Ignacio Formation are not similar in terms of thickness trends or facies distributions, suggesting these were separate depositional systems.

The U–Pb geochronology of detrital zircon grains from a sandstone in the ELCC show a prominent peak at 1,731 Ma and secondary peaks at 2,450, 2,600, 2,630 and 3,070 Ma (Figure 11). Significantly, there are Silurian (435 Ma) detrital zircons in the ELCC. The overlying Upper Devonian Ignacio Formation contains Ordovician detrital zircons (McBride, 2016). The detrital zircon record of the two units and biostratigraphy of the Ignacio
2.2 Facies analysis

Five conglomerate lithofacies and five sandstone lithofacies were observed in the ELCC (Table 4). The primary depositional units are conglomerate bodies with an erosional base and abrupt upper contact, and either tabular or sheet geometries. The sandstones were either thin beds between conglomerate successions or infilled lens-shaped bodies within conglomerates.

### 2.2.1 Lithofacies Gm

Most of the ELCC consists of tabular bodies of massive or crudely stratified boulder-cobble conglomerate (lithofacies Gm) interbedded with normally graded cobble-pebble conglomerate (lithofacies Gmn). Lithofacies Gm is typically 1–2 m thick but forms amalgamated or multistory conglomerate bodies up to 6–7 m thick. Megaclasst up to 1.4 m in length by 0.5 m in width and 0.5 m in depth can be found, and the internal conglomerate fabric shows draping or infilling around the megaclasst (Figure 5a). The base of each tabular conglomerate body can be obscured by large clasts protruding from one bed into the overlying bed, but where it can be observed there is typically 20–30 cm of erosional relief on the base of the bed. Seaward-dipping imbrication (see palaeocurrent section) is fairly common. The rare presence of classt shattered in situ suggests rock fall impacting on classt deposited at the base of a palaeo-sea cliff.

Lithofacies Gm is interpreted as tabular gravel bodies from the upper shoreface to beachface in a high-energy setting (Nemec & Steel, 1984; Watkins, 1992). These deposits probably sourced from sea cliff talus that was subsequently reworked by waves and/or resedimented as sediment gravity flows (Watkins, 1992). Observed features in the ELCC high-energy settings including a high degree of clast rounding (Hartley & Jolley, 1999), texturally uniform, laterally persistent tabular gravel bodies (Clifton, 1973) that have seaward-dipping imbrication (Maejima, 1982), and crude stratification due to changes in clast size or shape (Bluck, 1967a; Dobkins &

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**TABLE 4** Lithofacies descriptions

| Code | Lithology | Sedimentary structures | Interpretation |
|------|-----------|------------------------|----------------|
| Gm   | Conglomerate, boulder-cobble | Massive, includes in situ shattered clasts (rock fall debris) | Shoreface tabular gravel +/- sea cliff talus |
| Gmn  | Conglomerate, cobble-pebble | Massive with normal grading | Subaqueous debrite or wave-reworked |
| Gmv  | Conglomerate, cobble-pebble | Massive with inverse grading | Subaqueous debrite |
| Gx   | Conglomerate, pebble-cobble | Cross-bedded | Breaker zone (bar) or rip-current channel |
| Gl   | Conglomerate, pebble-cobble | Stratified, imbricated | Swash zone (gravel beach) deposit |
| Sm   | Sandstone, very coarse- to coarse-grained, pebbly | Massive (destratified?) | Multiple origins: beachface, subaqueous debrite, pocket structures |
| St   | Sandstone, coarse- to medium-grained | Trough cross-bedded | Breaker zone (bar) or rip-current channel |
| Sp   | Sandstone, coarse- to medium-grained | Planar-tabular cross-bedded | Breaker zone (bar) or rip-current channel |
| Sh   | Sandstone, medium-grained | Hummocky stratified, amalgamated | Storm deposit in upper shoreface |
| Sl   | Sandstone, medium-grained | Laminated | Swash zone deposit |
Although typically well sorted, these upper shoreface-beachface gravels can be bimodal due to infiltrated sand matrix (Nemec & Steel, 1984), as observed in grain-size transects on exposed bedding surfaces in the ELCC (Figure 6). The tabular gravel bodies within the ELCC include pocket structures of sandstone and pebbly sandstone up to 40 cm wide by 20 cm deep (discussed below). These are similar to deposits in upper shoreface gravels described elsewhere (Nemec & Steel, 1984).

### 2.2.2 Lithofacies Gmn

Where present, the normally graded cobble-pebble conglomerate (lithofacies Gmn) typically forms the upper part of multistory successions of lithofacies Gm (Figure 5a). In contrast to the metre-scale thickness of beds of lithofacies Gm, the normally graded portions of the tabular gravel sheets average 20–30 cm thick. The grading is coarse-tail normal grading where the size of incorporated matrix does not show fining trends. Lithofacies Gmn contains imbrication and often includes sandstone and pebbly sandstone infilled pocket structures in the conglomerate.

Although progradational coarse-grained coastal sequences tend to coarsen-upward (Bourgeois & Leithold, 1984), previous studies have observed normal grading in upper shoreface gravels (Nemec & Steel, 1984) and in adjacent backshore deposits (Maejima, 1982). Normal grading could develop due to wave reworking by mobilizing and redepositing the upper part of a tabular gravel sheet during a storm event. Alternatively, normal grading could be a result of resedimentation of the gravels as subaqueous sediment gravity flows (Watkins, 1992).

### 2.2.3 Lithofacies Gmv

In contrast to the association of lithofacies Gm and Gmn, there are other locations of the ELCC that are dominated by inversely graded cobble-pebble conglomerate (lithofacies Gmv). Lithofacies Gmv form tabular bodies 80–130 cm thick which show basal scour, crude stratification and abrupt upper contacts (Figure 5b). The upper contacts include evidence for reworking and sand drapes in the form of sand stringers or lenticular beds (Figure 12a). An analysis of maximum particle size (MPS) based upon the intermediate diameter of the 10 largest clasts (D10) in a bed and the bed thickness (BTh) shows a linear MPS-BTh relationship (Figure 12b). The outliers in Figure 12b are probably multistory sequences where the true bed thickness was obscured by the way the larger clasts protrude across-bedding surfaces.

Lithofacies Gmv is interpreted as subaqueous sediment gravity-flow deposits (debrites). The linear MPS-BTh relationship is a well-established indicator of flow competence of the entraining mass flow (Bluck, 1967b; Nemec & Steel, 1984) based upon the Coulomb-viscous rheological model (Johnson, 1970). The presence of sediment gravity-flow deposits in high-energy coastal environments has been observed in previous studies; for example, base-of-cliff
talus accumulations apparently sourced subaqueous debris flows in Mesozoic rift basin lakes (Tanner & Hubert, 1991) and Pliocene coastal exposures (Watkins, 1992). In other studies, debris flows transported sediment downslope to form wave-washed tabular gravels overlain by cross-bedded sands (Miller & Orr, 1988; Watkins, 1992).

### 2.2.4 | Lithofacies Gl

Stratified, pebble-cobble conglomerate forms sheetlike deposits typically 15–50 cm thick and characterized by discoid clasts exhibiting imbrication (Figure 5g). As seen in Figure 5g, these conglomerate sheets are often interbedded with thin or discontinuous sandstones that can be massive (lithofacies Sm), laminated (lithofacies Sl) or hummocky stratified (lithofacies Sh). At some locations, thin conglomerate sheets of lithofacies GI overlie coarse-grained conglomerates (lithofacies Gm, Gmn, or Gmv), but other locations are almost exclusively stacked sheets of lithofacies GI.

Lithofacies GI is interpreted as wave-washed upper shoreface-beachface gravels (Spalletti, 1993). Clast shapes and fabrics correspond to the “imbricate zone” of Bluck (1967a). The association with lithofacies Sm is interpreted as the adjacent “sand run” zone of Bluck (1967a). Previous studies of beachface conglomerates have noted the predominance of discoid clasts, seaward-dipping imbrication, sheetlike architecture, interbedded planar-laminated sandstone (lithofacies SI) and intervening small stream channels (lithofacies St and Sp) draining across the beach (Bourgeois & Leithold, 1984; Clifton, 1973; Hart & Plint, 1995). In this study, the beach deposits could represent seasonal beaches associated with rocky headlands (Figure 1) or pocket beaches between adjacent rocky headlands (next section).

### 2.2.5 | Lithofacies Gx

There are rare examples of low-angle pebble-cobble cross-bedded conglomerates (Figure 5h). Lithofacies Gx is typically 15–20 cm thick and consists of one cross-bed set. The deposits are lenticular in cross-section, and interbedded with stratified pebble-cobble conglomerate (lithofacies GI). Palaeocurrents are bimodal to the northeast and west-southwest (next section).

Lithofacies Gx is interpreted as small-scale rip-current channels cut into the beachface and upper shoreface. Previous studies have found similar deposits oriented approximately perpendicular to shoreline trends in the upper shoreface (Hart & Plint, 1995). Alternatively, the observed features might be erosional remnants of larger dunes due to rip, longshore or tidal currents or fluvial features near river mouths. These alternatives are less likely due to the smaller size, lack of supporting evidence (such as diagnostic fluvial or tidal sedimentary structures), and rarity of the features.

### 2.2.6 | Lithofacies Sm

Massive, pebbly, coarse-grained to very coarse-grained, well-sorted, quartz arenites form thin beds up to 30 cm thick (Figure 5i) or infill lenticular pocket structures up to 40 cm wide and 20 cm deep. As continuous beds, lithofacies Sm often forms partings between vertically stacked conglomerates. In addition, local concentrations of matrix within the conglomerates consist of lithofacies Sm, particularly the coarser-grained (cobble-boulder) tabular gravels. The massive sandstones may represent desratification by organisms or fluid escape, but no supporting evidence for this has been observed. It is also possible the massive sandstones contain sedimentary structures such as hummocky stratification, but the structures are obscured by the homogeneous grain size.

There are multiple possible interpretations of lithofacies Sm. Laterally continuous beds of lithofacies Sm most likely represent wave-washed pebbly sand from the “sand run” zone of a rocky shoreline (Bluck, 1967a), and repetitive lithofacies GI-lithofacies Sm sequences may represent seasonal winter beach-summer beach sequences. Alternatively, thin stringers of lithofacies Sm could represent the dilute trailing component of gravel-rich subaqueous debrites. Finally, the presence of lithofacies Sm as matrix within the framework of conglomerates is suggested by the affiliation of sandy matrix with the coarser-grained conglomerate beds (Hart & Plint, 1995).

### 2.2.7 | Lithofacies St

Trough cross-bedded, medium- to coarse-grained, well-sorted quartz arenites are found in beds that are typically <30 cm thick, with one observed bed 79 cm thick. Each bed consists of a single cross-bed set (Figure 5j). The beds are broadly lenticular and laterally discontinuous over distances of 10 m. The lenticular sandstones are interbedded with tabular conglomerates and incised into the lower gravel.

Lithofacies St is interpreted as the deposits of 3D sand dunes in the upper shoreface. Palaeocurrent directions from cross-bedding are bimodal NE-SW directed, which are interpreted as perpendicular to the palaeo-shoreline (next section). It is unlikely the dunes are tidal bedforms due to the absence of supporting tidal sedimentary structures. Given the incision, relatively small size and association with tabular gravels, lithofacies St may represent bedforms in the breaker zone, small dunes in rip-current channels, or small streams crossing the beachface (Bourgeois & Leithold, 1984; Hart & Plint, 1995).
2.2.8 | Lithofacies Sp

Planar-tabular, low-angle cross-bedded, medium- to coarse-grained, well-sorted quartz arenite is found in rare beds between 20 and 80 cm thick. Each bed consists of a single cross-bed set. The beds are incised into underlying gravels and overlain by tabular gravels. As with lithofacies St, the cross-bedding indicates bimodal NE-SW—directed transport.

Lithofacies Sp is interpreted as the deposits of 2D dunes in the upper shoreface. As with lithofacies St, the palaeocurrents are interpreted as perpendicular to the palaeo-shoreline (next section). The absence of tidal features or evidence for reactivation surfaces makes it unlikely these were tidal bedforms. Given the incision, relatively small size and association with tabular gravels, lithofacies Sp is interpreted as bedforms in the breaker zone or else small dunes in rip-current channels. Similar features have been described elsewhere (Bourgeois & Leithold, 1984; Hartley & Jolley, 1999).

2.2.9 | Lithofacies Sh

Lithofacies Sh consists of rare examples of hummocky stratification in pebbly, medium-grained, well-sorted quartz arenites. Lithofacies Sh is associated with small scours into the top of tabular gravel sheets (Figure 5l). Individual laminae are subparallel, infilling the underlying erosional micro-topography.

Lithofacies Sh is interpreted as the basal component of storm deposits (tempestites). The upper portions of tempestite sequences (Dott & Bourgeois, 1982) were not observed, in other words, these are amalgamated H.H.H sequences, which can be interpreted as proximal tempestites (Dott & Bourgeois, 1982) found in the upper shoreface (Greenwood & Sherman, 1986). Although tempestites are typically reworked above fair-weather wave-base, deposition within scours in tabular gravels may have improved preservation potential.

2.2.10 | Lithofacies Sl

There are rare occurrences of lithofacies Sl, which consists of laminated, medium-grained, well-sorted, quartz arenite in beds up to 50 cm thick. These deposits are associated with lithofacies Gl and form sheetlike deposits (Figure 5k). Heavy minerals, consisting of small opaque magnetite grains, are relatively rare in the ELCC, but can be observed in some examples of lithofacies Sl.

Lithofacies Sl is interpreted as beachface deposits due to its association with lithofacies Gl, sorting and rare magnetite concentrations along laminae. Similar deposits have been observed in swash zones on both sand and gravel beaches (Hou, Keeling, & Van Gosen, 2017; Spalletti, 1993).

2.3 | Palaeocurrent analysis

Palaeocurrent data show that the cross-bedding and clast imbrication data have bimodal SW-NE—directed palaeocurrents (Figure 13). For the bidirectional data, the convention is that the long-axis is the a-axis, the intermediate-axis is the b-axis and the short-axis is the c-axis. Figure 13 shows that the a-axis is strongly oriented east—west. Thus these conglomerates demonstrate an ordered a (t) b(i) fabric, where the a-axis is transverse to transport and clasts roll about the a-axis, producing seaward-dipping imbrication (Harms, Southard, Spearing, & Walker, 1975).

The spatial distribution of palaeocurrent data (Figure 13) suggests a palaeo-coastline oriented SE-NW, with indentations interrupting the overall trend, in other words, a series of SE-NW—trending rocky headlands and intervening pocket beaches. NE—directed palaeoflow (Figure 13) represents onshore transport towards these palaeo-shorelines. Bidirectional SE-NW—directed palaeoflow probably represents onshore-offshore swash transport on to pocket beaches between intervening rocky headlands. Some component of transport could be explained as longshore currents, however, the data do not suggest strongly established longshore current cells. In addition, the absence of tidal sedimentary structures is reflected in the absence of a strongly bimodal pattern with unidirectional indicators. This suggests a wave-dominated, micro-tidal depositional setting.

3 | DISCUSSION

3.1 | Depositional environment

Coarse-grained marine coastlines are controlled by geological material types, coastal configuration, history of geological and sea-level change, and relative importance of wave and tidal processes (Sammut, 2017). This study focuses on hard substrates producing a coastline of interspersed rocky headlands and pocket beaches, and experiencing a transgression under wave-dominant, micro-tidal conditions. The important observations supporting this synthesis are the exposures of buttressing relationships between Proterozoic igneous and metamorphic rocks with the conglomerates (Figures 7 and 8), which are interpreted as palaeo-sea cliffs, palaeo-tombolos and palaeo-wave-cut platforms. Transgressive conditions are indicated by the successive overtopping of these palaeotopographic features (Figure 10). Micro-tidal conditions are inferred from the coarse grain size, prevalence of wave-generated debris-flow...
deposits, presence of wave-generated sedimentary structures and absence of tidal sedimentary structures.

Lithofacies associations support the interpretation of alternating rocky headlands and pocket beaches. The rocky headlands facies association consists of tabular conglomerates that are massive (lithofacies Gm), normally graded (lithofacies Gmn), or inversely graded (lithofacies Gmv), with thin beds or pocket structures of pebbly sandstone (lithofacies Sm). Many of these deposits are interpreted as subaqueous debrites because of basal scour, crude stratification, consistent MPS-BTh relationships, normal, inverse, or inverse-to-normal grading, rare vertical clast orientations and reworking of the upper contact (Nemec & Steel, 1984). Other characteristics of this facies association include evidence for wave winnowing, sandy matrix infiltration and rare clasts that were “shattered” in situ, which is interpreted as due to rock fall from palaeo-sea cliffs. It is probable that these shoreface conglomerates, and the subaqueous debrites, sourced from sea cliff talus (Watkins, 1992). The thickest and coarsest-grained deposits in the ELCC are found adjacent to these palaeotopographic features, which is consistent with modern studies along rocky coastlines with limited accommodation space (Dixon, Green, & Cooper, 2015). Sea cliff recession controls sediment supply in these depositional systems, and is influenced by physical constraints of wave, tide and storm conditions, but also lithology and particularly the presence, orientation and propagation rates of discontinuities (Rosser, Brain, Petley, Lim, & Norman, 2013).

The gravel upper shoreface-beachface facies association consists of sheetlike conglomerates that are stratified, imbricated (lithofacies Sl) and cross-bedded (lithofacies Gx), with thin beds and pocket structures of laminated (lithofacies Sl), cross-bedded (lithofacies St and Sp), massive (lithofacies Sm) and hummocky stratified (lithofacies Sh) sandstone. The dominance of oblate clasts supports the marine origin of these deposits (Howard, 1992). The vertical and lateral relationships between these facies resemble the large disc zone, imbricate zone and sand run-infill zone components of gravel beaches described elsewhere (Bluck, 1967a), although in this study the lateral exposure is not sufficient to observe more subtle clast assemblages that have been seen in modern beaches (Bluck, 1999; Sherman et al., 1993).

Specific locations might be dominated by rocky headland facies or gravel upper shoreface-beachface facies, but
in other locations the two might be interbedded. The facies model shows that the rocky headland facies are associated with palaeo-sea cliffs and related features (Figure 14). The gravel upper shoreface-beachface facies might be found in pocket beach settings or, alternatively, as lower energy deposits in the rocky headland setting, such as seasonal accretion of beaches at the base of the rocky headland.

### 3.2 Palaeogeography, provenance and sequence stratigraphy

There is strong evidence that the clasts in the ELCC were locally derived. The quartzite clasts in the unit have sedimentary structures such as lamination and cross-bedding that can be matched to similar sedimentary structures in the underlying quartzites of the Uncompahgre Formation. While the vein quartz clasts could have been derived from any of the Proterozoic units, relatively rare clasts of schist, gneiss and banded iron formation, match lithologies observed in the underlying Twilight Gneiss and affiliated units. In contrast, evidently the Proterozoic granites did not produce numerous gravel-sized clasts. Instead, subaerial weathering of these granites probably produced the sand now found as sandy matrix within conglomerates or as interbedded sandstones in the ELCC, because these sandstones are texturally and compositionally similar to the field observations of grus produced on the weathered upper surface of the underlying granites. Judging from the prominent 1.71 Ga distribution peak of detrital zircon U-Pb ages (Figure 11), the sand fraction of the ELCC was primarily derived from erosion of the 1.72–1.68 Ga Bakers Bridge Granite.

The evidence suggests the ELCC was deposited above a subaerially weathered surface. Direct evidence for subaerial weathering includes the formation of a grus carapace on outcrops of Proterozoic granite, corestone weathering on quartzite clasts from the Uncompahgre Formation, redden- ing, weathering in fractures (later infilled by ELCC clasts), and local provenance for the ELCC clasts. This subaerial “landscape” on Proterozoic basement rocks had a minimal palaeo-relief of 65 m, prior to being overlain by the marine rocks of the ELCC and subsequent units. Thus the basal unconformity represents both a sequence boundary (SB) and transgressive surface of erosion.

The ELCC overlies a bedrock surface showing buttressing relationships interpreted as palaeo-sea cliffs, palaeo-tombolos and palaeo-wave-cut platforms. The overlap succession on this palaeo-surface indicates the ELCC is a partially preserved transgressive systems tract. The upper contact for the ELCC is a low-angle unconformity. Significant erosion and weathering presumably resulted in the loss of upper parts of the unit, which might have been sandstones and mudrocks associated with the upper part of the transgressive systems tract and/or high stand systems tract. In addition, the significant subaerial weathering of the ELCC generated pervasive sericite cements in the sandstones of the unit. These cements represent an episode of weathering and diagenesis not demonstrated in the overlying Upper Devonian sedimentary units. The overlying Upper Devonian units, the Ignacio Formation and Elbert Formation, are interpreted as a lowstand systems tract (fluvial facies in the Ignacio Formation) to transgressive systems tract (estuarine to marine facies in the Ignacio Formation and marine facies in the Elbert Formation).
(Maurer & Evans, 2011, 2013). Thus, this upper unconformity represents a SB.

4 | SUMMARY AND CONCLUSIONS

Careful analysis of stratigraphic relationships has revealed a new stratigraphic unit, the ELCC, of Early(?) Devonian age, in the San Juan Mountains of south-western Colorado. The unit represents a transgressive systems tract on a rocky shoreline setting, producing palaeogeomorphic features such as palaeo-sea cliffs, palaeo-tombolos and palaeo-wave-cut platforms. The unit (0–23 m thick) partly infilled the approximately 65 m of palaeotopography on the Proterozoic basement rocks in this region. The unit incorporated sea cliff talus, subaqueous debris-flow deposits and gravel beach deposits. Based upon palaeocurrent analysis, the palaeo-environment is interpreted as an alternating coastline of rocky headlands and intervening pocket beaches aligned approximately north–south in this region of south-western Colorado. Based upon transport of individual megaclasts up to 1.4 m long and with a mass >1.1 metric tons, and an absence of tidal structures, the setting is interpreted as a wave-dominant, micro-tidal, high-energy marine setting.

This type of environment has a low preservation potential, and is poorly recognized in the geological record; in fact the ELCC may be one of the oldest such set of deposits known (cf. Johnson, 1988). Recognition of subtle features in the unit has important implications for the palaeoclimate, sea level and tectonic history of this region.

ACKNOWLEDGEMENTS

This paper was significantly improved by helpful suggestions from two anonymous reviewers and the associate editor at the journal, and by several reviewers at the US Geological Survey, including members of the USGS Geological Names Unit. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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This paper was significantly improved by helpful suggestions from two anonymous reviewers and the associate editor at the journal, and by several reviewers at the US Geological Survey, including members of the USGS Geological Names Unit. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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Additional Supporting Information may be found online in the supporting information tab for this article.

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**How to cite this article:** Evans JE, Holm-Denoma CS. Processes and facies relationships in a Lower(?) Devonian rocky shoreline depositional environment, East Lime Creek Conglomerate, southwestern Colorado, USA. *Depositional Rec.* 2018;4:133–156. https://doi.org/10.1002/dep2.41