Ghost-rock karstification of Devonian paleotopography at the Hammerstone Quarry site in northeast Alberta

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Summary

A new style of ghost-rock karstification is recognized at a site 75 km north of Fort McMurray in northeast Alberta. The karstic area of the Upper Devonian paleotopography was localized at the western end of the Bitumount Trough, a 50 km long collapse structure that resulted from dissolution removal of Middle Devonian Prairie Evaporite strata only 200 m below. Ghost-rock karstification developed in massive light grey limestone beds that alternate with chlorite-rich argillaceous intervals of the Moberly Member, Devonian Waterways Formation. These weathered rock profiles were deepened by slowly moving hydraulic gradient-driven phreatic groundwater descending along clusters of closely spaced 2-10 cm wide joints cross-cutting the fracture-shattered limestone beds. The uppermost beds of greyish green chlorite-rich argillaceous limestone were decalcified as the flows along the clustered jointed carried insoluble residues of quartz silt mixed with illite-chlorite into the substrate. These chlorite-rich insoluble residues accumulated as replacement fabrics within porous zones of the decalcified altered limestone substrate. As the joint opening plugged with insoluble residues within the deepened decalcification weathered rock intervals, these alterite zones expanded laterally to form vertical pod-shaped structures. These 5-20 m diameter and 10-20 m deep pseudo-sinkhole zones consisting of alterite retained ghost-rock traces of the original limestone strata. This area was subsequently covered by the Lower Cretaceous Athabasca Oil Sands.

Introduction

The unusual weathered rock profiles exposed at the Hammerstone Quarry study area developed on the Devonian limestone paleotopography (Fig. 1). The quarry is located in the north-central area of the Athabasca Oil Sands deposit, 75 km north of Fort McMurray in northeast Alberta. The quarry site is along the east bank of the Athabasca River, adjacent to the southwest corner of the Muskeg River Mine oil sand lease.

The 5-20 m diameter and 10-20 m deep zones of alterite are characterized by the preservation of ghost-rock fabrics along the quarry cuts into the Upper Devonian paleotopography (Broughton, 2018). These weathered rock profiles form vertically oriented pod-form alteration zones, recognized as pseudo-sinkholes, that extend downward for 10s m into the limestone substrate. They encase multi-m scale traces of the original limestone stratification as ghost-rock fabrics. These pseudo-sinkhole karstic features resulted from intense weathering profiles permitted at sites preconditioned by concentration of joints that cross-cut previously fracture-shattered limestone beds. These pseudo-sinkholes originated as well-defined vertical zones of weathered rock (alterite). They are not dissolution-collapse sinkhole structures that are commonplace in the area.

Observations

Operations at the Hammerstone Quarry exhume a 30-40 m thick interval of Moberly Member strata of the Waterways Formation (Middle-Upper Devonian). The interval consists of light grey-cream colored massive to nodular limestone beds that alternate with greyish green illite-chlorite-rich argillaceous limestone. The quarry operations generally uncover a 2-4 m thick greyish green argillaceous limestone bed that overlies intervals consisting of 2-6 m thick massive light grey limestone beds. In some areas, the quarry floor extends downward to the base of the Moberly interval contact with the underlying Christina Member. The Moberly interval is overlain by thinned and patchy deposits of bitumen-stained sand of the lower McMurray Formation (Aptian).

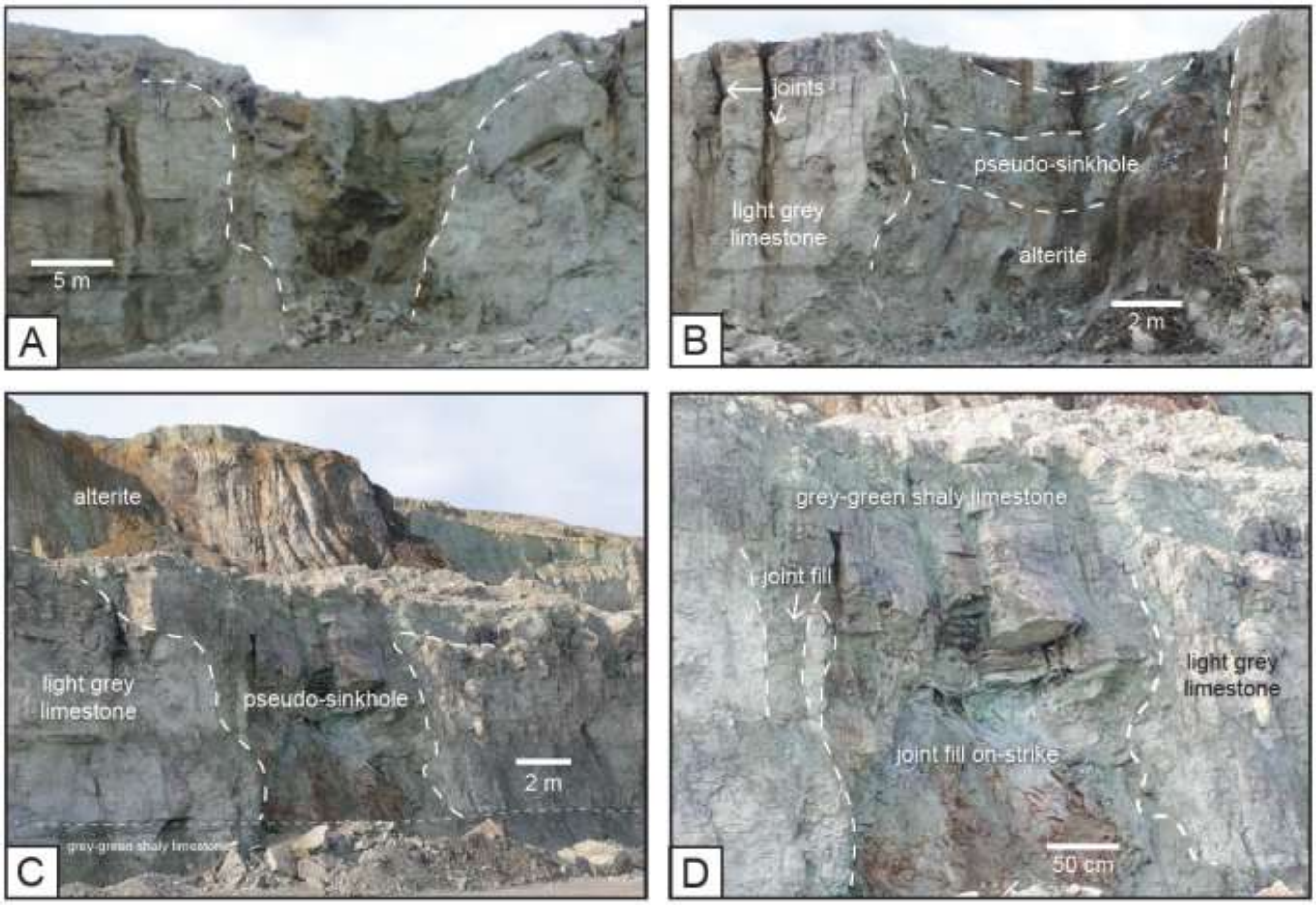

Figure 1. Vertical alterite zones developed as pseudo-sinkholes forms within Moberly Member, Waterways Formation, limestone beds exhumed at the Hammerstone Quarry in northeast Alberta. (A-B) These vertical pod-shaped alterite zones developed as weathered rock profiles deepened into the phreatic zone as descending groundwater flows concentrated along clusters of joints. Decalcification of the overlying chlorite-rich argillaceous limestone mobilized insoluble illite-chlorite silt residues until accumulated within patchy dissolution zones in the limestone substrate. Alterite zones expanded laterally as the joint conduits plugged, resulting in 5-20 m diameter pseudo-sinkholes that encased ghost-rock fabrics outlining traces of the original limestone beds. (C) Example of a vertical alterite zone, a pseudo-sinkhole, overlain by a mostly decalcified limestone bed. (D) Strike-length section of a joint and sediment fill consisting of insoluble residues connected to overlying grey-green argillaceous limestone.

The weathered rock profiles include partial to largely decalcified zones of altered limestone substrate. The uppermost bed of the chlorite-rich argillaceous deposit transition into zones of subsoil weathering along the Devonian paleotopography. The metres thick weathered rock profiles altered the uppermost greyish green argillaceous limestone bed, resulting in alterite zones that deepened vertically for 10s m into the substrate. Replacement zones are observed to have formed within the light grey-cream colored massive limestone substrate resulting from deposition of insoluble residues sourced from the overlying weathered beds. These weathered rock profiles are observed to have been localized at sites dominated by concentration of joints that cross-cut fracture-shattered beds.

Joint Sets

The Moberly covered karst interval at the Hammerstone Quarry site is characterized by rectangular patterned sets of sediment-filled joints that cross-cut the moderate to intensely fracture-shattered limestone beds. There are two types of interrelated joint sets observed at the quarry: (1) commonplace joints with narrow 2-10 cm wall separations characterized by chemically unaltered surfaces, and (2) solution-enlarged joint channels lined with multi-cm thick alteration zones (Fig. 2). The joint sets overprint limestone beds that have been fracture-shattered to varying extents that in some areas obliterate the host rock bedding and result in significant subsoil weathering extending for 3-4 m below the Devonian unconformity surface. Joints, 2-10 cm-wide, extend from top of the Moberly Member interval downward for 10s m to the contact with the subjacent strata of the Christina Member, and deeper to an unknown extent. Joint set orientations observed along the Athabasca River Valley, including the Hammerstone Quarry site, vary within a range of 40-60º with offsets of 130-150º. Less commonly, the cross-cut alignments are nearly N-S at 10º.

In some quarry areas, the upper reaches of the commonplace narrow joint sets have been solution enlarged to form a reticulate maze-like distribution pattern. This latticework of 1-2 m wide and 2-3 m deep solution-enlarged channels overprint the earlier formed narrow joint sets. This solution-enlarged joint-channel latticework extends across a surface area of several 1000 m^2 (Fig. 2). The commonplace narrower, 2-10 cm wide, joint system continues at depth below this joint-guided solution enlarged channel network. These solution enlarged joint expansion features are observable upon removal of the infilling sediment between the joint walls, a routine quarry procedure to prepare a cleaner, indurated, crushed limestone product. The solution enlarged channels are characterized by thin alteration crusts of micrite that penetrated 1-2 cm, but as much as 10-15 cm into the host limestone bed, in contrast to the unaltered wall rock surfaces of the commonplace narrow joints.

Small areas, 10s m across, of the solution-enlarged joint-channel network uncovered at the quarry site retain a thin roof of indurated limestone, mostly less than a metre thick. Other than these relatively small areas, there is no observational evidence that these enlarged joints were once extensively covered by similar indurated limestone roofing, however thin. Cupola corrosion structures have been preserved along roofs of the extant joint guided solution/alteration channels.

Joint-filling Sediments

The sediment-filled joint sets are readily observed along the 30-40 m high quarry walls and bench cuts. Most of these vertical joints have walls with 2-10 cm wide separations. The joint outlines become increasingly obliterated with weathering of the surrounding rock. All of the narrow joint sets and the joint guided solution/alteration channels were infilled by insoluble residues consisting of decalcified illite-clinochlore and quartz silt sediment. These chlorite-rich sediments completely infill the spaces between the walls of the narrow joint sets and the solution-enlarged channels. The sediment fills have vertical continuity with the overlying decalcified greyish green argillaceous beds. Both the roofed areas and the adjoined roofless joint-guided solution channels were infilled with similar sediment consisting of insoluble residues of chlorite-rich quartz silt. The observational evidence indicates that these fills are entirely homogeneous. There are no visibly open voids or cavities within the joint and channel fills at the quarry site. These joint fills lack evidence for any fluvial stratification such as grain-size sorting or bedding. During deposition of the lower McMurray strata, narrow curvilinear sheet-form fractures were emplaced between joint wall rock and the now indurated sediment fills. As such, these open fissures permitted influxes of coarsely grained sand sourced from the overlying lower McMurray sand beds, resulting in fracture fills consisting of vertically oriented, discontinuous, sand sheets. These may extend along joints up to 20 m below the top of the Moberly interval. The porous sand stringers and the fracture-shattered wall rock to a lesser extent trapped hydrocarbon migrations into the area during Late Cretaceous-Early Paleogene tectonism.

Figure 2. Joint sets oriented NW and NE resulted in latticework of 100s m-long, 1-2 m wide and 2-3 m deep solution enlarged channels uncovered at the Hammerstone Quarry. These enlarged joints rapidly narrow to widths less than 10 cm in the substrate and extend at depth to the quarry floor, 30-40 m below, and for unknown depths into older strata of the Waterways Formation. Groundwater movements decalcified overlying greyish green argillaceous limestone. Insoluble residues consisting of illite and chlorite clay mixed with quartz silt were carried by descending waters into the phreatic zone and accumulated as joint-filling sediment. (A-B) Quarrying operations remove the joint-filling sediment from the solution-enlarged channels to facilitate processing of the limestone beds for commercial purposes.

Vertical Alterite Zones: Pseudo-sinkholes

A prominent feature of the 30-40 m thick Moberly interval exhumed at the Hammerstone Quarry is the distribution of vertically oriented pod-shaped alteration zones. These oval form alterite zones are 5-20 m long, up to 10 m wide and several 10s m deep (Fig. 1). They developed with an elongated direction oriented to the northwest, paralleling the joint alignments. These zones, termed pseudo-sinkholes, extend downward from the upper surface of the Moberly interval to depths as much as 20-25 m towards the quarry floor. Pairs of these pod-form alterite zones are similarly aligned to the northwest.

These vertical alterite zones, termed pseudo-sinkholes, consist of grayish green silt accumulations that cross-cut stratified light grey massive limestone beds and intervals with stratified chlorite-rich argillaceous limestone. These unusual features consist mostly of greyish green chlorite-rich silt facies, but often incorporate patchy traces of the original massive light grey limestone beds. These 10s m size vertical alterite zones have morphologic, geometric and facies similarities to more diminutive greenish alteration zones that protrude downward from the decalcified argillaceous limestone beds into the underlying light grey massive limestone. In a similar manner, these 5-20 m diameter sinkhole-like zones of alterite have vertical continuity with the overlying chlorite-rich weathered rock profiles at the top of the Moberly interval.

Interpretation

The weathered rock profiles of the Moberly interval at the quarry study area consist of metres thick greyish green chlorite-rich argillaceous limestone beds that were moderately to strongly decalcified, forming alterite zones that retain trace outlines of the original limestone bedding. These altered rock intervals overlie and extends for metres into substrate where the fabrics of the underlying massive light grey limestone were impacted by partial to extensive replacement by chlorite-rich silt detritus. The replacement zones have vertical continuity with overlying decalcified greyish green argillaceous beds or their rubble equivalents. Patchy grey-green replacement zones often protrude downward into the underlying light grey massive limestone. Traces of the original massive limestone fabrics are preserved following the partial dissolution/replacement process, resulting in patchy and discontinuous replacement zones. Insoluble residues, consisting of illite-chlorite-rich quartz silt, accumulated within patchy dissolution zones within the massive light grey limestone, clogging the dissolution-induced porosity. These chlorite-rich alterite zones formed at a wide range of diameters from dm to 10s m, extending as protrusions into the underlying light grey limestone beds. They preserve traces of the original unaltered bed textures as ghost-rock fabrics.

The joint sets extending at depth below the water table functioned as traps for the downward percolating insoluble residues of illite-chlorite clay and quartz silt as the particulate matter settled out of suspension. The particulate matter in the groundwater flows were directed downward along the joint system as the subsoil weathering advanced above, and at least until these conduits were plugged. The joints below the water table filled with slowly downward settling sediment without any evidence for stratification. This resulted in relatively homogeneous textures of the grayish green silt sediment plugging the 10s m deep joints. The plugging rerouted vertical flows laterally, and resulting in an increased radius of dissolution and accumulation of insoluble particulate matter into the surrounding fracture-shattered limestone as pseudo-sinkholes.

Impact of joint sets within the uppermost greyish green argillaceous limestone at the level of the pre-Cretaceous unconformity was significant but the evidence for this was often largely obliterated by advanced subsoil weathering of the karst cover (Fig. 3). Presumably, the uppermost reaches of the joint system near surface were sufficiently well-developed to guide shallow water flows deeper into the substrate and towards clusters of open joints, which functioned as gateways into the substrate below the water table. The weathered rock alteration profiles resulted with hydraulic gradient driven downward flow of the groundwater deeper into the phreatic zone. A more extensive zone of decalcified rock evolved into sites that trapped descending insoluble residues. This process facilitated localized deepening of the weathered rock profiles as vertical alterite zones, the pseudo-sinkholes, that extended downward for 10s m into the phreatic zone.

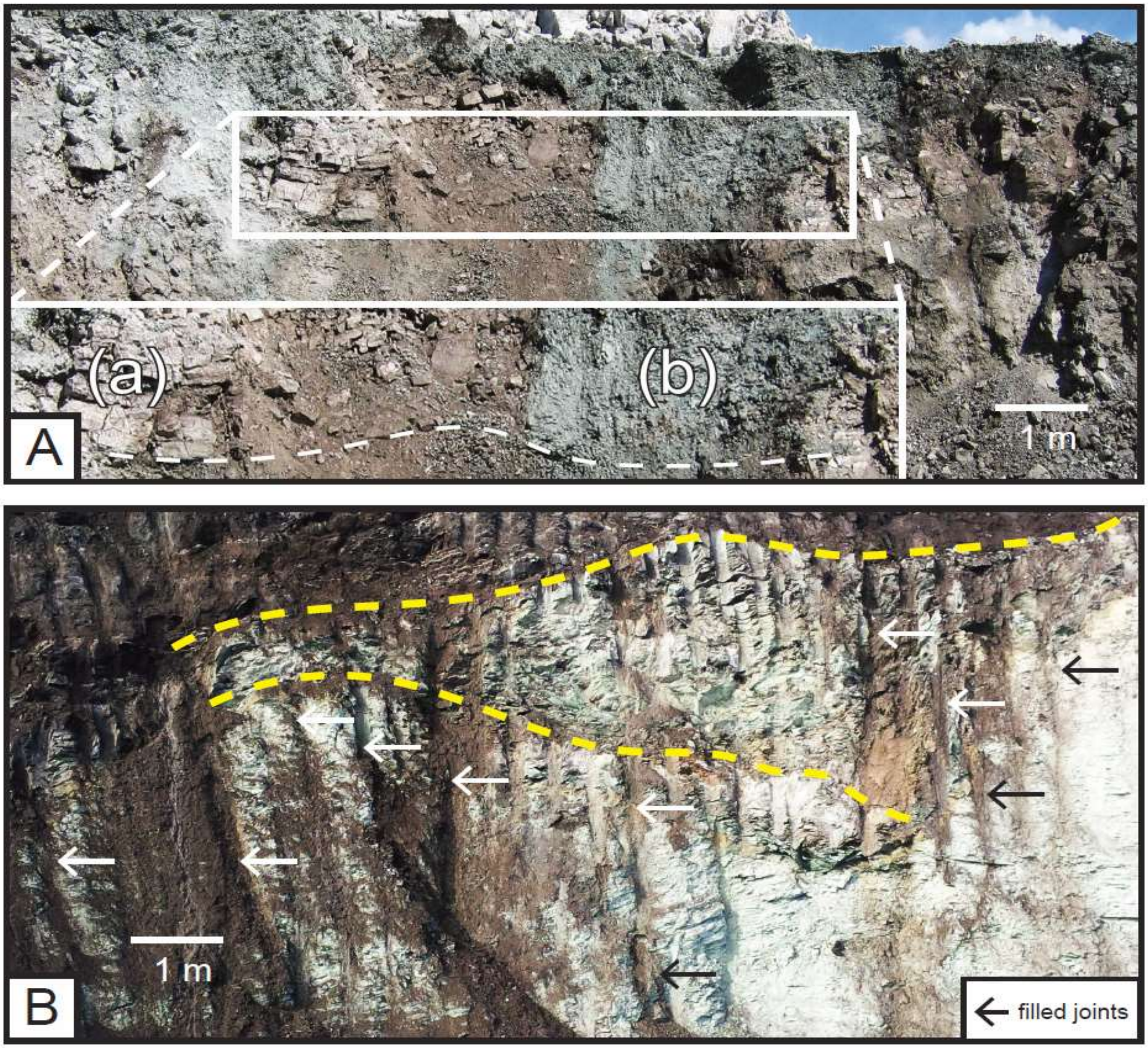

Figure 3. Weathered rock profile that deepened into the phreatic zone at the Hammerstone Quarry resulted from groundwater flows channeled along joint sets. Subsoil weathering expanded into these vertical alterite zones as the host rock beds surrounding the joints were decalcified. The insoluble residues plugged the joints resulting in accumulations within adjacent patchy dissolution zones of the light grey limestone. The clinochlore chlorite-rich alterite zones encased ghost-rock fabrics, outlining traces of incomplete dissolution fabrics of the light grey limestone beds. (A) Descending groundwater flows along the clusters of joints resulted in decalcification of the chlorite-rich argillaceous limestone. Flows downward into the phreatic zone carried insoluble residues, infilling patchy dissolution zones in porous areas of the light grey limestone substrate. (B) Conduits provided by clustered joints that cross-cut the fracture-shattered limestone beds controlled water flows into the phreatic zone and distribution of mobilized insoluble residues. As the joints were plugged by insoluble residues, the deepened alterite zones expanded latterly. The chlorite-rich insoluble residues partially replaced the surrounding limestone beds, tracing the original bedding fabrics as ghost-rock fabrics. As soluble ions were removed from the system, meters long intra-bed solution front surfaces developed concurrent with volumetric reduction. Modified from Broughton (2018).

Vertical alterite zones, termed pseudo-sinkholes, developed at sites where closely spaced vertical joints guided slowly moving water flows laden with insoluble residues into favorably porous depositional sites below the water table. This process resulted in deepening and lateral expansion of the weathered rock profiles into the substrate for 10s m. These pseudo-sinkhole zones include ghost-rock fabrics resulting from incomplete replacement of the light grey massive indurated limestone beds and greyish green argillaceous beds by mobilized insoluble residues that were sourced from the overlying weathered rock mantle of the covered karst. As the joint conduits in the substrate became plugged by downward circulation and accumulation of insoluble residues, the alteration fronts expanded laterally with the result of increased obliteration of the joint outlines (Fig. 3). This process resulted in vertically oriented bowl shaped and pod form alterite zones, which commonly encase ghost-rock traces of the original stratified bed textures.

The illite-chlorite-laden quartz silt sediment fills of the 1-2x2-3 m joint-guided solution channels display no evidence of fluvial or depositional stratification, consistent with the homogeneous fills of the narrow joints elsewhere at the Hammerstone Quarry site. This suggests that the corrosion-dissolution process that expanded the separation of the joint walls and resulted in channels with alteration crust lining was constrained to zones below the water table, back-filling joint openings with particulate matter within very slow downward circulating groundwater.

Conclusions

A unique style of ghost-rock karstification is associated with Upper Devonian paleotopography exposed at the Hammerstone Quarry site. This processes resulted from very slow hydraulic gradient groundwater flows descending along clusters of joints, resulting in decalcification of the limestone beds and transfer of the insoluble residues into the substrate. Descending groundwater flows were channeled into the substrate along clusters of joints. These flows partially decalcified the uppermost chlorite-rich argillaceous limestone beds along the Devonian paleotopography. Slowly moving hydraulic gradient-driven phreatic flows mobilized insoluble residues, consisting of chlorite-illite clays and quartz silt, deeper into the substrate along the joint sets. The insoluble residues accumulated within patchy corrosion-dissolution zones formed within the light grey limestone substrate. The weathered rock profiles deepened and expanded laterally to encase zones of closely spaced joints. This resulted in vertically oriented alterite zones 5-20 m diameter and 10-20 m deep that preserved trace outlines of the original limestone bedding as ghost-rock fabrics as the joint clusters were increasingly plugged and obliterated. Commonplace joints with 5-10 cm spacing between wall surfaces were solution enlarged to 1-2 m wide joint-guided solution/alteration channels, resulting in a latticework distribution pattern of cross-cutting channels extending across part of the quarry study area. These 1-2 m wide and 2-3 m deep channels were also filled by chlorite-rich insoluble residues sourced from decalcification of overlying argillaceous limestone. As the joint-guided solution channels widened and deepened, alteration rinds up to 10-15 cm thick developed along the channel walls.

Acknowledgements

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Reference

Broughton, P. L., 2018. Ghost-rock karstification of Devonian limestone flooring the Athabasca Oil Sands in western Canada. Geomorphology, 318: 303-319.