GRANT & IOWA COUNTIES

Geologic map of the Highland West and Highland East 7.5-minute quadrangles, Grant and Iowa counties, Wisconsin

MAP 510–SUPPLEMENT • 2024

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Introduction

The Highland East and Highland West 7.5-minute quadrangles are centered on the Village of Highland, Wisconsin, straddling the border between Grant and Iowa counties (fig. 1). The quadrangles lie within the Driftless Area of southwestern Wisconsin, just north of Military Ridge, an east-west trending cuesta created by the regional southward dip of Paleozoic strata at about 17 feet (5 m) to the mile (Heyl and others, 1959). The Highland area preserves several remnants of the late Ordovician carbonates making up the crest of the cuesta, which form a series of narrow uplands extending north from Military Ridge into the deeply dissected southern slope of the lower Wisconsin River valley. The Village of Highland is situated on a divide, separating two drainage basins: Otter Creek on the east and the Blue River on the west. Both basins produce up to 400 ft (120 m) of relief from valley bottom to ridge top (fig. 1). The relatively high-relief landscape, combined with the lack of Quaternary glacial sediment, provides excellent exposure of bedrock units spanning the late Cambrian Tunnel City Group to the late Ordovician Galena Formation (Furongian to Upper Katian, 497-445 Ma).

Geologic mapping in the Highland quadrangles is part of the U.S. Geological Survey's (USGS) Earth Mapping Resources Initiative (EarthMRI), established to collect more information about the presence and distribution of critical minerals within focus areas across the United States (Nassar and Fortier, 2021). Highland was a long-lived and important sub-district within the Upper Mississippi Valley (UMV) lead-zinc district and is the northernmost area in the district where intensive mining took place. The Highland sub-district is distinctive for having significant copper in addition to lead and zinc in some deposits, as well as for the presence of lead deposits within the Prairie du Chien Group (**Opc** on map). Within the Highland sub-district, sulfide mineralization has the potential to host critical minerals including arsenic, barite, cobalt, germanium, nickel, and zinc.

The primary goal of this map and supplemental report is to create a detailed structural and stratigraphic framework for the two Highland quadrangles in order to identify features spatially associated with sulfide mineralization. Although the UMV lead-zinc district, and the Highland sub-district in particular, has been the subject of previous investigations (Grant, 1906; Agnew and

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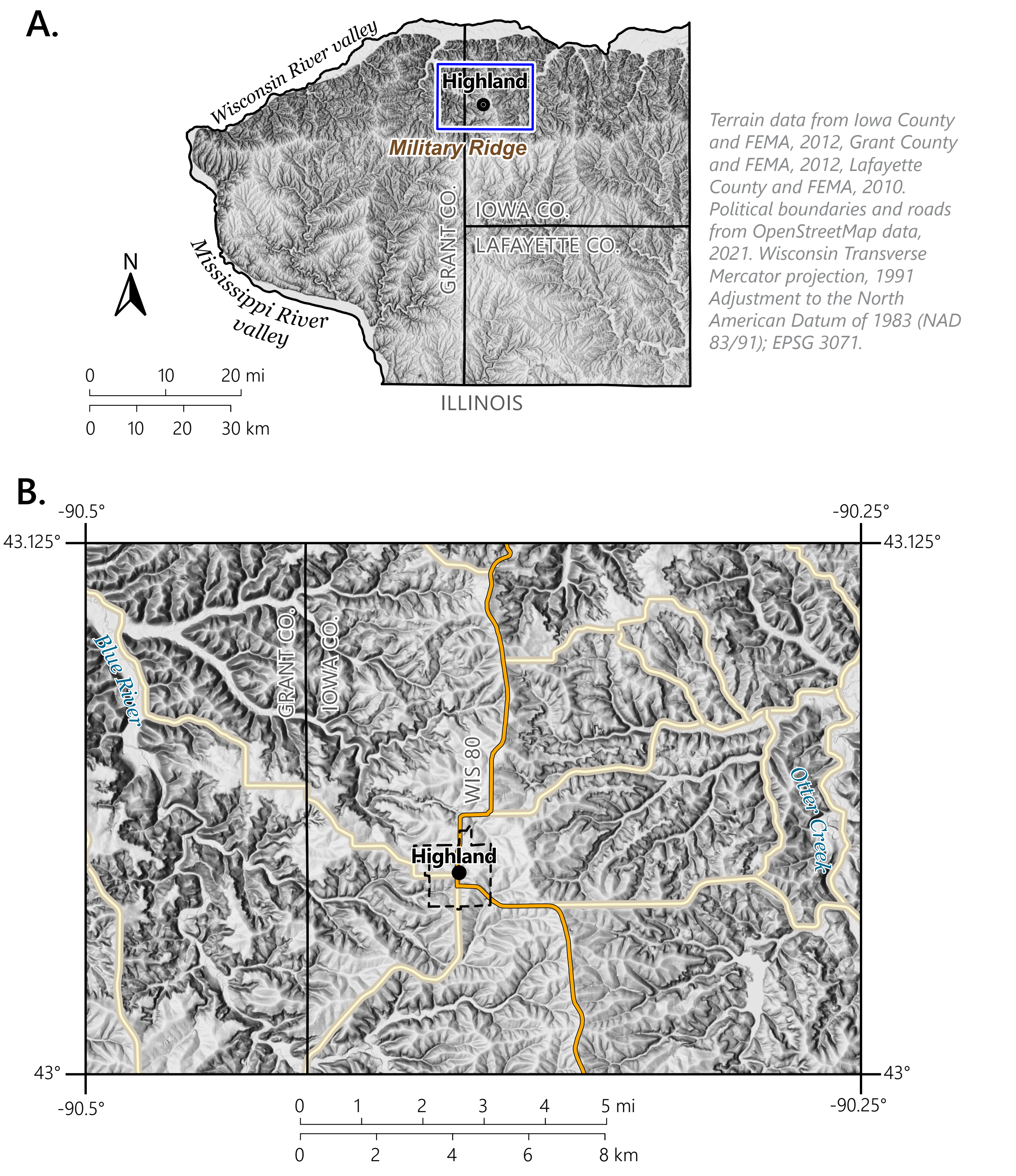

Figure 1. Panel A, overview map of southwestern Wisconsin with hillshade from 5 ft (1.5 m) resolution lidar data. Blue rectangle marks area covered by the Highland quadrangles, black dot is the Village of Highland. Panel B, map of the Highland quadrangles with hillshade from 5 ft (1.5 m) resolution lidar data and major drainage features labelled. State and county highways are orange, yellow lines. Dashed black line encloses area covered by the Village of Highland.

others, 1953; Batten and Attig, 2010), research related to sulfide mineralization in the region has declined since mining activity ceased in the 1970s. This mapping project combines new detailed field work with geologic information from sources such as well construction reports, historic drill logs, and maps of mining activity compiled in the 1950s as part of the USGS Mineral Development Atlas (MDA) program (archived in Pepp and others, 2019).

Historical mining records are an invaluable resource allowing structural and stratigraphic features identified during mapping to be compared to areas with known mineralization, providing insight to the location of undiscovered deposits in the sub-district. Furthermore, features associated with sulfide deposits in the Highland sub-district are likely applicable to the broader UMV lead-zinc district. Future mining in the Highland sub-district is unlikely due to the small size of the deposits, but environmental impacts caused by sulfide mineralization and past mining activity continue to affect southwest Wisconsin (Lecce and Pavlowsky, 1997; Siemering and others, 2019). Due to the risks that lead, zinc, and other metals released from sulfide mineralization pose to water quality, ecological conditions, and agricultural activity, identification of potential areas of mineralization is of great importance to a wide variety of land uses.

Description of Map Units

Full bedrock unit descriptions are provided below. Brief descriptions of both Quaternary and Paleozoic units are included on the map plate. Bedrock unit names and stratigraphic assignments follow Agnew and others (1956).

Galena Formation (Og on map):

Full uneroded thickness is 220–230 ft (67–70 m). Only the cherty unit of the Prosser Member of Agnew and others (1956), upper Dunleith of Ostrom (1969), is preserved in the Highland quadrangles, where the Galena Formation reaches a maximum thickness of approximately 100 ft (30 m).

Thick-bedded, gray and tan, fine- to coarse-grained silty crystalline dolomite. Contains abundant chert as nodules, ribbons, and bands that are 2–6 in. (5–15 cm) thick. *Receptaculites* fossils are present as ridged bands ⅕–¾ in. (1–2 cm) thick concentrated within select beds. The majority of the formation in the Highland quadrangles contains branching networks of *Thalassinoides* burrows which form soft, porous areas, giving the Galena its characteristic honeycomb weathering pattern. Many exposures also contain 1–15-ft thick (0.3–4.5 m) packages of thin- and medium-bedded, dense, light-gray crystalline dolomite and tan dolomitic silt. Dolomitic silt is seen mixed into crystalline dolomite layers along 0.4–1.2-in-wide (1–3 cm) winding trails and patchy areas but is not present within the groundmass to the same degree as the honeycomb weathering layers. Basal contact with the Decorah is marked by an increase in the frequency and thickness of shale partings over an interval of 3–4 ft (1 m).

Decorah Formation (Od on map): 30–40 ft (9–12 m) thick

Ion Member 20–25 ft (6–7.6 m) thick

Medium-bedded, gray and tan, shaly, fine- to medium-grained limestone and dolomite. Contains abundant gray to green shale partings especially in lower part of member. Fossils include abundant brachiopod shell fragments and sparse rugosa. The Ion Member is not exposed at the surface in the Highland quadrangles. The Ion was logged in a drill core at the Croft Quarry in Fennimore, WI, (15 mi/24 km to the southwest of Highland), and the base was marked by abrupt change in color of shale partings to chocolate brown, which coincides with a decreased shale component within carbonate beds. See Bremmer and others (2023) for a complete log of this core.

An issue of stratigraphic classification arises in assigning the Ion Member to the Decorah Formation. The Ion Member marks the transition between shaly limestones and dolomites of the Decorah Formation (**Od** on map) and the cherty crystalline dolomites of the basal Galena Formation (**Og** on map). The Ion had long been assigned to the Decorah Formation by investigators in Iowa and southwest Wisconsin (e.g. Kay, 1929; Agnew and others, 1956; Allingham, 1963) due to the sharp lithologic and faunal boundary between it and the overlying Galena Formation. Investigators in Illinois (Templeton and Willman, 1963) proposed an alternative classification where the Ion was integrated into the basal Dunleith Member of the Galena Formation. This is because to the south, in Illinois, the Ion represents a continuous gradation from the shaly lithologies of the Decorah into the argillaceous basal Galena. Further confusion followed when the classification of Templeton and Willman (1963) was used by Ostrom (1969) to define the stratigraphy of the Platteville, Galena and Decorah Formations in Wisconsin without consideration to the Decorah–Galena boundary. The official WGNHS stratigraphic column for Wisconsin (WGNHS, 2011) is based on Ostrom (1969) and left the Ion in the Galena Formation despite different assignments being appropriate for different areas. In this report, the Ion will be assigned as a member of the Decorah Formation, as done in Agnew (1956) because this categorization of the Decorah–Galena boundary better reflects the lithostratigraphic character of the contact for the portion of the UMV lead-zinc district that lies within Wisconsin.

Guttenberg Member 9–16 ft (2.5–5 m) thick

In outcrop, the Guttenberg is a thin-bedded, light-brown, fine-grained fossiliferous limestone with abundant interbedded tan-brown shale. Commonly contains veins and cm-scale spherical nodules of coarsely crystalline white calcite. In cores drilled near ore deposits and in float on mine dump piles, the Guttenberg is typically a light-gray porous dolomite with fetid dark-brown to black shale interbeds. The distinctive presentation of the Guttenberg in areas with known mineralization is persistent throughout the UMV lead-zinc district in Wisconsin and was specifically noted by Bain (1906).

Spechts Ferry Member 2–3 ft (0.5–1 m) thick

Very thin-bedded bluish green and olive-green shale with lesser limestone interbeds ranging from fossil lags to micrite. Easily weathered and not encountered in outcrop. In drill core, the base of the Spechts Ferry corresponds to a change in shale color to chocolate-brown and an abrupt switch to the carbonate-dominated Quimbys Mill Member. Regionally, this contact has been described as a low-relief unconformity (Choi and others, 1999).

Platteville Formation (Op on map): 45–55 ft (14–17 m) thick

Quimbys Mill Member: 3–6 ft (1–2 m) thick

Thin- to medium-bedded, light-purplish gray to tan, very hard and dense, fine-grained, moderately fossiliferous limestone separated by tan- to chocolate-brown shale beds. Contains sparse intraclastic beds. In drill core, the base of the Quimbys Mill is marked by a distinctive layer of shale with nodular limestone inclusions. Alteration commonly obscures the identifying characteristics of the Quimbys Mill producing a softer rock with decreased bedding thickness and increased shale content.

McGregor Member 25–30 ft (7.6–9 m) thick

Thin to medium wavy-bedded, light-gray, very fossiliferous fine-grained limestone and dolomite. Abundant tan- or medium-gray shale layers separate carbonate beds ranging from micrite to fossil lags. Fossil assemblages are comprised of brachiopods, and with lesser crinoids, bryozoans, and rugosa. Divisible into two submembers of roughly equal thickness (Bays, 1937), the upper submember (Magnolia) is generally more thickly-bedded and less shaly than the lower submember (Mifflin).

Pecatonica Member 15–20 ft (4.5–6 m) thick

Thin- to medium-bedded, tan- to light-gray, slightly porous, fine-grained crystalline dolomite with wispy, thin, tan- to medium-gray shale partings. Characteristically breaks in 2–3 ft (0.6–0.9 m) blocks giving it the appearance of being thickly-bedded. Commonly contains red to brown limonite filling porosity between dolomite crystals. Contains numerous hardgrounds marked by 0.75–4-in. (2–10 cm) thick zones of intense burrowing and pyrite/marcasite mineralization. Slightly to very fossiliferous with variable component of dark-gray brachiopod shell fragments. Bedding thickness, decreased shale component, dolomitic character and slight porosity distinguish unit from overlying McGregor.

Ancell Group (Oa on map): 45–300+ ft (14–90 m) thick

The Ancell Group contains the upper thin, shaly Glenwood Formation underlain by the sandstone-dominated St. Peter Formation. The St. Peter Formation is further divided into two members: the upper Tonti and basal Readstown.

Glenwood Formation: 0–3 ft (0–0.9 m) thick

Rarely seen in outcrop, the Glenwood Formation is recognizable in float from shale chips on slopes just above the uppermost St. Peter Formation sandstone outcrops. Seven pits were dug at the contact between the Platteville Formation (**Op** on map) and the Ancell Group (**Oa** on map) across the Highland quadrangles to expose and directly observe the Glenwood Formation. In most cases the Glenwood is 1.3–2 ft (40–60 cm) thick consisting of equal thicknesses of a lower sandstone/shaly sandstone and an upper shale/sandy shale. The lower sandstone is an orange to tan to white fine to medium grained or fine to medium and coarse-grained bimodal sandstone. Sandstone is commonly cemented by dolomite and contains sparse to abundant black phosphate grains, rarely accompanied by lumpy cm-scale areas of orange iron oxide cement. Sandstone may also be bioturbated and mottled with gray-green shale along burrow zones. Above the sandstone is gray-green to tan laminated shale with quartz sand absent to abundant. Where sand is present it forms thin lenses, especially near the base of the shale unit, or mixed into bioturbated shale along burrow zones. Several pits revealed that the Glenwood is absent or only present as a very thin seam of gray-green sandy shale with St. Peter sandstone containing abundant orange to brown to purple to red iron oxide cemented zones directly underlying dolomite of the Platteville Formation.

The Glenwood was intersected in 10 boreholes in a series of fences west of the Village of Highland during an exploratory drilling program by the USGS (Agnew et al., 1953). Logs record 1–3 ft (30–91 cm) of Glenwood with an average thickness of 2.1 ft (64 cm). The Glenwood is described as gray-green shale with a variable component of quartz sand, phosphatic nodules and iron oxides after sulfide minerals.

St. Peter Formation: 40–300+ ft (12–90+ m) thick

Tonti Member

The uppermost 2–5 ft (0.5–1.5 m) of the St. Peter is distinctive in outcrop and float, consisting of hard, vuggy, variegated white, orange, red, brown, and yellow sandstone. Lumpy concretion clusters and burrow networks are cemented by colorful iron oxides, which are also present in pore space between sand grains. These iron oxide cements are present in the uppermost Tonti at highly increased abundance relative to lower in the St. Peter. Iron oxides at the top St. Peter are the weathering products of iron sulfide minerals pyrite and marcasite, which are rarely preserved in outcrop (see photo 1). Horizons with abundant iron cement may also contain sparse to moderate amounts of phosphate grains, black when fresh but colored red to orange by iron oxides in weathered exposures. Occasionally, calcite and dolomite are major cementing phases. Optically continuous terminated overgrowths are strongly developed as the top St. Peter contact is approached. Unique to some exposures of the top

St. Peter is a texture where sand grains on freshly broken surfaces appear to be dimpled where once in contact with surrounding grains. When viewed in thin section, samples with this texture show a moderate amount of pressure solution where adjacent quartz grains have indented into one another.

The rest of the Tonti Member is composed of tan to white to orange to red, fine- to coarse-grained quartz sandstone. Most exposures are thick- to massively-bedded with lesser low angle cross bedding, and thin planar bedding. Optically continuous terminated quartz overgrowths are variably developed, imparting different degrees of cementation and giving the sandstone its characteristic sparkly appearance in sunlight. Lumpy clusters of purple goethite after pyrite and marcasite cement concretions, a few mm to several cm across are present throughout the Tonti at low abundance. Euhedral authigenic potassium feldspar crystals are sparsely present in pore spaces throughout. The Tonti Member forms spectacular near vertical cliffs of sandstone in the Highland West Quadrangle along the Blue River valley. Where examined, these cliffs are capped by benches of the iron oxide cemented horizon at the top of the St. Peter, or quartzitic horizons lower down in the Tonti where terminated overgrowths have interlocked to produce an extremely hard and resistant rock. Where well-exposed, the upper 40 ft (12 m) of the Tonti Member commonly contains a 10–30 ft (3–9 m) package of beds with vertical and horizontal burrow trail networks partially cemented by brown and tan limonite. Within this sequence are 7.5–19.5 in. (20–50 cm) brown to tan limonite cemented sandstone beds with abundant 1–2 mm thick limonitic siltstone laminations.

The St. Peter formation blankets a deeply incised weathering surface developed after deposition of the Prairie du Chien Group, resulting in an unconformity of significant relief widely recognized in the upper Midwest (Strong, 1877; Trowbridge, 1917; Agnew et al., 1953; Heyl and others, 1959; Palmquist, 1969; Davis, 1971; Mai and Dott, 1985). In cross section, the southern part of the Highland East and Highland West quadrangles contain two ~3-km-wide (2 mi) paleovalley networks along the approximate axes of the modern Blue River and Otter Creek valleys (see map). In both paleovalley systems, the St. Peter was mapped continuing down to or below the top of the Jordan Formation (**Ꞓj** on map), with the Prairie Du Chien Group completely removed. In the central part of the quadrangles between these two paleovalleys networks, the St. Peter is relatively thin (50–60 ft or 15–18 m) except where cut by steep, smaller paleovalleys that may represent tributaries feeding into the larger drainages.

Photo 1. **Large goethite after iron sulfide clusters at the top of St. Peter Formation. Pen for scale.**

Readstown Member

The Readstown Member (not exposed in map area) forms the base of the St. Peter Formation and is deposited directly on the unconformity surface. It consists of fine-grained sandstone and red to green shale, commonly containing abundant chert and blocks of white, chalky, silicified dolomite. Where investigated in the field, paleovalleys commonly localize abundant angular float of silicified dolomite, and white and gray chert up to 1.6 ft (50 cm) in diameter. This may represent eroded colluvium deposits in the Readstown Member where the paleotopography is steep. Where the St. Peter is relatively thin (≤100 ft or 30 m thick), well logs show that the Readstown is typically 0–10 ft (0–3 m) thick, which can be much thicker within filled paleovalleys and depressions. Shallow hand auger borings near the top of the Prairie du Chien Group commonly encountered distinctive clay deposits below Pleistocene loess (**Qlc** on map) that are regarded as a weathered presentation of the Readstown Member. Clay is light-gray to reddish orange, with sparse slightly sandy horizons, and pebbles of white to gray chert, which increase in abundance as the top of the Prairie du Chien is approached. Clay representing weathered Readstown characteristically contains wavy horizons of fine-grained purple goethite, as well as abundant, porous, patchy areas that are strongly colored by orange to red iron oxide. The top of the Prairie du Chien Group is marked by the inability of the hand auger to penetrate further. The deepest samples consist of large angular chunks of variably silicified dolomite, as well as numerous chert pebbles accompanied by disaggregated dolomitic sand.

Prairie du Chien Group (Opc on map): 0–225 ft (0–69 m) thick

Regionally, the Prairie du Chien Group has been divided into the upper Shakopee and lower Oneota Dolomites separated by the quartzose New Richmond Sandstone (e.g. Smith and others, 1993). Within the Highland quadrangles, a discrete sandstone layer representing the New Richmond was not seen in outcrop. The complex lateral facies variations within the Prairie du Chien lead to difficulty differentiating the two dolomitic formations with any confidence. A similar conclusion was reached by Agnew and others (1953) after logging a series of closely-spaced boreholes west of the Village of Highland that penetrated some or all of the Prairie du Chien Group.

The dominant texture of the Prairie du Chien in outcrop is a vuggy, variably cherty, gray and tan, fine- to coarse-grained, thick- to massive-bedded crystalline dolomite. Contains sparse thin to medium beds of dolomitic sandstone, and green to light-gray dolomitic siltstone. Coloration varies sharply between adjacent beds and ranges from dominantly gray with tan patches, to tan with gray patches. Areas with tan coloration often appear to replace gray dolomite and are observed in thin section to be a network of trails 0.05–0.2 in. (1–5 mm) in diameter. These trails disrupt internal layering and are reminiscent of burrows. The tan areas are coarser-grained and slightly porous with coloration due to very fine-grained tan-orange limonite. Additionally, fine-grained purple goethite is disseminated within dolomite grains and in open spaces between coarse dolomite crystals.

Many exposures, especially those in the lower 150 ft (45 m) of the Prairie du Chien contain a 0.3 in.–6.5-ft-thick (0.1 cm–2 m) bed of gray, fine-grained, very dense and hard, variably silicified, finely laminated crystalline dolomite with stromatolitic domes or digitate colonies. At a 60 ft (18 m) quarry face in the southern part of the Highland West quadrangle (43°0′8.8N, 90°26′58.5″W), these distinctive layers pinch and swell irregularly along strike and are seen stacked every 10–20 ft (3–6 m) separated by gray and tan crystalline dolomite. At this locality numerous large stromatolitic domes 1.5-3 ft (0.5–1 m) in diameter are seen to weather out of these layers. Characteristically, this lithology localizes dense fracturing relative to adjacent layers. At its most extreme, the fractured stromatolitic horizons form loose recemented breccias with abundant open

Photo 2. **Cave in the Prairie du Chien Group. Map board for scale.**

space, which ranges from small vugs to traversable caverns (see photo 2). These open spaces are variably filled by reddish to orange clay. Highly fractured, or brecciated layers, also localize mineralization, including chert, drusy quartz, calcite, and sulfides such as marcasite and galena. Despite being intensely fractured, these horizons are quite resistant and form steep slopes or cliffs with high outcrop potential. As a result, individual stromatolitic horizons were able to be traced laterally for up to 0.6 mi (1 km) among closely spaced outcrops.

At another quarry (43°4′59.3″N, 90°27′43″W) 60 ft (18 m) of the Prairie du Chien Group is exposed. Here, 40 ft (12 m) of typical massive- to thick-bedded, cherty, vuggy crystalline dolomite is underlain by a minimum of 13 ft (4 m) of laminated, thinly-bedded stromatolitic dolomite, which lacks chert, with abundant dolomitic siltstone layers up to ⅖ in. (1 cm) thick. At this location the contact between laminated dolomite and overlying massive dolomite localizes a 6.5 ft (2 m) thick layer of extensive brecciation and mineralization. The lower laminated unit at this location closely resembles the fractured and brecciated layers seen elsewhere. However, it is less hard and dense, and, aside from the contact zone, is no more fractured than the overlying massive- to thick-bedded dolomite.

The base of the Prairie du Chien Group was not seen in outcrop but from well logs is marked by 5–10 ft (1.5–3 m) of oolitic, sandy dolomite.

Jordan Formation (Ꞓj on map): 40–80 ft (12–24 m) thick

Variable unit with complex series of lithologies exposed over the two quadrangles. Upper 15–20 ft (4.5–6 m) in the northern part of Highland East includes distinctive beds of white, vuggy, fine- to medium-grained 4–11 in. (10–30 cm) cross bedded quartzite. Sandstone is almost entirely cemented by optically continuous terminated quartz overgrowths partially to completely interlocked to form a quartzitic fabric. Commonly present with quartzite is tan to orange to red, thick- to massive-bedded, fine- to coarse-grained friable sandstone with abundant cm-scale flat pebbles of fine- to very fine-grained, resistant, silica cemented sandstone/siltstone. These two lithologies are interlayered in packages several feet thick with sharp boundaries marking the transition between the two units. Lenses 0.4–2.75 in. (1–7 cm) thick of uncemented sandstone with and without silicified flat pebbles are commonly present within cross stratified quartzite. Sparse lenses up to 1.2 in. (3 cm) thick of fine- to medium-grained quartzitic sandstone are also present within the pebble conglomerate unit. The distinctive presentation of the top Jordan as a white quartzitic sandstone is known as a “clinkstone” and has been recognized at several other localities in southern Wisconsin (Twenhofel and Thwaites, 1919; Clayton and Attig, 1990).

A diverse set of lithologies make up the Jordan either below the quartzitic sandstone or interlayered for its full thickness where the upper quartzite is absent. These include: tan to white, fine- to medium-grained, friable, thick-bedded cross stratified sandstone; pink, very fine- to coarse-grained, bioturbated, thin-bedded dolomitic sandstone and sandy dolomite; and white to tan, fine- to medium-grained, variably bioturbated, intraclastic, thin to medium bedded cross stratified sandstone with both uncemented and dolomite-cemented beds. All of these lithologies are typically seen within the total thickness of the Jordan, in a given area of semi-continuous exposure, but their relative proportions and positions within the Jordan were not able to be correlated at the quadrangle scale. The pink sandy dolomite/dolomitic sandstone facies is exposed in the upper 40 ft (12 m) of the Jordan in a discontinuous belt at the northern margin of the Highland East quadrangle (see map).

The basal contact of the Jordan Formation is gradational with the underlying St. Lawrence Formation and is marked by a gradual decrease in bedding thickness, grain size, and degree of roundness. The final transition between the two formations is marked by the first appearance of dolomitic siltstone interbeds.

St. Lawrence Formation (Ꞓsl on map): 50–100 ft (15–30 m) thick

Most exposures in the upper part of the formation are composed of alternating thin-bedded white to tan, subangular, very fine- to fine-grained, and fine- to medium-grained cross bedded sandstones separated by ⅕-¾ in. (0.5–2 cm) beds of light green-tan dolomitic siltstone. Dolomitic siltstone layers vary from intact to thoroughly bioturbated and mixed with surrounding sandstone. In the northwestern part of the map, the exposed St. Lawrence is a light tan-buff cross bedded sandy dolomite with a dominantly fine-medium quartz sand fraction accompanied by isolated coarse grains. In this area, the dolomitic St. Lawrence either continues until the base of the formation or is underlain by thin-bedded sandstones and dolomitic siltstones typical of the St. Lawrence elsewhere. The only full geologic logs through the entire St. Lawrence near the mapping area are in deep boreholes drilled for the Highland and Montfort municipal wells. At the Highland well, the St. Lawrence is 80 ft (25 m) of slightly sandy crystalline dolomite that becomes glauconitic near the basal contact with the Tunnel City Group. In the Montfort well, the St. Lawrence consists of 100 ft (30 m) of sandy dolomite. Total thickness of the Trempealeau Group, composed of the Jordan and St. Lawrence Formations, varies from 120–160 ft (37–49 m).

Tunnel City Group (€tc on map): 100 ft (30 m) thick

The Tunnel City Group is poorly exposed in the Highland quadrangles and was only examined in one 20-ft-thick (6 m) outcrop of the upper part of the group in the northeastern part of the mapped area. At that location, the Tunnel City consists of very thinly-bedded, highly bioturbated, white and tan, shaly, dolomitic, glauconitic, fine-grained sandstone. Alternating beds of friable uncemented sandstone and slightly resistant dolomite-cemented sandstone are separated by tan dolomitic shale partings a few mm-thick. Bioturbation commonly disrupts shaly partings and mixes it into underlying sandstone beds. This sequence is interrupted every 2–3 ft (0.6–1 m) by 2–4 in. (5–10 cm) beds of white and green, cross bedded, medium-grained, glauconitic sandstone with conspicuously less bioturbation than the very thinly bedded sequences. These sandstone beds have basal scour surfaces with abundant flat pebbles ripped up from the underlying thinly bedded sequence. Where the entire thickness of the Tunnel City Group was intersected in the Highland and Montfort Municipal wells, it is composed of 100 ft (30 m) of gray-green, glauconitic, dolomitic sandstone and shale, before transitioning into sandstones of the underlying Elk Mound Group.

Structure

Folds

The structural geology of the Highland East and West quadrangles is primarily interpreted from examining the geometry of the base Platteville Formation (**Op** on map). This surface was chosen due to its extensive exposure in outcrop and its physiographic expression as a steep scarp where the underlying Ancell Group (**Oa** on map) is exposed. The base Platteville surface in the Highland quadrangles defines an overall gentle dip to the south of 12 ft (3.5 m) per mile overprinted by folds with E-W and N-S to NNE-SSW trends (fig. 2). Folds are generally broad features with amplitudes of 20–40 ft (6–12 m) except for one large anticline–syncline pair in the southwestern Highland West quadrangle which localizes 120 ft (36.5 m) of structural relief (fig. 2).

A pronounced feature of the base Platteville surface in the Highland quadrangles are a series of synclines which stairstep east and north between structural highs, before a lack of preserved Platteville in the Otter Creek Valley precludes any further detailed interpretation (fig. 2, see fig. 1b for location). These synclines also contain many small elliptical pit zones where the base of the Platteville drops steeply for an additional 40–80 ft (12–25 m) below the trough of the rest of the syncline. Pit zones are concentrated over local areas where the St. Peter sandstone (**Oa** on map) is thicker and much, or all, of the Prairie du Chien Group (**Opc** on map) is absent. This most commonly forms at the intersection of St. Peter paleovalleys (see the map) and the synclines oriented at N80°E and N20°E. Elliptical pit zones are also present to the south in the far northern part of the Monfort and Linden quadrangles (Carlson, 1961), strongly resembling the features mapped in the Highland quadrangles in both areal extent and amplitude.

Because of the relief along the unconformity marking the base of the St. Peter, the next surface conducive to structural interpretation is the top of the Jordan Formation (**€j** on map) at its conformable contact with the Prairie du Chien Group (**Opc** on map). The exposure of this contact is limited, but it appears that many of the fold zones well defined by the base of the Platteville are not apparent in the top of the Jordan. The top of the Jordan instead appears to follow an approximately 13 ft (4 m) per mile southern dip corrugated by tentative NE-SW folds of 10–30 ft (3–10 m) amplitude.

Deformation bands

Deformation bands are a widespread feature of the St. Peter Formation forming 0.05–0.1 in. (1–3 mm) wide, dominantly steep and lesser inclined/horizontal single bands and swarms of bands. In outcrops, deformation bands typically stand out on weathered surfaces, being slightly more resistant and commonly bleached, which contrasts with the surrounding sandstone. Porosity is greatly reduced within deformation bands, with compaction producing pronounced pressure solution relative to the surrounding sandstone (see photo 3). Some grains within deformation bands are shattered, and many grains show a greater degree of undulose extinction under cross-polarized light. No evidence of shear movement was seen in deformation bands, and compaction and crushing features appear to be produced by compression normal to the bands. Many deformation bands also contain patchy areas along them cemented by purple goethite after iron sulfides.

Large fold zones localize extremely dense deformation banding in the St. Peter Formation comprising 10–50% of the total rock volume, compared to 1–10% in smaller fold zones, and 1% or less in typical St. Peter exposures (where no significant folding is present). Deformation bands are also concentrated at the top of the St. Peter Formation near the contact with the Glenwood and Platteville Formations. Within the largest fold zone at the southwest corner of the mapping area, the upper 20 ft (6 m) of the St.

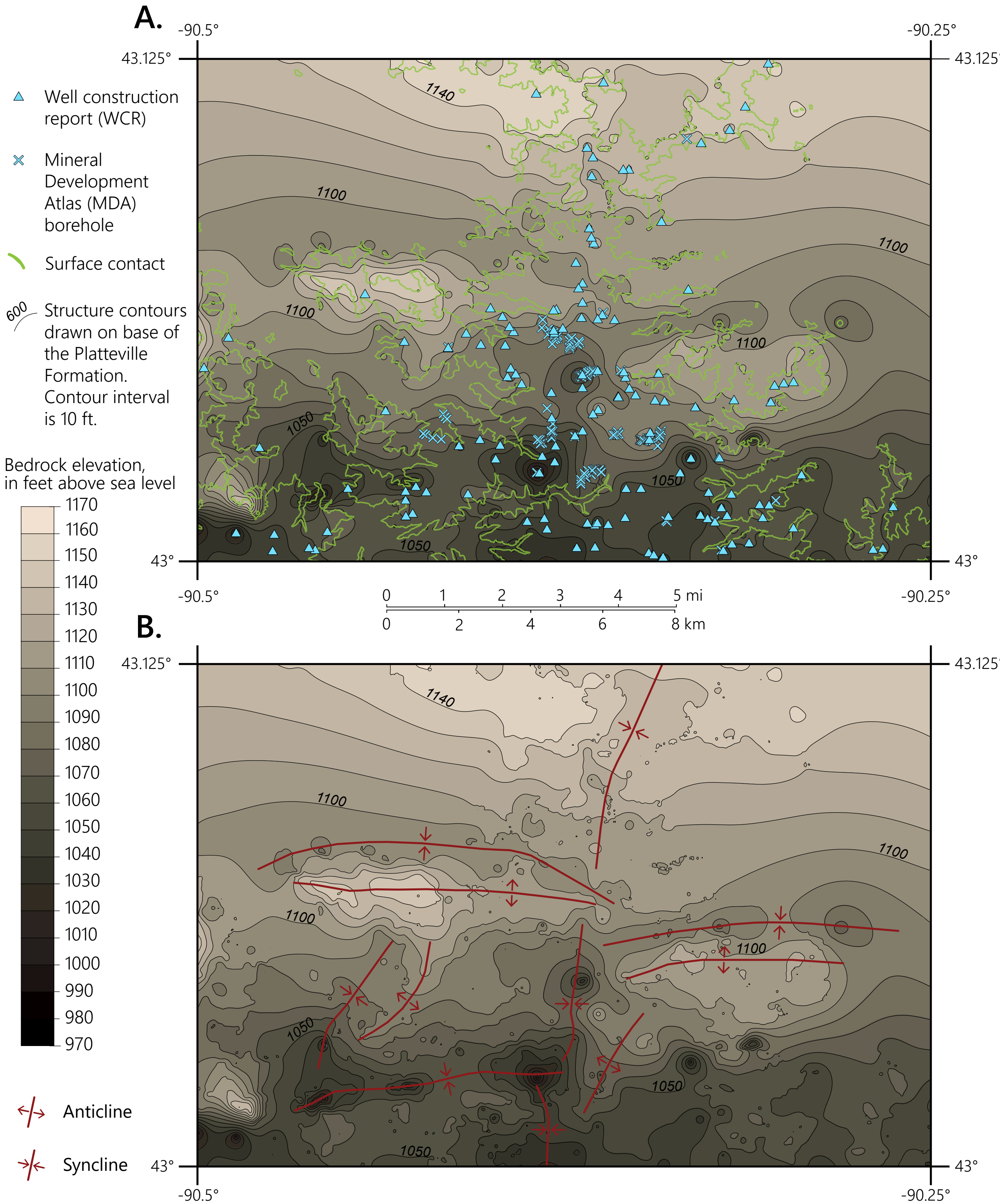

Figure 2. Panel A, structure-contour map for the base of the Platteville Formation in the Highland quadrangles showing sources of data used to interpolate the raster. Surface contacts include both areas where the base Platteville is present and places where the top Ancell Group occurs at the surface. Elevations are in feet above sea level with contours at intervals of 10 ft (3 m). Panel B, structure-contour map for the base of the Platteville Formation with data removed to highlight structural trends. Red lines show interpreted fold axes with arrows denoting synclines and anticlines.

Peter is a hard, well-cemented sandstone cut by a dense network of steep and inclined deformation bands. Below this the St. Peter is virtually uncemented and cut by only isolated swarms of deformation bands 2–4 in. (5–10 cm) across. Additionally, many other exposures of the top few feet of the St. Peter—even where not affected by dense deformation banding—localize a moderate amount of pressure solution (seen in thin section), which decreases rapidly with depth below the base Platteville.

Despite deformation band orientations (fig. 3) being highly variable between localities, there are several consistencies over the Highland quadrangles. E-W and N-S orientations are dominant among steeply dipping bands with lesser NE-SW and NW-SE orientations common. Moderately to gently inclined deformation bands have a complex range in orientations, but interestingly have preferred dips to the west, south, and north with few inclined bands dipping to the east. A pit feature with 60 ft (18 m) of amplitude and a strike of N75°E is well exposed (41°1′0″N, 90°27′30″W on the map), with steep deformation bands oblique to the structure and clustering in orientation around N75°W.

Deformation bands were only seen at one exposure of Cambrian sandstones in the Highland quadrangles and were not seen in the Jordan Formation, even in locations where continuous exposure reveals their presence in directly overlying St. Peter Formation of similar lithology. The lack of deformation bands within Cambrian sandstones could be due to unequal partitioning of strain over the stratigraphic section but this relationship is unclear. The most numerous exposures of Cambrian sandstones occur in the northern half of the map area, which has experienced less deformation, as indicated by measurements collected on the base Platteville surface (fig. 2).

Photo 3. **Deformation band swarm. Six-inch ruler for scale.**

Joints

Joints are a ubiquitous feature of bedrock units that outcrop in the Highland quadrangles and are consistent in orientation over the exposed stratigraphic section. Steep conjugate joint sets striking NE-SW and NW-SE are most common with many conjugate sets also striking towards E-W and N-S. Moderately to gently inclined joints with dips <70° are almost exclusively confined to the St. Peter Formation (**Oa** on map) where they commonly accompany steeply dipping sets. Joint abundance as number of fractures per meter was estimated for 230 measurements including all bedrock units except the Tunnel City Group. Joints in an individual set are typically spaced 5–15 ft (1.5–5 m) apart with joint spacing generally decreasing upwards in the stratigraphic section. Joints specifically in outcrops of Cambrian sandstone are spaced much more widely than those in the Prairie du Chien Group, St. Peter Formation, and the Galena, Decorah, and Platteville Formations (the latter three are referred to as the Sinnipee Group in this discussion). A conspicuous feature of joints in the Sinnipee Group, and to a lesser extent the St. Peter Formation, are discrete damage zones 10s of cm to several ms wide where fractures are much more abundant ranging from 20–300/m. Despite intense fracturing within these damage zones, they do not appear to localize any discernible vertical offset. Most damage zones are N-S to NW-SE oriented with fewer oriented E-W to NE-SW. Conversely, a feature exclusive to E-W and NE-SW joint sets are fissure zones where one or several fractures in the space of an outcrop localizes significantly more open space than others. Fissures are especially well developed in the Galena Formation, creating voids 10s of cm wide with surrounding beds commonly sagging slightly into them. In the Sinnipee Group as a whole, and especially in the Galena Formation, fissures are typically filled with a mixture of red clay and disaggregated dolomitic sand.

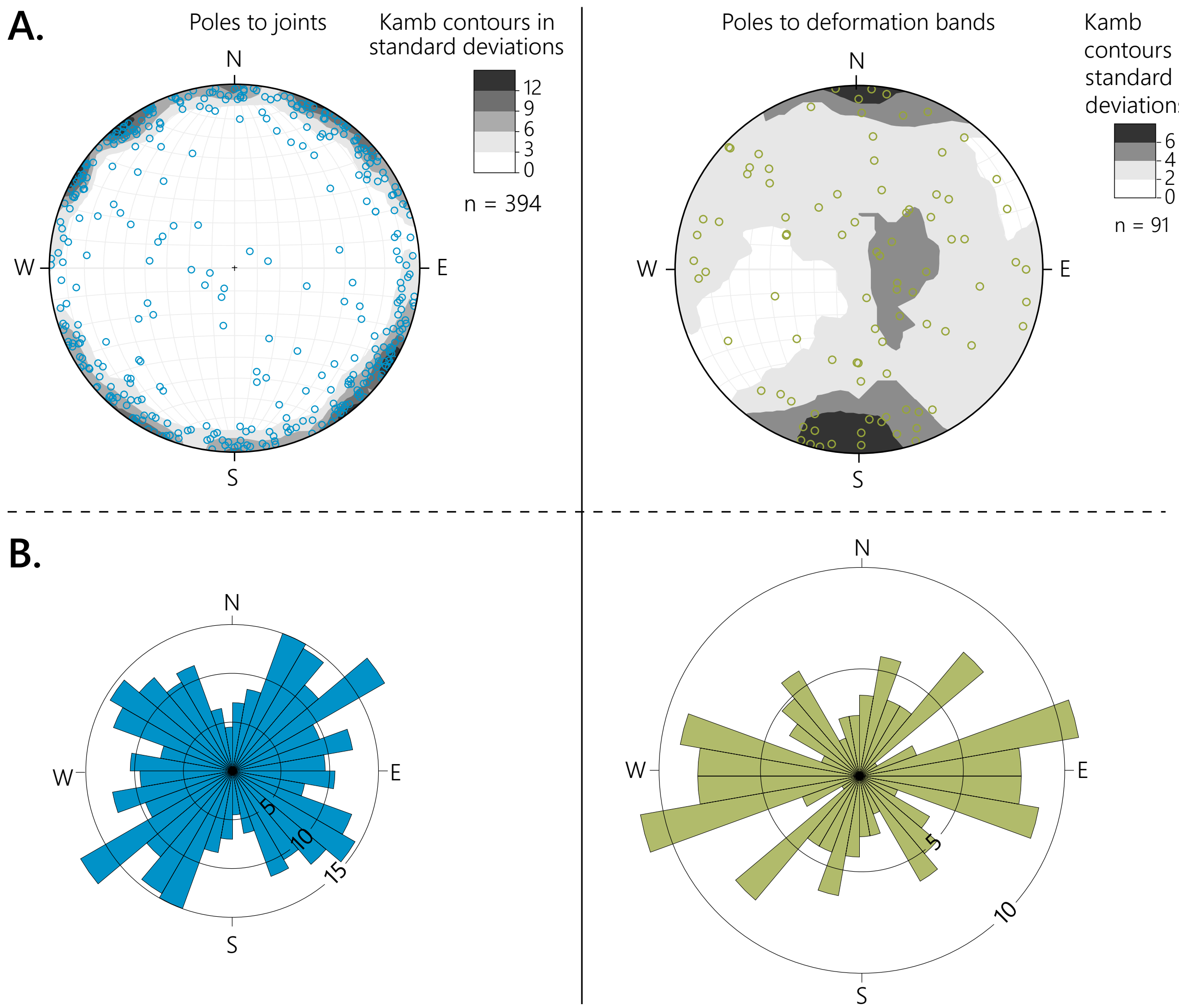

Figure 3. Panel A, lower hemisphere equal area projections of contoured poles to planes for joint (left) and deformation band (right) measurements from the Highland quadrangles. Contouring was performed in Stereonet 10.0 according to the Kamb method at a spacing interval of 3 standard deviations for joints and 2 standard deviations for deformation bands. Panel B, rose diagrams of joint (left) and deformation band (right) orientations at a bin size of 10°. The length of each bin indicates the number of measurements.

Mineralization

Lead and zinc mineralization has long been recognized in the area covered by the Highland quadrangles with active mining taking place from 1827 to 1931 (Heyl and others, 1959). Several former mines were visited, with mineralized samples commonly present at the surface in many dump piles and prospect pits, despite the long lapse of time since mining activity took place. No open mine workings were accessible for direct investigation, but detailed first-hand descriptions of the deposits and accounts of the various operations when they were actively producing are found in several older references (Percival, 1856; Whitney, 1862; Chamberlin, 1882; Strong, 1877; Bain, 1906).

Lead-zinc mineralization hosted by the Sinnipee Group in the district forms two prominent ENE mineralized trends or "ranges". These "ranges" are in the southern third of the quadrangles with an additional area of mineralization present just north of the village of Highland in the central part of the quadrangles (see map; fig. 4). From the descriptions of Heyl and others (1959) and quantitative assay data from MDA boreholes, ore bodies have estimated grades of 4–8% Zn and 0.25–4% Pb and are noted for having higher lead grades and less iron sulfide than ore from other areas of the UMV District. Most of the mines in the area were small and developed in ore-bodies, estimated from the dimensions described by Heyl and others (1959), to be ≤50,000 tons. Many clusters of these

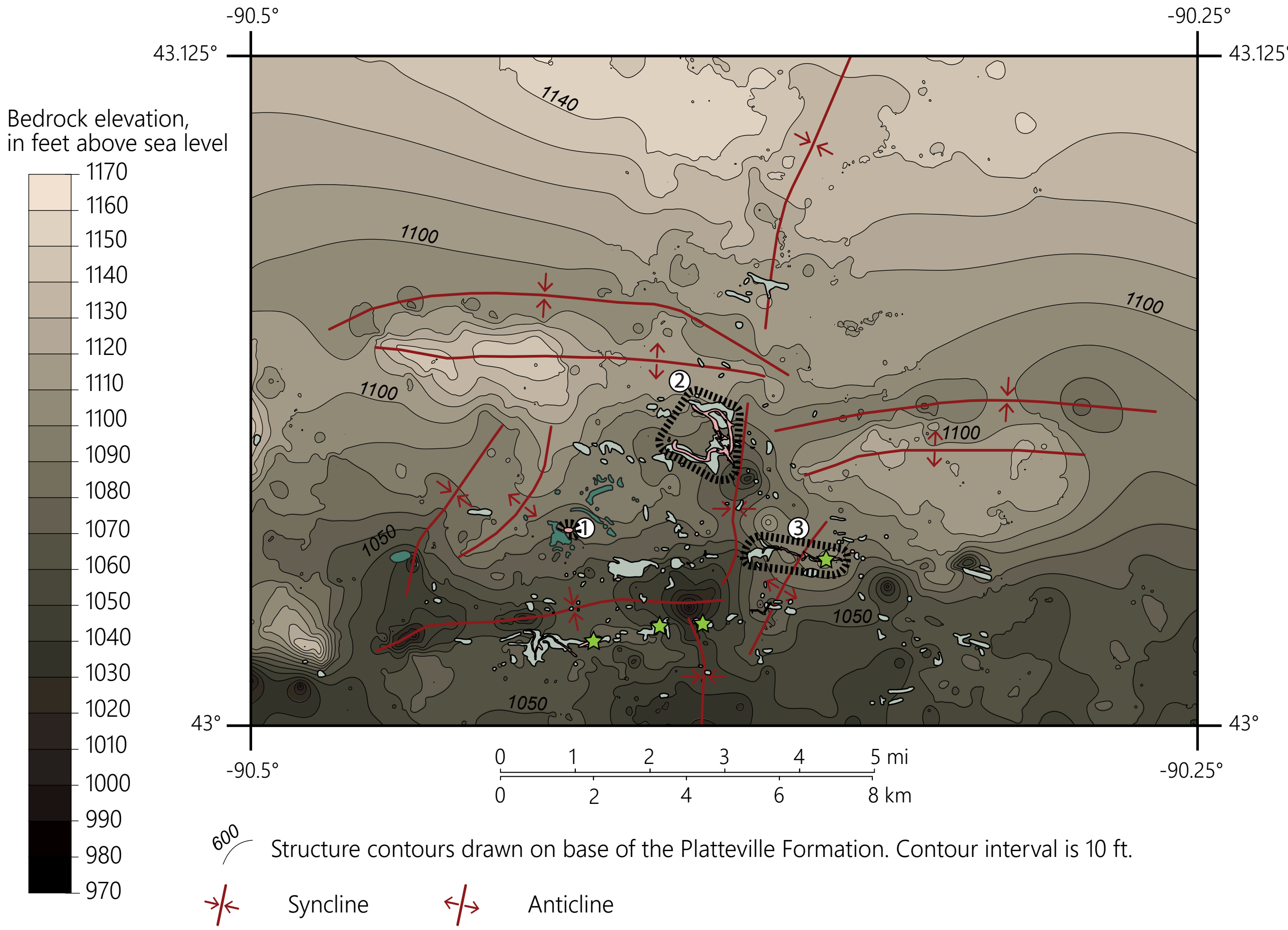

Figure 4. **Structure-contour map for the base of the Platteville Formation with interpreted fold axes as in Figure 2B. Colored polygons indicate Mineral Development Atlas (digitized by Pepp and others, 2019) surface diggings from the Prairie du Chien group (dark green), surface diggings from the Sinnipee Group (gray), and underground diggings (pink). Stars indicate areas of copper mineralization. Dashed black lines enclose mine areas discussed in text: 1: Ohlerking Mine, 2: Highland Mines, 3: Clark Mines.**

smaller mines are closely spaced along the mineralized trends and are likely to have worked semi-continuous ore bodies. The two largest mining centers are referred to by Heyl and others (1959) as the Clark Mines and the Highland mines, which produced approximately 400,000 tons and 750,000–1,000,000 tons of ore, respectively.

Most known mineralization is confined to flanks of the synclines which stairstep across the southern half of the quadrangles, with the larger ore bodies found close to pit zones in the base of the Platteville that drop below the troughs of the synclines (fig. 4). The Sinnipee Group directly within pit zones is not well-exposed within the Highland quadrangles, but one identified by Carlson (1961) is well exposed in a quarry in the northern Montfort quadrangle (42°58′49″N 90°22′17″W). Field investigations revealed sub-economic sulfide mineralization in the form of small sphalerite veins. These veins are hosted within horizontal and inclined fracture systems filled with red clay and disaggregated dolomitic sand in the Decorah Formation (**Od** on map) near its upper contact with the Galena (**Og** on map). The structural setting of the large Highland and Clark mines is distinctive; they lie on gently sloping ramps defined by the base Platteville (fig 4) below the crest of adjacent anticlines. An additional constraint on known mineralization is its presence exclusively where the St. Peter is relatively thin (40–60 ft or 1220 m thick, see map), primarily in the south-central part of the map area.

The primary ore horizon in the Highland area is from the Quimbys Mill Member of the Platteville Formation (**Op** on map) through the Spechts Ferry and Guttenberg Members of the Decorah Formation (**Od** on map), with lesser mineralization extending into the Ion member. From mine descriptions and MDA assay data, the Guttenberg Member—referred to as “brown rock” or “oil rock” in local miners terminology—appears to have been the locus of mineralization and the principal target of most mines in the area. Sphalerite and galena are the primary ore minerals accompanied by variable amounts of iron sulfides, with marcasite predominating over pyrite. Chalcopyrite is an additional constituent of the ore in several areas, present over restricted lateral extents either along a continuous ore body or within a mineralized trend (fig. 4). Hypogene sulfides are weathered in portions of deposits lying above the water table, with sphalerite converted to smithsonite, or "dry bone", and chalcopyrite to various copper carbonates, copper silicates, chalcocite, and mixed Fe-Cu oxides.

Sulfide mineralization occurs within steep, inclined, and horizontal fracture networks referred to as pitches and flats, or as stratabound sheets dotted by numerous disseminated clusters of sphalerite and galena (Percival, 1856; Whitney, 1862; Strong, 1877; Bain, 1906; Heyl and others, 1959). Disseminated ore typically occurs within 1–2 ft (30–60 cm) thick shaly horizons of the Quimbys Mill, Guttenberg, and Ion Members, or within the Spechts Ferry. Mineralized pitches and flats form networks of banded veins a few inches to 1 ft (30 cm) thick filled with sphalerite, galena and iron sulfides. A distinct paragenesis to the banded vein fillings was noted by Bain (1906) in the major deposits just north of the Village of Highland, where iron sulfides coat altered wall rock followed by layers of sphalerite, then octahedral galena, then a thin additional layer of sphalerite, and finally marcasite as the last mineral deposited in the middle of the veins. Many ore deposits contain several stacked mineralized horizons worked by separate mine levels, commonly with different combinations of pitch and flat hosted and disseminated mineralization.

The Prairie du Chien Group (**Opc** on map) forms a second mineralized zone in the Highland district which is distinctive for being one of only two localities in the entire UMV lead-zinc district where it was worked at a large scale (Heyl and others, 1959). In the Highland area lead was mined from the Prairie du Chien Group among a series of surface diggings in the upper tributaries of the Blue River and one underground operation known as the Ohlerking Mine (fig. 4). Mineralization is present in voids and cavern networks mostly filled by orange to red clay with disseminated clusters of galena crystals embedded within the clay deposits and weathered wall rock. Some of these clusters were quite massive, with Percival (1856) reporting examples commonly in the range of 100 lbs (45 kg), and one purportedly weighing around 3000 lbs (1360 kg). Samples found on dump piles near the former Ohlerking Mine shaft are variably silicified dolomite with galena clusters occurring in the center of cavities lined by banded layers of fine terminated quartz. Descriptions of the Ohlerking Mine by Percival (1856), Whitney (1862), and Chamberlin (1882), combined with an exposure of the Prairie du Chien Group examined in a nearby quarry, indicate lead mineralization is hosted by features identical to the vugs and numerous clay filled open spaces seen widely in the Prairie du Chien Group (see unit descriptions). The structural setting of the area worked for lead in the Prairie du Chien Group is similar to the Highland Mines to the northeast: on the flank of a syncline occupying a gently-sloping ramp up to the crest of the adjacent anticline.

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Supplemental material

The following material are available for download at https://doi.org/10.54915/xqaf2637:

Map: Geologic map

A map (.pdf format) of the geology of the Highland 7.5-minute quadrangles.

Dataset 1: GIS data

A geodatabase (.gdb) including bedrock elevation contour, map unit contacts, and other geologic data.

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