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Controls on the Stratiform Copper Mineralization in the Western Syncline, Upper Peninsula, Michigan

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Abstract: The Western Syncline hosts reduced-facies, or Kupferschiefer-type, sedimentary rock-hosted stratiform Cu deposits (SSC) in the lowermost meters of the Nonesuch Formation, which is part of a thick section of clastic sedimentary rocks that comprise the upper fill of the Mesoproterozoic Midcontinent Rift of North America. Located in the Porcupine Mountains Cu district in Upper Peninsula, Michigan, these blind deposits were discovered in 1956, but are not yet developed, although recent renewed interest may result in near-term production. The deposits are distinguished by their relatively undeformed nature and lack of superposed hydrothermal events. Prior to lithification, chalcocite mineralization replaced diagenetic pyrite within two discrete tabular, albeit discontinuous, potential orebodies referred to as the lower Cu-bearing sequence (LCBS) and the upper Cu-bearing sequence (UCBS). The Top Cu Zone transgresses lithologic boundaries, suggesting that a limited volume of Cu-bearing fluids moved vertically upwards through the unlithified stratigraphy, since reductant pyritic rocks above this zone are essentially barren of Cu. The total Cu inventory that has a reasonable expectation of economic extraction is 3678 M lbs. of Cu with 15.3 M oz. of byproduct Ag. When a cutoff grade of 0.9% Cu over a minimum thickness of 2 m is applied to justify an underground room-and-pillar mine, the LCBS and UCBS are not continuous over the Western Syncline. Sedimentology is the first-order control of potential ore and its continuity; dark-gray shales and siltstones deposited under low-energy, anoxic conditions are preferred host rocks, whose thickness must be >2 m to be potential ore since host-rock thickness determines economic viability of extraction. Furthermore, stratigraphy influences the time constraints on mineralization as the lithification process impedes vertical permeability and thus the flow of Cu-bearing fluids upward through the unlithified section. Syn-sedimentary tectonic movements, likely along pre-existing buried faults, are a third-order control as the thickness of host rocks is enhanced under such conditions. Therefore, an understanding of the depositional and tectonic history throughout the Western Syncline is fundamental to understanding the limits of possible economic exploitation and to optimizing ore extraction.

Keywords: stratiform copper; chalcocite; pyrite; anoxic; orebodies; economic extraction

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1. Introduction

Sedimentary rock-hosted stratiform Cu deposits (SSC) account for between 15% and 25% of known Cu resources and almost 15% of the world's Cu production, approximately 80% of which originates from deposits in the Permian Kupferschiefer and Neoproterozoic Katangan basins located in Europe and south-central Africa, respectively [1–3]. Initially, these deposits formed along basin margins after sedimentation, but before lithification, because of basin-scale fluid flow driven by gravity and/or compaction whereby Cu in underlying red-bed sediments and/or volcanics was scavenged and converted to an aqueous phase. The Cu-bearing fluids were transported upwards through areas where reductants sequestered the aqueous Cu, and given that sulfur, primarily derived from organic matter

in marine or lacustrine waters, was present in the unlithified sediments, Cu sulfides formed. Later hydrothermal and/or deformational events commonly enhanced Cu grades and these processes upgraded the pre-lithification mineralization [2].

The Western Syncline, located in the Porcupine Mountains Copper District in the southwestern Upper Peninsula, Michigan, USA, hosts Mesoproterozoic SSCs related to the Midcontinent rift system [4,5], where Cu of economic interest is hosted by the lowermost six meters of the siliciclastic Nonesuch Formation [6,7] (Figure 1). The Western Syncline and the nearby White Pine deposits [8–10] are reduced-facies or Kupferschiefer-type SSCs [1]. Importantly, these deposits lack characteristics empirically related to the supergiant Permian and Neoproterozoic deposits, such as voluminous proximal evaporites and synchronous glaciation and mineralization [2] and, at the Western Syncline, essentially no superposition of additional mineralization; in addition, the Western Syncline is not significantly deformed thus rendering it ideal to discern the low-temperature genetic processes that formed this class of deposits. At Copperwood, the highest-grade potential ore deposit within the Western Syncline, the economic importance of sedimentological and stratigraphic analysis was emphasized [7]. The objective of this paper is to further elaborate on this concept and include the other potential orebodies elsewhere in the Western Syncline, referred to as the satellite deposits, in the analysis.

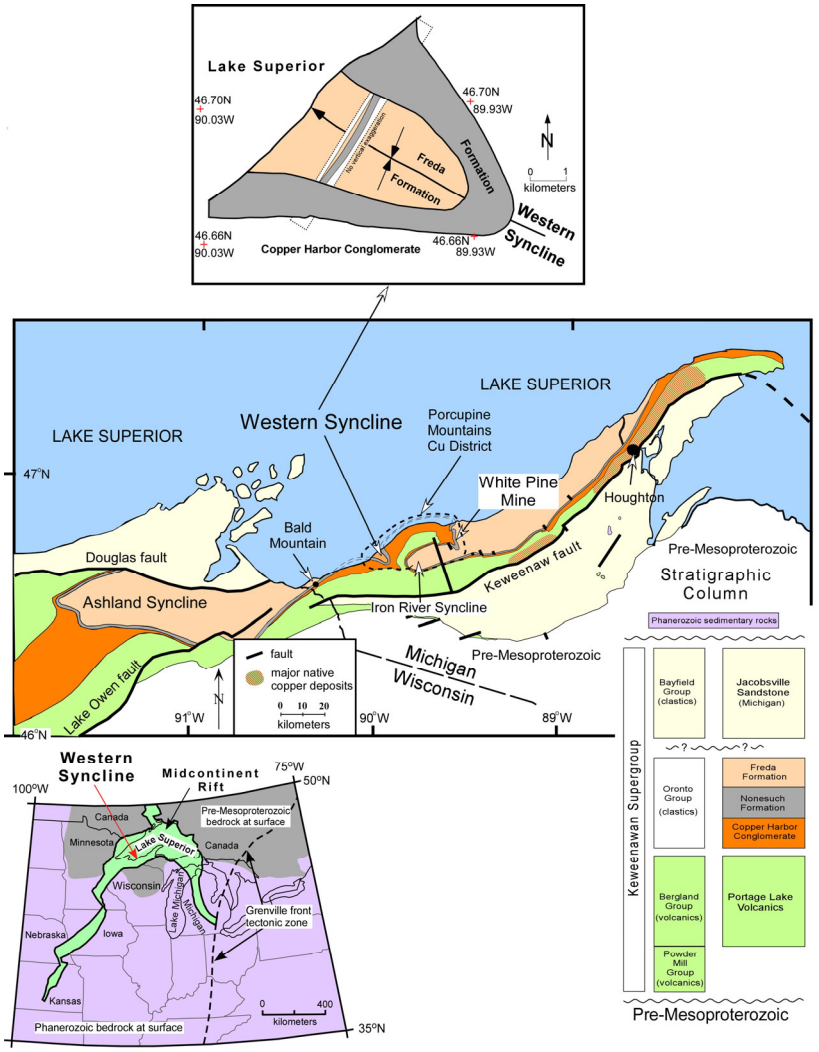

Figure 1. Generalized bedrock geologic setting of the Western Syncline, Upper Peninsula, Michigan.

2. Methods

The Western Syncline database used herein contains information from 161 holes (34,050 m) drilled by United States Metals Refining Company (USMR), a subsidiary of AMAX, during 1956–1957, 23 holes (3998 m) drilled by Bear Creek Mining in 1959, and 140 holes (21,466 m) drilled by Orvana Minerals Corp (OMC) between 2008 and 2013 (Figure 2A). Core from 234 of the 324 diamond drill holes was logged by at least one of the authors; if core was not available, detailed logs were relied on. During 2017 and 2018, the Highland Copper Company Inc. (HCC) drilled 48 holes and 14 wedges for 10,691 m in the Copperwood deposit, but none of these holes were logged or sampled for this study.

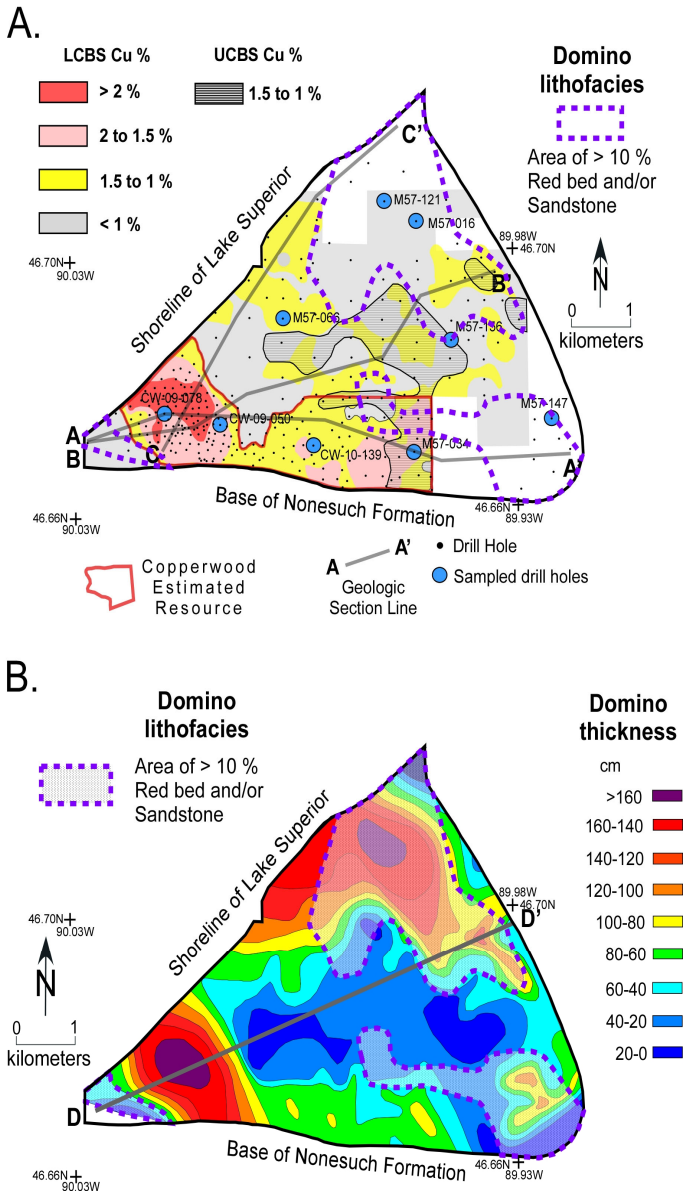

Figure 2. (**A**) Western Syncline base map showing distribution of estimated resources using a 0.9% cutoff and minimum thickness of 2 m (simplified after [11]) and location of drill holes sampled for this study (blue dots). The red line marks the limit of Copperwood potential ore in the LCBS, the yellow areas outside of the red line are potential ore in the satellite LCBS deposits, and the UCBS potential ore is shown by the area outlined in black with horizontal lines, and (**B**) Isopach, which was generated digitally and revised manually, of Domino, the key Cu host rock in the LCBS. The map shows an overlay of areas within the Domino that consist of >10% red beds and/or sandstone layers.

After an agua-regia digestion, 37 elements were analyzed by the ICP method on half-core samples from OMC drill holes, quarter-core from 73 USMR drill holes, and pulps from 21 Bear Creek drill holes; samples with >2000 ppm Cu or 25 ppm Ag were subsequently analyzed by the ICP-OES method after four-acid digestion. Samples from eight of the OMC drill holes were analyzed by a mass spectrometer after a four-acid digestion. The authors participated in the collection of 134 samples from USMR quarter core and pulps from OMC-analyzed half core for major elements using fusion for XRF method and FeO by titration, and total organic carbon (TOC) and sulfur (S) by a carbon/sulfur analyzer with an induction furnace [12]. The S results using the ICP method compared favorably with the results from this method and were, therefore, preferentially used for interpretations. Final TOC values were obtained by subtracting total inorganic carbon from total carbon, which was measured after acidification and oxidation.

3. Geologic Setting

3.1. Regional Geology

The Western Syncline is located on the shore of Lake Superior in Michigan's Upper Peninsula along the southeastern flank of the 2125 km-long Midcontinent rift system of North America (Figure 1). Approximately 30 km of Keweenawan Supergroup volcanics and clastic sediments filled the intracratonic basin between approximately 1.15 and 1.0 Ga [4,5,13,14]. Tholeiitic flood basalts comprise the basal Powder Mill and Bergland Groups. In the latter, intercalated layers of conglomerate and thick tholeiitic basaltic lavas characterize the Portage Lake Volcanics; eruptions occurred between 1094 and 1090 Ma [15]. This phase was followed by passive subsidence and the rift was infilled by the clastic sediments of the Oronto and Bayfield Groups. Regional compression caused by continental collision along the Grenville front occurred between 1.06 and 1.03 Ga [16,17] resulting in the fracturing, folding, and faulting of the rift-related rocks and inversion of graben-bounding normal faults into reverse faults, e.g., Keweenaw fault (Figure 1); the Keweenaw Peninsula native-Cu mineralization, which is hosted by the Portage Lake Volcanics, is temporally related to this event [18,19].

The Oronto Group is well exposed in the far western Upper Peninsula with a maximum thickness of 5.5 km. The basal Copper Harbor Conglomerate (CHC) is a basinward and upward-fining sequence comprised of red-brown conglomerates and sandstones with lesser siltstones; it is interpreted as coalescing fluvial and alluvial fan deposits deposited within 10° N of the equator [20,21], yet pseudomorphed gypsum as well as sedimentological features, especially in the upper 200 m of the formation, indicate deposition in a paralic environment [22]. Maximum exposed thickness is about 2000 m but approaches 8000 m in the middle of Lake Superior [4]. A thin succession of lava flows in the lower half of the formation erupted at approximately 1086 Ma [23].

The Nonesuch Formation conformably overlies the CHC [24]. As much as 240 m of siltstones and shales as well as minor carbonate laminates and sandstones, whose colors are generally black and gray tones with minor red, red-brown, and white shades, comprise the Nonesuch Formation. Based on regional considerations, deposition occurred in a marginal lacustrine or perennial lake environment, although marine incursions were not precluded [24,25]. Alternatively, sedimentological features, e.g., abundant flaser, wavy and pinstripe bedding, and herring-bone and meter-scale hummocky cross bedding, suggest deposition in a marine embayment characterized by tide- and wave-influenced shorelines under evaporitic conditions [22]. The geochemical fingerprint also indicated a marine-influenced estuarine system [26]; characteristic organic biomarkers, e.g., steranes, sulfur-isotope values, and sulfur and carbon abundances, are compatible with these interpretations [27–30]. A Pb-Pb isochron age of 1081 ± 9 Ma was obtained from a thin carbonate laminate [31], referred to as the "Junior" [9], approximately 3 m above the base of the Nonesuch Formation, and samples approximately 30 m above the same basal contact yielded a Re-Os age of 1078 ± 24 Ma [32].

The Freda Formation conformably overlies the Nonesuch Formation and concluded the passive subsidence phase and infilling of the central rift graben. Red-brown, fine- to very fine-grained sandstones, siltstones, and shales, whose maximum exposed thickness exceeds 4000 m, characterize the sequence. The depositional environment is interpreted as fining-upward sequences formed by shallow meandering rivers [33]. Based on regional correlations, an estimated age of this formation is as young as 1.04 Ga [5].

In Michigan, the overlying Jacobsville Formation of the Bayfield Group consists of more than 3000 m of red-brown sandstones with minor siltstones and shales that were deposited in a rift-flanking basin whose western margin is delimited by the Keweenaw Fault. Deposition occurred during and after the Grenvilian compressional event. The maximum age of the uppermost exposed formation is 969 ± 19 Ma [34].

The period between ~1000 Ma and 500 Ma was dominated by erosion that likely exposed the Cu deposits hosted by the Nonesuch Formation and the Portage Lake Volcanics [35]. Deposition of sedimentary rocks resumed during the late Cambrian and continued into the middle Jurassic [36], and most of these rocks were removed from the western Upper Peninsula by Pleistocene glaciers. Unconsolidated glacial sediments overly bedrock.

3.2. Local Geology and Potential Ore

The Western Syncline is a N 60° W-plunging, open fold that is largely buried by unconsolidated glacial sediments (Figure 1). At the synclinal nose, the plunge approaches 7°, flattens to 1° westward, and then steepens to 2.5° near the Lake Superior shoreline [7]. The steepest dip of the basal Nonesuch Formation is about 22° in and around the synclinal nose; along the synclinal limbs, the dip is generally 8° to 12°. No penetrative fabric was recognized.

Chester Ensign, a USMR geologist, initiated field work in the Western Syncline area based on a United States Geological Survey assessment of the White Pine mine and surrounding areas wherein the economic importance of the lowermost 20 m of the Nonesuch Formation was demonstrated [8,9]. Copper oxides outcrop in the basal Nonesuch Formation within the synclinal nose along the Presque Isle River and a subsequent drill program to the west targeted these beds beneath 10 to 40 m of unconsolidated glacial deposits during 1956–1957. The first hole, drilled along the southern synclinal limb, intercepted 0.43 m of 3.01% Cu and 6.6 ppm Ag in the LCBS and 1.36 m of 1.73% Cu and 3.7 ppm Ag in the UCBS (Figure 3). Subsequently, another 160 drill holes and a shallow shaft and drifts along the LCBS in the higher-grade Copperwood area delineated and characterized copper mineralization. In areas, post-mineral reverse faults were recognized, albeit with small net displacements, although later evaluations traced such a fault over 3 km of strike within Copperwood [11]. Notably, Cu mineralization occurred at various stratigraphic levels, the top of which is locally demarcated by lead and cadmium anomalies as well as bornite, chalcopyrite, greenockite, galena, and/or pyrite over a few centimeters, which are overlain by pyrite-only bearing strata; this is the Top Cu Zone, which is equivalent to the Fringe Zone at White Pine [8,9]. In addition, the potential ore hosted by the LCBS and UCBS was not laterally continuous. AMAX did not proceed with development.

Table 1. Cu, TOC, and S values within stratigraphic units at Western Syncline. Abbreviations: t—thickness, n = number of samples, BLS—Black Laminated Sandstone, SS—sandstone, MGS—Massive Gray Limestone, UZV—Upper Zone of Values, UTZ—Upper Transition Zone, CHC—Copper Harbor Conglomerate. Data are summarized from [12].

Unit	n	Min Cu, %	Max Cu, %	Median Cu, %	n	Min TOC, %	Max TOC, %	Median TOC, %	n	Min S, %	Max S, %	Median S, %
Stripey	7	0.003	4.68	0.01	7	0.33	0.66	0.44	7	0.64	1.16	1.00
Upper Shale-BLS	8	0.008	0.66	0.01	7	0.03	0.35	0.13	8	0.03	0.44	0.11
Upper Shale-Tiebel SS	9	0.003	0.11	0.01	7	0.03	0.12	0.07	9	0.03	0.07	0.03
Upper Shale-MGS	18	0.005	1.00	0.22	10	0.03	0.35	0.10	18	0.03	0.24	0.06
Upper Shale-Lower	87	0.001	0.78	0.60	12	0.05	0.14	0.09	87	0.00	0.21	0.06
Upper Shale-UZV	125	0.005	2.83	0.81	7	0.09	0.21	0.13	125	0.03	0.71	0.16

Table 1. *Cont.*

Unit	n	Min Cu, %	Max Cu, %	Median Cu, %	n	Min TOC, %	Max TOC, %	Median TOC, %	n	Min S, %	Max S, %	Median S, %
Brown Massive	67	0.006	0.43	0.04	7	0.03	0.09	0.07	67	0.02	0.12	0.03
Thinly/UTZ	153	0.004	5.17	1.29	12	0.07	0.33	0.20	153	0.02	1.18	0.35
Upper Sandstone	152	0.001	3.70	0.16	8	0.06	0.63	0.15	152	0.01	0.65	0.08
Red Siltstone	7	0.001	0.04	0.00	4	0.02	0.05	0.05	7	0.01	0.03	0.03
Gray Siltstone	39	0.008	1.78	0.14	4	0.08	0.24	0.09	39	0.02	0.45	0.05
Red Laminated	489	0.004	1.61	0.23	8	0.06	0.17	0.11	489	0.01	0.39	0.08
Gray Laminated	515	0.014	3.22	1.12	10	0.06	0.22	0.12	515	0.01	0.75	0.28
Red Massive	182	0.001	1.39	0.24	8	0.06	0.13	0.08	182	0.01	0.35	0.07
Domino	433	0.003	7.30	2.24	10	0.13	0.28	0.17	433	0.01	1.60	0.53
CHC Siltstone	49	0.003	1.14	0.02	2	0.06	0.07	0.07	49	0.01	0.25	0.02
CHC	363	0.000	2.71	0.01	11	0.01	0.27	0.10	363	0.01	0.71	0.03

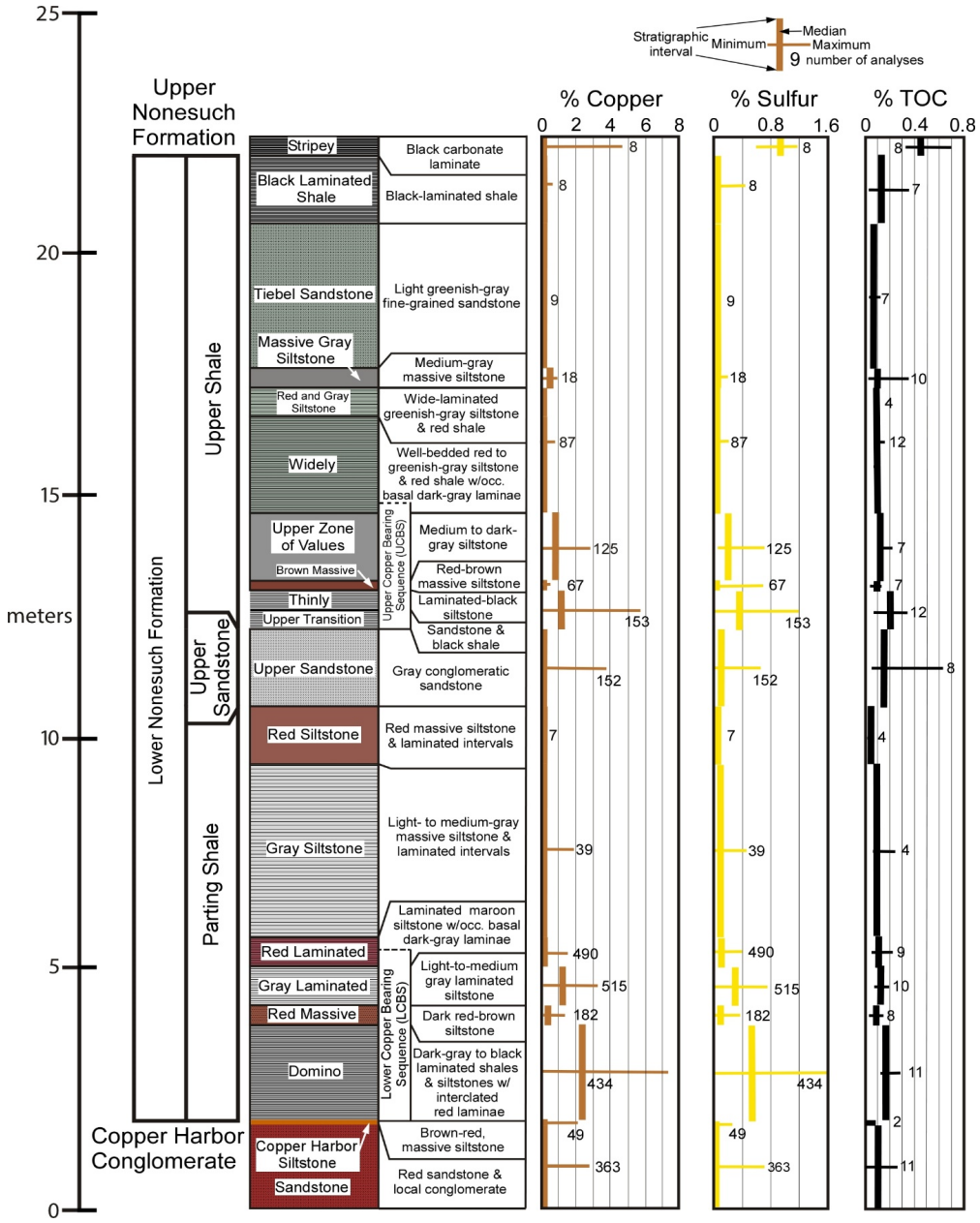

Figure 3. Western Syncline lithostratigraphic column of the lowermost Nonesuch Formation showing sample intervals and abundance of copper (Cu), total organic content (TOC), and sulfur (S). Nomenclature of beds in Upper Shale member are after White Pine [9] and Cu, TOC, and S data are from Table 1.

In 2008, OMC rejuvenated activity with a focus on the higher-grade area, referred to as Copperwood, and in early 2013 all of the necessary permits to proceed with development were granted (Figure 2A) [7]. Amendments to those permits submitted by HCC were granted in 2019 to construct and develop an expanded Copperwood. The proposed underground, room-and-pillar mine is based on an estimated proven and probable reserve, applying a 1.0% cutoff, a minimum mining height of 2.1 m, and 35% overall dilution and 3% ore loss, of 25.7 Mt of 1.45% Cu and 3.91 ppm Ag, or 820 M lbs. Cu, and 3.2 M oz Ag [11]. The measured and indicated estimated resources for Copperwood, applying a 0.9% Cu cutoff grade and a 2 m minimum thickness, are 44.0 Mt of 1.57% Cu and 3.7 ppm Ag in the LCBS and 10.2 Mt of 1.13% Cu and 3.1 ppm Ag in the UCBS, with an estimated inferred resource of 2.3 Mt of 1.12% Cu and 1.2 ppm Ag in the LCBS, for a total of 1838 M lbs. Cu and 6.4 M oz. Ag (Figures 2A and 3). In the proximal satellite deposits, an inferred resource of 49.7 Mt of 1.1% Cu and 2.5 ppm Ag and 27.1 Mt of 1.1% Cu and 5.7 ppm Ag was estimated in the LCBS and UCBS, respectively, for a total of 1840 M lbs. Cu and 8.9 M oz. Ag. Thus, the total Western Syncline Cu inventory that has a reasonable expectation of economic extraction is 3678 M lbs. Cu and 15.3 M oz. Ag [11], which renders it an SSC of moderate size [2].

4. Sedimentology and Stratigraphy at Western Syncline

The lithologic descriptions in this section focus on the lowermost ~20 m of the Nonesuch Formation and the footwall to mineralization, the uppermost CHC. These descriptions complement those that focused on the Copperwood deposit [7] (Figures 3–6).

4.1. Copper Harbor Conglomerate

The uppermost ~10 m of this interval is characterized by 2–5 cm thick fining-upward sequences represented by gray-white arkosic conglomerates and sandstones capped by >30 cm-thick, massive, and finely-laminated red-brown siltstones with local gray siltstones. Both lithologies are characterized by irregular gray colorations and contain numerous calcareous zones as well as occasional gypsum. Median values for TOC and S are 0.10% and 0.03%, respectively, although locally TOC and S values can reach 0.27% and 0.71%, respectively, with the TOC from pyrobitumen and the S most likely as sulfate (Table 1).

The uppermost dark red-brown siltstone is as much as 3 m thick but is typically less than 1 m thick, and it marks an important change to lower-energy conditions that continued into the onset of the overlying Nonesuch Formation deposition, albeit with a change to reduced depositional conditions. The TOC and S values of the red-brown siltstone are generally insignificant (Table 1).

4.2. Nonesuch Formation

The conformable contact between the Nonesuch Formation and the CHC is the first dark-gray to black shale or siltstone overlying a red siltstone or sandstone (Figures 3 and 4A,B). The upper contact with the Freda Sandstone is gradational and is distinguished by a color change from grayish intervals to brownish intervals. Siltstones comprise most of the Nonesuch Formation, and informal lithologic subdivisions are based on color and sedimentary features (see Figures 3 and 4, [7] and references therein). The thickness of the Nonesuch Formation at Western Syncline is between 168 m and 201 m and averages 183 m. The ensuing discussion will focus on the lowermost ~20 m, which is subdivided into three informal members, originally defined at White Pine [8,9], from bottom upward: (1) Parting Shale (1.2 to 10.7 m thick) within which lies the LCBS, (2) Upper Sandstone (0.2 to 4.2 m thick), and (3) Upper Shale (8.7 to 12.1 m thick), within which lies the UCBS (Figure 3). These three informal members have been subdivided into lithostratigraphic units. They are capped by the Stripey unit.

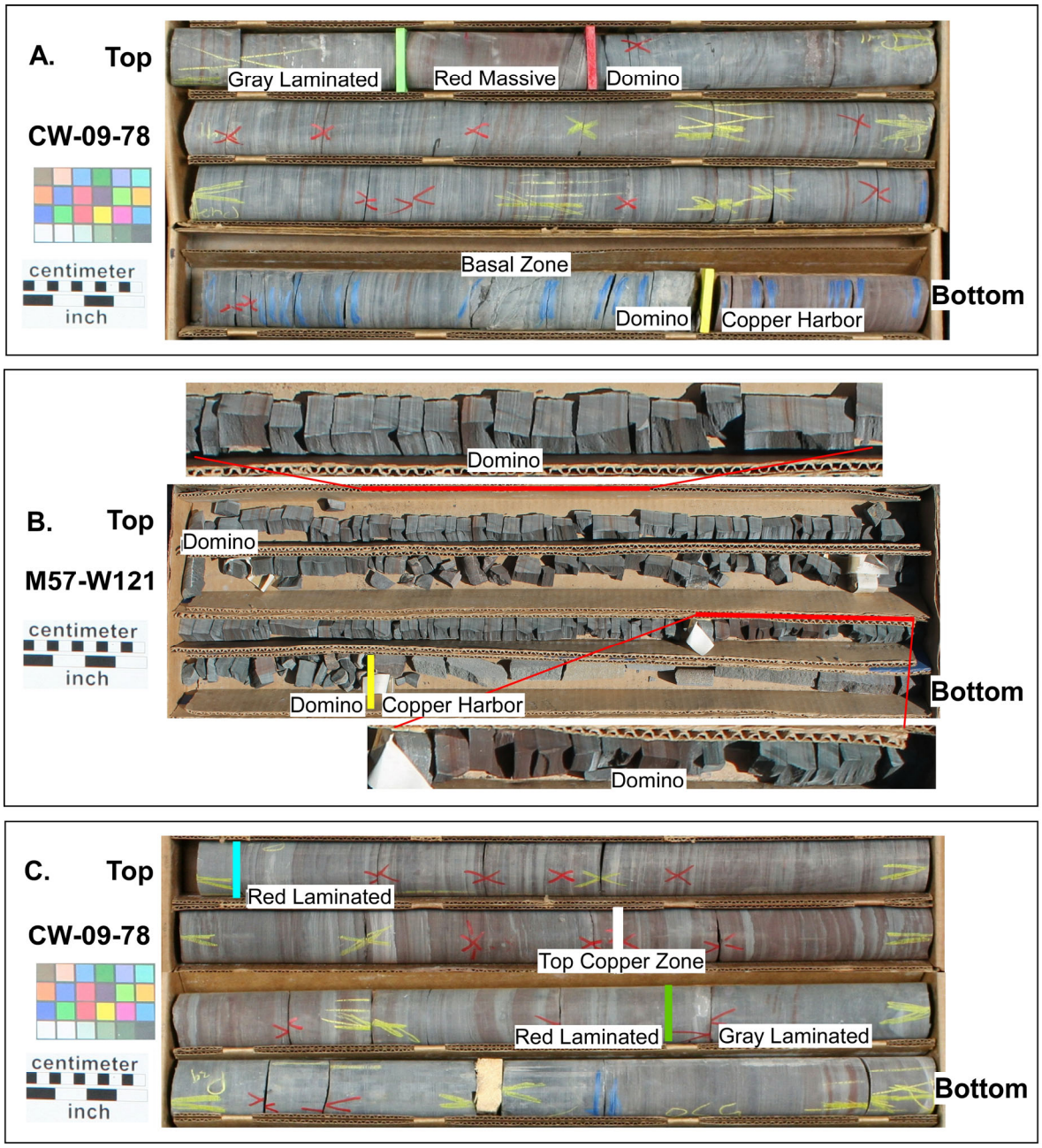

Figure 4. Drill core in the LCBS showing the various lithofacies in drill holes CW-09-078 and M57-121 (see Figure 2A). (**A**) Basal Gray Laminated to uppermost Copper Harbor Conglomerate (CHC). The Domino is dark- and light-gray, 1.9 m thick intercalated shales, siltstones, and fine-grained sandstones with occasional red-bed laminae and a storm sand near its top; note the soft-sediment deformation feature (basal zone). (**B**) The lowermost Domino in M57-121, where it is a light-gray and red-brown, sandy 2.6 m thick sequence with more abundant red-bed layers. (**C**) Red Laminated and upper Gray Laminated that includes the Top Cu Zone. Note wavy bedding and load structures. In Red Laminated, the 35 cm interval above the Top Cu Zone hosts 0.02% Cu and 0.20% S (pyrite only) and the 35 cm interval below the Top Cu Zone hosts 0.21% Cu and 0.21% S (pyrite + chalcocite); no anomalous Pb or Zn was encountered.

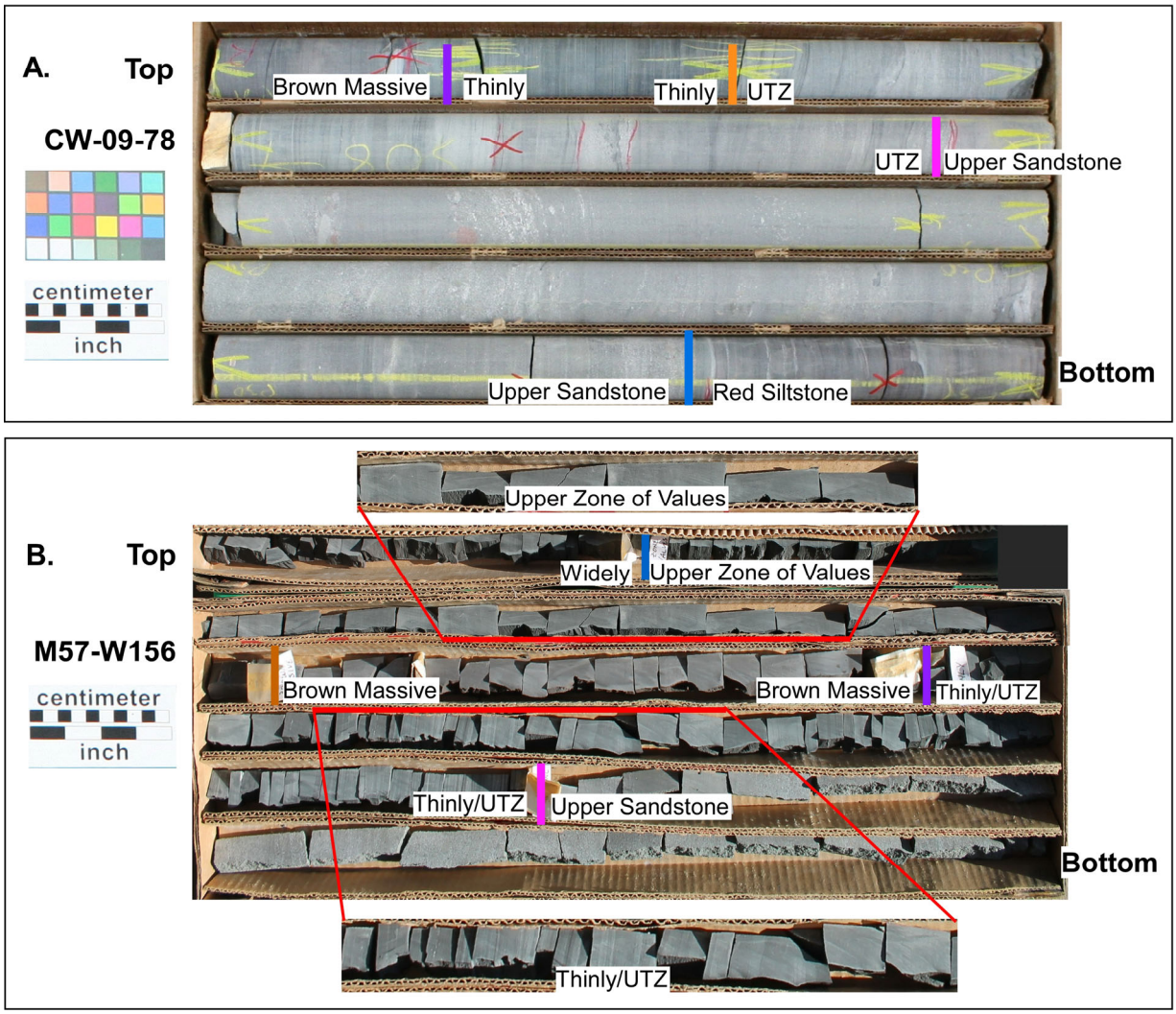

Figure 5. Drill core in the UCBS showing the various lithofacies in drill holes CW-09-078 and M57-156 (see Figure 2A). (**A**) Top Thinly to base Upper Sandstone member that includes the stratigraphic equivalent of the UCBS where the UTZ is mostly a sandstone, with occasional thin black shales, that is essentially barren of any sulfides (0.01% Cu, 0.06% S, and 0.08% TOC), and the overlying Thinly hosts 0.01% Cu, 0.25% S (pyrite), and 0.24% TOC (above the Top Cu Zone). (**B**) The 0.9 m-thick Thinly/UTZ hosts 1.85% Cu, 0.44% S, and 0.18% TOC wherein the lower part (UTZ) is much finer-grained than that in CW-09-078, rendering the contact between the Thinly and UTZ indistinguishable; the 2.28 m total thickness of the UCBS (to the top of the Upper Zone of Values) hosts 0.96% Cu and 6.6 ppm Ag.

4.2.1. Parting Shale Member—LCBS

The Parting Shale member includes the LCBS, which is comprised of four informal lithostratigraphic beds that are the principal host rocks at Western Syncline, from bottom upward: (1) Domino, (2) Red Massive, (3) Gray Laminated, and, in part, (4) Red Laminated (Figures 3 and 4); the overlying Gray Siltstone and Red Siltstone are not of economic importance.

The top of the Parting Shale is an erosional disconformity. The thickest section is in the western part of Copperwood, where minimal, if any, erosion occurred [7]; erosion is more prevalent elsewhere and reaches as deep as the Gray Laminated bed in the easternmost sector of Copperwood. The Parting Shale member thickness ranges from 1.2 m to 10.7 m and averages 6.1 m.

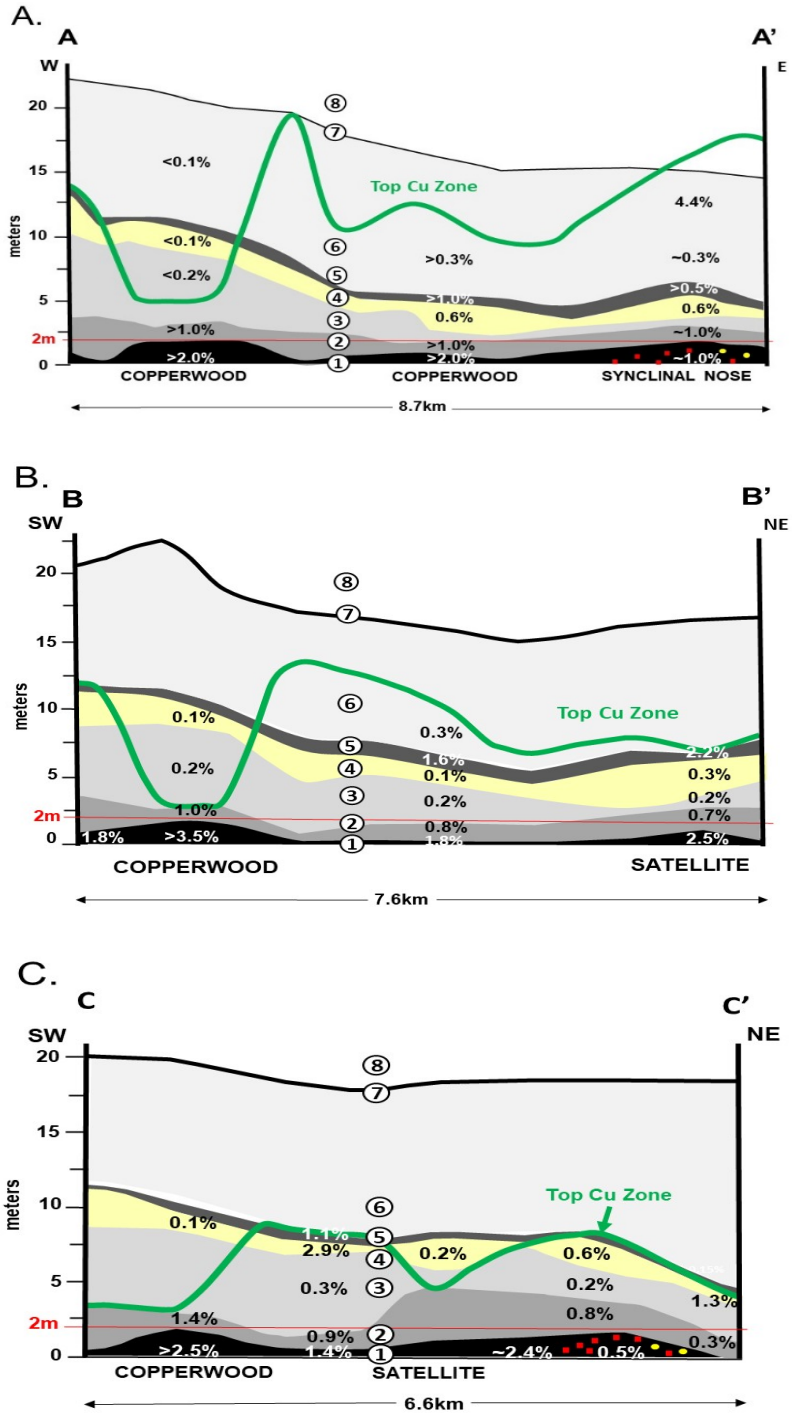

Figure 6. Cross-sections showing key units, generalized Cu grades, and Top Cu Zone (see Figure 2A for locations of A-A′, B-B′, and C-C′). (**A**) E-W cross-section through Copperwood to synclinal nose. (**B**) SW-NE cross-section through Copperwood, UCBS estimated resource, and an LCBS satellite deposit. (**C**) SSW-NNE cross-section through Copperwood, a LCBS satellite deposit, and over an area with thick red-bed and abundant sandstone layers within Domino. Generalized Cu grades are derived from drill holes proximal to the line of section. Red rectangles and yellow circles in Domino bed indicate relatively higher volumes of red beds and light-colored sandstones, respectively. The red line at 2 m from the base of the Domino bed is the minimum thickness at which resources in the LCBS were estimated [11]. Units labeled in circles are: (1) Domino, (2) Red Massive + Gray Laminated, (3) Red Laminated + Gray Siltstone + Red Siltstone, (4) Upper Sandstone member, (5) Thinly/UTZ, (6) Upper Shale undifferentiated, (7) Stripey, and (8) Nonesuch Formation undifferentiated.

Black to dark-gray, thinly-laminated shales and siltstones with less common intercalated laminated red shales and siltstones as well as thin layers of grayish-white siltstones and fine- to medium-grained sandstones characterize the Domino (Figure 4A,B); the shale and siltstone laminae are 0.2 to 0.5 cm thick. Load structures are common at the base of laminations and low-amplitude ripples and crossbedding characterize coarser-grained intervals. Thin reddish laminae occur throughout the Western Syncline but are more abundant to the north and east of Copperwood, where they are spatially related to coarser-grained layers; thin sandstone layers are common in the uppermost section throughout the Western Syncline (Figures 2B and 4A,B). The "basal zone" of the Domino, which lies as much as 30 cm above the basal stratigraphic contact and whose thickness is a much as 17 cm, is a soft-sediment deformation feature that occurs at the same approximate stratigraphic position throughout the Western Syncline [7,37]. The Domino is 0.0 m to 2.6 m thick and averages 1.0 m. The median TOC and S values are 0.17% and 0.53%, respectively (Table 1). Domino is the key host rock of the LCBS and nearly all S in the Domino occurs in chalcocite.

The Domino isopach shows a distinct EW-trending zone in the central part of the Western Syncline where the bed is as thin as 8 cm; the increase in thickness to the southwest and north is abrupt, changing as much as 1.4 m over a 200 m distance (Figures 2B and 6). However, the Domino thickness is not related to sedimentary facies. For instance, black to dark-gray shales and siltstones dominate the thicker Domino at Copperwood (CW-09-078: 2.61% Cu, 0.61% S, 0.18% TOC over 1.9 m) (Figure 4A), but 3 km to the northeast, red and light-gray siltstones with interbedded gray-white sandstones are more prevalent (M57-121: (0.46% Cu, 0.12% S, 0.15% TOC over 2.6 m) (Figure 4B).

The base of the Red Massive is the Junior, a thin carbonate lamina, or, where Junior is not recognized, the first reddish layer [9]. Its upper contact is transitional over a few centimeters but was determined by a color change from reddish to gray as well as a zone of calcite nodules in the lower part of the overlying Gray Laminated (Figure 4A) [7]. Massive to laminated siltstones with intercalated fine- to medium-grained sandstones, including fining-upward packages, comprise this bed throughout the Western Syncline. Dark-gray laminae are common throughout the bed in and proximal to Copperwood. The bed thickness ranges from 0.0 m to 1.3 m and averages 0.4 m. Relatively low concentrations of TOC and S in this bed are consistent with its overall oxidized nature, but darker laminae contain elevated concentrations where nearly all the S occurs in chalcocite (Table 1).

The lower and upper contacts of the Gray Laminated are color changes that are transitional over approximately 10 cm (Figure 4A,C). Light- to medium-gray, thinly-laminated (0.2 to 0.5 mm) siltstones with interbedded dark-gray to black shales and siltstones, and lesser reddish shales and whitish, fine-grained sandstones comprise this bed. Low-amplitude ripple marks and crossbedding characterize the finer-grained intervals, whereas coarser-grained intervals are typically massive. Slump structures were described in the exploratory underground workings at Copperwood [37]. Where not eroded, the Gray Laminated is 0.9 m to 3.5 m thick and averages 1.2 m. The median TOC and S values are 0.12% and 0.28%, respectively (Table 1) and nearly all the S occurs in chalcocite. The basal contact of the Red Laminated is not only a color change but also demarcates the appearance of wavy bedding; the color changes to light gray upwards (Figures 3 and 4C). The bed is distinguished by wavy undulations and crossbedding within laminae that are up to 1 cm thick. Coarser-grained thin laminae often form load structures when overlying finer-grained layers (Figure 4C). Dark-gray laminae occur locally in the lowermost section, which section may be included in the LCBS (Figure 3). The bed was eroded and unconformably overlain by the Upper Sandstone member over most of the eastern half of the Western Syncline (Figure 6). Where it was not eroded, the thickness ranges from 0.2 m to 3.7 m and averages 1.5 m. The TOC and S values are as high as 0.17% and 0.39%, respectively (Table 1); the higher values are mostly hosted by basal dark-gray laminae where S can occur in chalcocite (Figure 4C).

4.2.2. Parting Shale Member—Gray Siltstone and Red Siltstone Units

These two units, where not eroded, comprise the uppermost Parting Shale member and are sedimentologically similar [7] (Figure 5A); they are not of economic importance. Both units are comprised of massive siltstones, but the Gray Siltstone locally includes dark-gray to black laminae and 2- to 4-cm thick very fine- to fine-grained, lighter-colored whitish-gray sandstones. The thickness of the bed is as much as 5.1 m. Locally, TOC values reach 0.24% and S values 0.45% (Table 1); the S occurs in both pyrite and chalcocite, but Cu grades are generally less than 0.40% and thus are not of economic interest. The Red Siltstone thickness is as much as 1.5 m in the western sector of Copperwood where the upper contact may be conformable (Figure 5A), but was completely eroded beyond this area (Figure 6A,B). The TOC and S concentrations are insignificant.

4.2.3. Upper Sandstone Member

The Upper Sandstone member consists of light-colored sandstone and local conglomeratic beds, most of which are up to 50-cm thick fining-upward sequences that can be capped by dark-gray to black shale laminae (Figure 5A,B). The lower contact is mostly an erosional disconformity. The conformable upper contact is defined by the appearance of the first dark-gray to black shale lamina of the UTZ.

Well- to medium-sorted, fine- to medium-grained sandstones as well as fine-to medium-grained, poorly-sorted, conglomeratic, matrix-supported sequences are equally a part of the Upper Sandstone member (Figure 5A); pebble-sized clasts are mostly mafic volcanic rocks, commonly hematitic. Both reddish and dark-gray shale and siltstone laminae occur in the middle part of the member in places and, north of Copperwood, grayish siltstone laminae are common. Crossbedding and scour contacts in the sandstones and local basal conglomerates attest to a predominantly high-energy depositional environment. The Upper Sandstone member ranges from 0.2 m to 4.2 m thick and averages 1.7 m. Overall, the Upper Sandstone thins westward. NS-trending thicker sections occur east of Copperwood, nearly coincident with an erosion level that reached as deep as the Gray Laminated (Figure 6A,B). TOC content is 0.06% to 0.63% with a median value of 0.15%, and from 0.01% to 0.65% S with a median of 0.08% (Table 1). Whereas the higher S values coincide with the occurrence of chalcocite, which is hosted by darker, finer-grained laminae, the higher TOC values mostly reflect zones with pyrobitumen.

4.2.4. Upper Shale Member—UCBS

The UTZ, Thinly, Brown Massive, and Upper Zone of Values (UZV) are the principal components of the UCBS (Figures 3 and 5A,B); locally, the lowermost Widely unit can be included. The lower contact of the UTZ bed with the overlying Upper Sandstone member is typically chosen at the first dark-gray to black shale or siltstone lamina, commonly <1 mm thick (Figures 3 and 5A,B). The UTZ consists of fine- to medium-grained, medium- to well-sorted, fining-upward sandstone intervals, up to 10 cm thick, which are commonly capped by dark-gray to black, thinly-laminated (0.2 to 0.5 mm) shales and siltstones. Locally, its upper contact is recognized by a sharp change to dark-gray to black, thinly-laminated Thinly shales and siltstones (Figure 5A); otherwise, the contact cannot be distinguished (Figure 5B). The grain size and laminae thickness of Thinly generally increases upwards and the uppermost Thinly can include fine-grained, well-sorted sandstones with very thin, dark-gray to black shale or siltstone partings. The upper contact of the Thinly is characterized by a change to red-brown, massive siltstone (Brown Massive) (Figures 3 and 5A,B). The combined thickness of the UTZ and Thinly ranges from 0.24 m to 2.15 m and averages 0.85 m; thicker intervals occur on the outer edges of the Western Syncline. These beds are the key host rocks of the UCBS and the median values of TOC and S are 0.20% and 0.35%, respectively (Table 1). Sulfide minerals are pyrite, most notably in the southwestern sector of the Western Syncline where the LCBS is thickest and of higher Cu grade, and chalcocite throughout most of the Western Syncline where the units underlie the Top Cu Zone (Figures 2 and 6).

The overlying Brown Massive consists of reddish-brown, massive siltstone with calcite nodules and is overlain by dark-gray siltstones of the UZV (Figure 5A,B). It is as thick as 1.92 m and averages 0.41 m. TOC and S concentrations are relatively low (Table 1). Most of the S occurs in pyrite although chalcocite occurs locally.

The UZV overlies the Brown Massive and is a massive dark-gray siltstone that occasionally grades upwards into finely-laminated, dark-gray siltstone (Figure 5B). The TOC and S median values are 0.13% and 0.16% and with values as high as 0.21% and 0.71%, respectively (Table 1). The overlying unit, Widely, is generally a well-bedded, red to green-gray siltstone with intercalated red-shale laminae but can include basal dark-gray siltstone with sulfides, which may or may not be a part of the UCBS (Figure 3). The median TOC and S values are 0.09% and 0.06% with maximums of 0.14% and 0.21%, respectively; the higher S values are spatially related to the occurrence of pyrite or chalcocite.

4.2.5. Upper Shale Member—Other Units

The units overlying the UCBS are mostly siltstones and sandstones with only the Massive Gray Siltstone and Black Laminated Shale of potential economic importance (Figure 3). The Massive Gray Siltstone is host to elevated levels of TOC and S that reach 0.35% and 0.24%, respectively; however, its thickness is generally <50 cm. The Black Laminated Shale, whose thickness is typically less than 1 m, is a dark-gray to black, finely-laminated shale and siltstone whose TOC and S contents are up to 0.35% and 0.44%, respectively. Sulfide minerals include pyrite and chalcocite.

4.2.6. Stripey Unit

The Stripey is a thinly-laminated sequence of interbedded dark-gray to black siltstones and white calcareous layers that conformably overlies the Upper Shale member. The thickness of this bed ranges from 0.16 m to 0.41 m and averages 0.29 m; its thickness is remarkably consistent regionally [38]. TOC ranges from 0.33% to 0.66%, with a median value of 0.44%, and S ranges from 0.64% to 1.16%, with a median value of 1.00% (Table 1). The S occurs in pyrite except in the synclinal nose of the Western Syncline wherein it occurs in chalcocite. It is not of economic importance given its limited thickness.

5. Depositional Environment of the Lower Nonesuch Formation at Western Syncline

The Oronto Group was deposited in a post-rift sedimentary basin during passive subsidence at about 10° north of the equator [21]. The siliciclastic sequence does not include known distinctive evaporite layers, though the Nonesuch Formation locally contains anhydrite nodules and halite [25]. The onset of Nonesuch Formation deposition marks an abrupt change from the higher-energy, clastic sedimentation of the CHC deposited under oxidizing conditions to lower-energy, subaqueous, clastic sedimentation under overall anoxic conditions that occurred broadly throughout the exposed Michigan and Wisconsin segment of the rift [21,24,32,39]. The laminated nature of the Domino, Gray Laminated, and Red Laminated beds manifest rapidly-changing energy conditions and thus varying sedimentation rates influenced by subsidence and/or fluctuations of water depth [24]. Conditions became more stable for the Gray and Red Siltstone deposition, culminating in the higher-energy fluvial and shallow-water clastics of the Upper Sandstone member. The UTZ-Thinly beds that overlie the Upper Sandstone member mark a return to anoxic depositional conditions that became more oxidized up-section, but local dark-colored siltstones of the overlying UZV suggest a return to a more reduced environment, which can extend upwards into the Widely. The Upper Shale member above the Brown Massive includes siltstones and fine-grained sandstones deposited under varying degrees of reduced conditions. The overlying dark-gray to black Stripey unit was deposited under lower-energy conditions in an anoxic environment, similar to the deposition of the Domino and UTZ-Thinly beds. Notwithstanding the ambiguity of the depositional setting, i.e., lacustrine versus marine [22,24–29,32], these three units mark the onset of a transgressive-regressive sequence. The Domino and Stripey are easily correlated to the White Pine stratigraphy

30 km to the east [9] and 120 km further north near the Houghton [38] (Figure 1), but in the Ashland Syncline to the southwest, only the time-equivalent of the Domino was clearly recognized [39], which thereby establishes it as a regional chronostratigraphic marker within the larger depositional basin; on the other hand, the UTZ-Thinly and Stripey units likely mark local flooding events. Overall, deposition of the Lower Nonesuch Formation at Western Syncline occurred in a shallow-water setting at or just below wave base and exhibits exceptional continuity on a regional scale, which is compatible with deposition in a marine embayment and/or estuarine environment [22,26].

A low-energy, anoxic depositional environment is not only conducive to the decomposition and preservation of organic material, as measured by TOC, but also to reduction of soluble sulfates to sulfur to form authigenic pyrite. Both the TOC and S contents are relatively enriched in the darker beds of targeted host rocks, as compared to intercalated reddish and light-colored shale, siltstone, and sandstone layers, e.g., Red Massive and Red Laminated, that were deposited under more oxic conditions (Figures 3 and 4, Table 1). The Domino is characterized by a variable amount of thin, reddish shale and siltstone laminae throughout the Western Syncline; these beds notably are host to negligible amounts of TOC and S. In the eastern and northern sectors of the Western Syncline, red laminae interfinger with and are peripheral to sandy facies in the Domino (Figures 2B and 4B); this spatial relationship supports the concept that these red layers are related to higher-energy, albeit short-lived, depositional conditions, such as those generated by storm-induced oxygenated turbidity and/or bottom currents [7].

The Domino thickness changes abruptly over a short distance in the southwestern sector of the Western Syncline (Figures 2B and 6), where deposition occurred under low-energy, anoxic conditions; this requires a topographical change of the depositional surface, whose probable cause was syn-depositional tectonic movement(s). Notably, the thick Domino in the northern sector, which includes relatively more red beds and sandstones, was also affected by syn-depositional tectonic movements. Therefore, thickness is not a function of depositional environment.

In summary, the Domino in the lowermost Nonesuch Formation was deposited under changing energy and oxidation-reduction conditions with periodic syn-depositional tectonic movements, all of which are relevant to the formation of potential orebodies within the Western Syncline. Elevated quantities of TOC and S are key components of the Domino sedimentary depositional environment, especially in those layers deposited under lowest-energy and anoxic or reduced conditions. Thus, the Domino manifests the key requisite conditions of the preferred host rocks in Western Syncline, conditions that could be applied to other potential host rocks in the Nonesuch Formation; it is the key component of the LCBS. Similarly, the UTZ-Thinly unit is the key component of the UCBS. Certain zones in the remainder of the Upper Shale member may contain elevated TOC and/or S values but are invariably less than 2 m thick and/or have relatively low S values, e.g., Stripey, Black Laminated Siltstone, Massive Gray Siltstone, and thus would not be primary targets for potential ore.

6. Mineralization of the Lower Nonesuch Formation at Western Syncline

The Western Syncline SSC deposits are comprised of Cu-bearing strata that can be classified as potential ore, but with limited continuity of sufficient Cu grade and/or thickness. In addition, these Cu deposits are characterized by a simple mineralogy of primary chalcocite with no later superposed mineralization, virtually no deformation, and minimal fault displacements. Since its discovery in 1956, various studies showed that conventional underground room-and-pillar methods and flotation technology as employed at the nearby White Pine mine are the most viable mining and processing methods [11,40,41]. Thus, the economic margins achieved by applying these proven methods can only be improved with a thorough understanding of the sedimentary and tectonic processes that formed the deposit so that thicker, higher-grade Cu intervals can be better defined, predicted, and properly sequenced in a mine plan.

Main-stage mineralization at Copperwood putatively formed during early diagenesis in finer-grained sediments and was not subsequently overprinted [7,9,42–44]; related alteration is illite and interstratified illite-smectite after diagenetic albite and K-feldspar, based on host-rock geochemistry [44]. At White Pine, however, early diagenetic Cu mineralization was overprinted by late-stage native-Cu mineralization focused along thrust faults [9,45]. The later mineralization event in the Western Syncline is locally represented by pyrobitumen with local native Cu in the coarser-grained sediments of the CHC and Upper Sandstone member of the Nonesuch Formation, but this is not of economic interest.

Pyrite is the most common and widespread sulfide mineral in unmineralized Nonesuch Formation. Pyritic sedimentary rocks are separated from mineralized rocks by the Top Cu Zone, below which chalcocite is the dominant sulfide mineral [37] (Figures 4C and 6). Cadmium and/or lead anomalies occur only at a few locations in the Western Syncline suggesting that this upward zonation is either thin and weakly developed or is not laterally continuous, unlike at White Pine where the Fringe Zone is ubiquitous [8,9,43,46]. Chalcocite is the main Cu mineral at Copperwood and White Pine; native Cu and native Ag rarely occur at Copperwood but are more abundant at White Pine.

Chalcocite and pyrite predominantly occur as disseminated grains and grains forming lamination-parallel seams in the host shales and siltstones (Figure 7, see Figure 8B in [7]). Most sulfide minerals are very fine-grained, ranging from <1 to as much as 150 microns across and average 10–20 microns (Figure 7). Ovoid grains up to 3 mm in diameter occur in all lithologies, including sandstones, but are not common; thin-section studies revealed micro-corrugated surfaces that suggest chalcocite precipitation outward from a nucleus during or soon after deposition of the sediments [37]. Rounded grains as well as ragged edges on subrounded grains were interpreted as relic framboidal pyrite at Copperwood [7] and hematite locally envelops chalcocite clots suggesting that chalcocite replaced pyrite (Figure 7B).

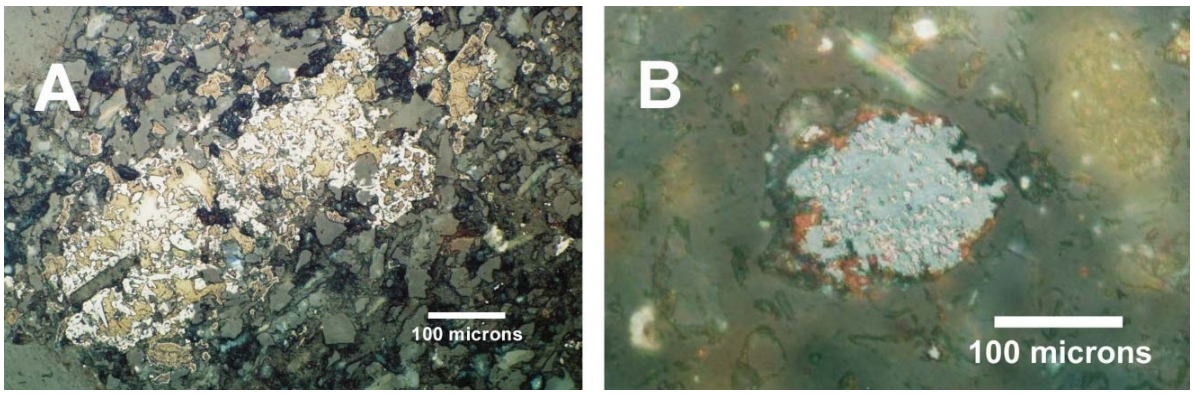

Figure 7. (**A**) Microphotograph of strongly tarnished chalcocite (brown) and hematite (white) from an LCBS composite sample under reflected light. (**B**) Microphotograph showing an orbicular liberated chalcocite grain (gray) with hematite (red) along the grain boundary from an LCBS composite sample under reflected light, crossed nicols.

In summary, the potential ore at the Western Syncline Cu deposits is a function of sedimentary, stratigraphic, and tectonic controls that dictate economic viability of extraction. The later oxidation event is an additional control in that Cu recovery from the resultant Cu-oxide minerals, mostly as chrysocolla [40], is negligible with the application of flotation techniques.

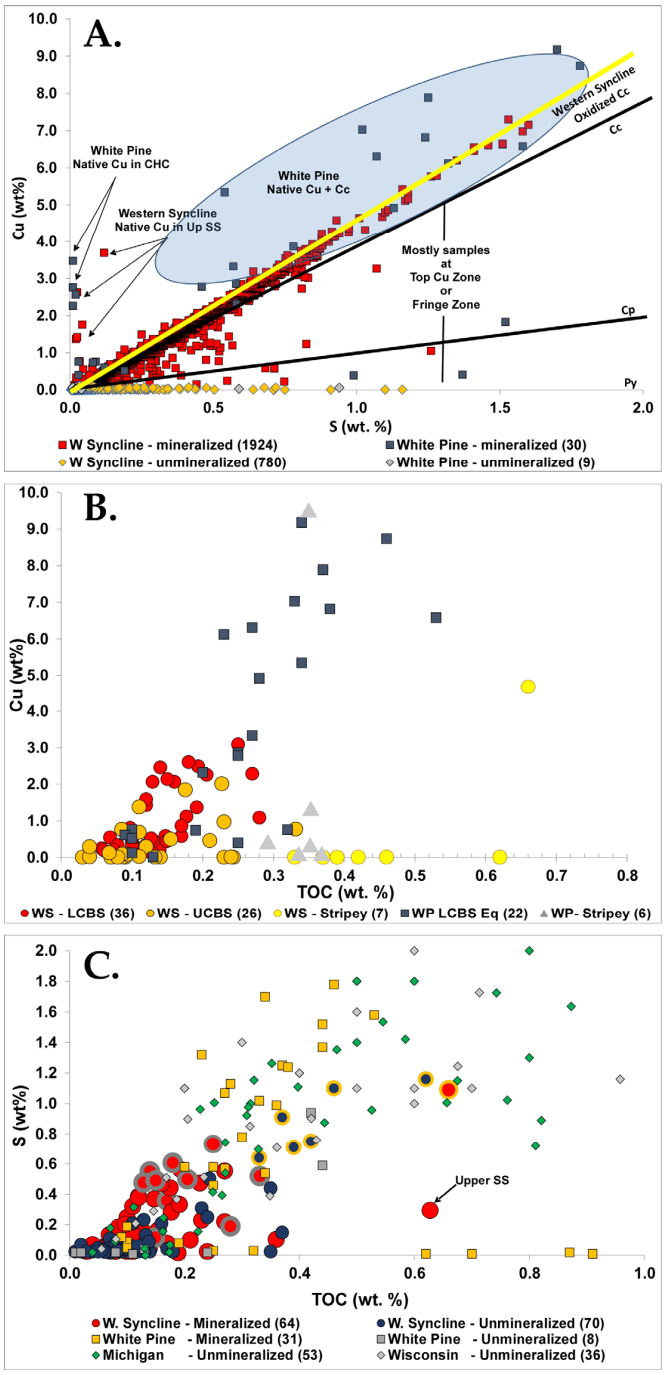

Figure 8. Cu-S-TOC relationships at Western Syncline and White Pine. (**A**) Cu-S graph depicting mineralogy of mineralized and unmineralized (<0.1% Cu) samples at Western Syncline and White Pine. The chalcocite (Cc) and chalcopyrite (Cp) lines are the molar ratio of Cu and S in an ideal mineral formula. (**B**) Cu-TOC graph comparing the key host rocks at Western Syncline and White Pine; the LCBS equivalent at White Pine consists of the Lower Transition zone, Domino, Red Massive, Dark-gray Massive, and Top Zone beds [9]. (**C**) TOC-S graph showing mineralized and unmineralized samples (<0.1% Cu) at Western Syncline and White Pine as well as regional unmineralized samples that were selected over the entirety of the Nonesuch Formation; gray and orange borders indicate Western Syncline samples from the Domino and Stripey units, respectively. Western Syncline data are from [12,32]; White Pine data are from [47–49]; and regional data are from [29,30,32] and include samples above the Stripey.

6.1. First-Order Control

As expected in any SSC, sedimentology and stratigraphy are first-order controls on Cu mineralization in the Western Syncline deposits. Low-energy, anoxic clastic environments, where organic-rich, fine-grained sediments were deposited, resulting in the formation of receptive host rocks, which enabled bacterial sulfate reduction that led to diagenetic pyrite formation. The reduced dark-colored shales and siltstones that were enriched in pyrite, as a proxy for S, and TOC were geochemically ideal for sequestration of Cu from through-going oxidized, Cu-bearing fluids as manifested by chalcocite replacing pyrite (Figure 7). Thus, higher Cu grades are facies dependent and are fundamentally constrained by the abundance of pyrite prior to Cu mineralization given that exogenous S input was, at most, negligible.

Relationships among Cu, TOC, and S contents in the Nonesuch Formation reflect cumulative processes that occurred during sedimentation, diagenesis, and mineralization. Data from the Western Syncline and White Pine deposits include mineralized and unmineralized samples, the latter defined as containing Cu < 0.1% [12,32,47–49]. Regional data beyond the Western Syncline and White Pine deposits provide additional insights from samples without mineralization [29,30,32].

Figure 8 shows relationships among Cu, TOC, and S. The Cu vs. S graph shows the relative importance of mineralogical fields relative to stoichiometric chalcocite and chalcopyrite; the values along the *x*-axis represent zones that host pyrite only (Figure 8A). Those few samples that lie between the chalcopyrite line and the *x*-axis, along the chalcopyrite line, and between the chalcopyrite and chalcocite lines are from the Top Cu Zone. In addition to various samples that lie along the chalcocite line up to 3% Cu, many Western Syncline samples tend to follow a linear trend with a steeper slope than the chalcocite line. These samples contain Cu oxides, a characteristic confirmed by a Cu recovery of <90% using conventional flotation techniques [7,11,40,41]; oxidation of chalcocite likely occurred in the period between 1050 Ma and 500 Ma when the mineralization was exposed or very close to the surface [35]. White Pine samples that lie above the chalcocite line reflect a mix of native Cu and chalcocite as well as a possible component of Cu oxides. More importantly, the mineralized samples that lie on or proximal to the chalcocite line demonstrate that pyrite is not a constituent of these rocks. The few samples that have low S but high Cu, i.e., native Cu, are representative of post-lithification mineralization that is spatially related to pyrobitumen.

Figure 8B shows that potential ore grades of at least 1% Cu are spatially related to intervals with >0.1% TOC content. Figure 8C shows that most of the mineralized samples contain less than 0.8% S and less than 0.4% TOC except for most Stripey samples and an Upper Sandstone member sample with pyrobitumen. Finally, the unmineralized regional samples, which are from the entire length of the Nonesuch Formation at undifferentiated stratigraphic levels, show that both TOC and S are enriched throughout the section, yet nearly all the S is in pyrite.

The Cu-TOC-S interrelationships provide further insight into the overall genetic model applied to the Western Syncline deposits. It was established above that the Cu-bearing rocks are the dark-colored, finest-grained strata wherein TOC and S were important constituents (Figures 3 and 4; Table 1), the latter sourced from pyrite that formed via sulfate reduction during deposition [29,30], which is a common phenomenon in modern processes [50–53]. The covariation of Cu and TOC has its basis in the covariation of S and TOC, which enhanced the reducing conditions to sequester Cu from passing fluids that results in the replacement of pyrite by chalcocite. The high S, low TOC values in the White Pine samples that lie above the restricted S-TOC field of mineralized samples have been cited as evidence for S addition during second-stage mineralization [47,49,54]. Comparison to the Western Syncline data reinforces this interpretation since these samples, which lack second-stage Cu mineralization, do not show similar S enrichment. The relatively high TOC and S values in beds that do not host Cu clearly suggest that circulation of Cu-bearing fluids was restricted

and/or permeability barriers impeded access to these beds along a 250-km long trend between Houghton, MI and the southwestern edge of the Ashland Syncline.

Geochemical analyses from Western Syncline and White Pine revealed relationships among highly reactive Fe, total Fe, poorly-reactive silicate Fe, and pyritized Fe indicating that the Nonesuch Formation was deposited in an anoxic but not euxinic environment [32]. Nonetheless, TOC- and S-enriched beds do not necessarily host Cu, although the S content reflects variable concentrations of pre-mineralization pyrite. In the case of the Stripey member, which is a carbonate laminate, it only hosts Cu in the nose of the syncline (Figure 6A) and adjacent to faults at White Pine [45,47], despite its enriched TOC and S contents as compared to the Domino and UTZ-Thinly beds, which are key host rocks of the Western Syncline and White Pine deposits (Table 1).

Whereas Cu grades are sufficiently enriched in the black to dark-gray shales and siltstones within the Domino and Gray Laminated, the UTZ-Thinly, and the Stripey to warrant consideration as potential orebodies, Cu grades in Red Massive, most of Red Laminated, Gray Siltstone, Red Siltstone, Upper Sandstone member, and most of the Upper Shale member are merely Cu anomalous (Figures 3 and 6), although they may have an impact on the economic evaluation, e.g., Red Massive is included in the LCBS, albeit as internal dilution. Copperwood is host to the highest Cu grade in the LCBS, mostly due to a thicker and higher-grade Domino; for this reason, it was selected for near-term development [7,11]. The Domino Cu grades exceed 1%, except in areas where no resource has been delineated, which are typically areas where red beds and/or lighter-colored, coarser-grained layers predominate (Figures 2B, 4A,B and 6). In addition, thickness-grade of drill holes outside the limits of the resource estimate are characterized by a relatively thin Domino with an average Cu grade of <1%; potential ore in the UCBS has been delineated in this area (Figure 2A). Thus, the principal linkage of Cu grade is with the sedimentary facies.

Locally, the Upper Sandstone member hosts Cu grades of economic interest but are not laterally continuous (Figure 6). Typically, chalcocite, along with very minor bornite and chalcopyrite, occur in thin, dark-colored, shale or siltstone laminae; indeed, it could be included as potential ore where the overlying UTZ-Thinly is not of a minable thickness (Figure 5A,B). Locally, the uppermost section hosts pyrobitumen with associated native Cu. This association reflects post-lithification generation of petroleum that then acted as a reductant to precipitate Cu from passing oxidized fluids.

The overlying UTZ-Thinly beds are the principal component of the UCBS (Figures 3, 5A,B and 6). Cu-grade continuity occurs in the central part of the Western Syncline where the thickness exceeds 2 m (Figure 2A); it overlies an area of thin Domino. The chalcocite volume is relatively higher in the finer-grained, dark-colored layers, analogous to the Domino (Figure 5A,B).

6.2. Second-Order Control

Vertical percolation of Cu-bearing briny waters through unlithified sediments is the putative first-stage mechanism of Cu deposition in the Porcupine Mountains Copper District [7–9,42,43,46]. The time constraints on mineralization are controlled by the lithification process, which impedes vertical permeability and thus the flow of Cu-bearing fluids upward through the unlithified section. Therefore, vertical permeability is a second-order control on mineralization given that the lowermost Nonesuch Formation lithologies are shales and siltstones, which have limited post-lithification vertical permeability. This concept is further supported by vertical zonation of sulfide minerals to and beyond the Top Cu Zone, which is a fluid-flow front that crosscuts stratigraphic contacts as dictated by the volume of Cu sequestered from the passing fluids. The stratigraphic level of the Top Cu Zone is geographically constrained based on the volumes and thicknesses of favorable host rocks below it, as well as the grain size and composition of the stratigraphic intervals within it. Either Cu supply was limited and/or fluid ascent was impeded by vertical permeability destruction due to compaction, lithification and/or mineralization to preclude significant Cu mineralization stratigraphically higher.

It was suggested that Cu-bearing fluid flow was compaction driven and initiated during the Freda Formation deposition, later supported by paleomagnetic data [55], and that mineralization in the Porcupine Mountains Copper District proceeded as waters in the underlying red-bed CHC aquifer moved upwards in areas of a thinner sequence [56]; however, the mineralization at White Pine and Western Syncline did not overlie a thinner CHC [57], the reputed source of Cu [7,8,43,55,57,58]. Cuprous-chloride stability in fluids is only possible after introduction of oxygenated surface waters and the subsequent formation of diagenetic hematite after mafic minerals, from which it was concluded that mineralization occurred prior to Freda Formation deposition [57,58]. Both detrital and diagenetic hematite are constituents of the CHC and the latter reputedly formed shortly after deposition [20,22]. Fundamental to the arguments is that after the diagenesis of the poorly-sorted arkosic sediments of the underlying CHC, a high vertical permeability was maintained.

6.3. Third-Order Control

Syn-sedimentary faulting is postulated as the third-order control on Cu mineralization at the Western Syncline deposits as faults controlled the thickness of favorable lithologies below the Top Cu Zone. However, whereas subvertical faults have not been identified within the Nonesuch Formation in the Western Syncline deposits, it is postulated that faults in the underlying CHC facilitated, and perhaps expedited, vertical ascent of Cu-charged brines through the overlying sediment pile that became the Nonesuch Formation (Figure 9). The abrupt thickness changes of Domino surrounding a thinner area in the central part of the Western Syncline suggest a syn-sedimentary tectonic control that caused downwarping of the depositional surface via pre-existing faults, perhaps as grabens or half grabens, in the underlying CHC (Figure 9). Thickening of Domino due to pre-existing fault reactivation in the underlying CHC explains the accumulation of a thicker Domino at Copperwood and in the northern half of the Western Syncline (Figures 2B and 6), regardless of facies, and also explains certain thickness variations in the overlying Gray Laminated bed as well, especially in the satellite deposits where the Domino is relatively thinner (Figures 6 and 9). Notably, potential minable Cu grades are hosted by the UCBS generally where it overlies a thinner Domino (Figures 2 and 6). This relationship supports the notion that the volume and the rate of soluble Cu moving vertically through the sediment pile was relatively uniform throughout the area yet constrained by the time interval from deposition to lithification [44]. Furthermore, Cu-bearing strata above the UCBS are generally underlain by Domino consisting mostly of coarser-grained facies and/or Cu grades <1% in the UCBS, with both intervals containing relatively lower TOC and S contents, which is additional evidence supporting this notion (Figure 6A).

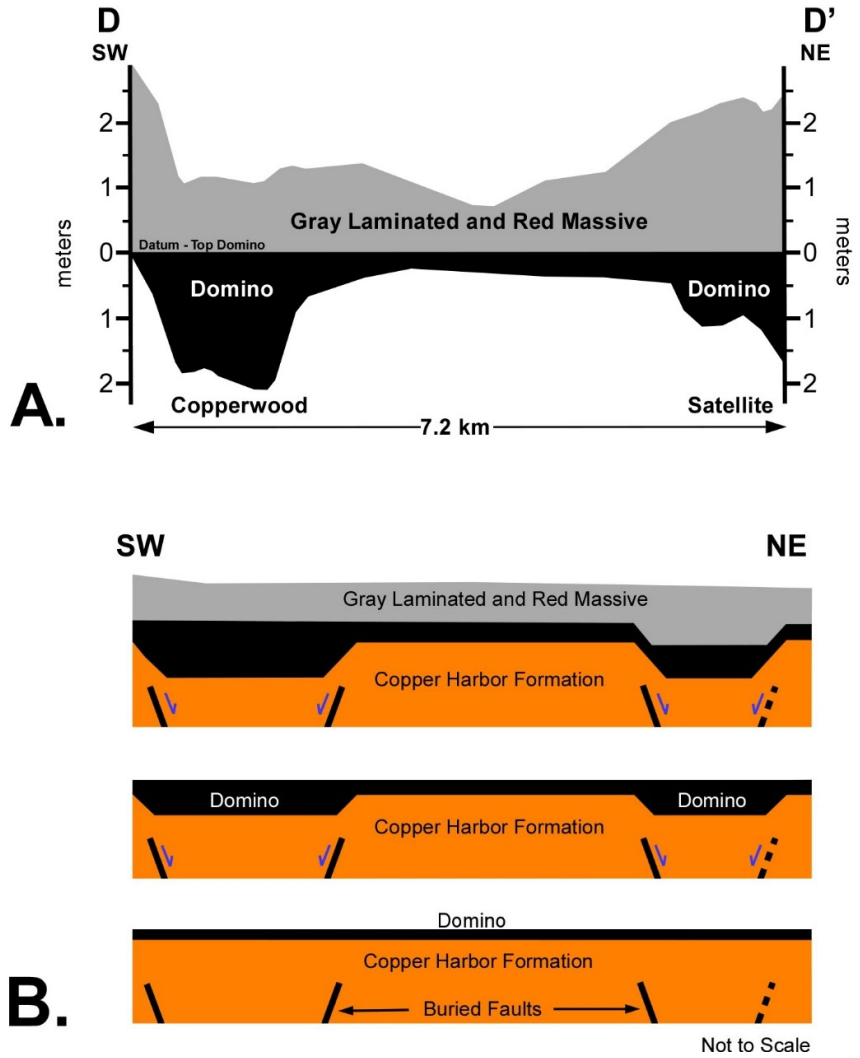

Figure 9. Cross-section depicting postulated mechanism for variable unit thicknesses. Location of cross-section shown in Figure 2B. (**A**) SW-NE cross-section showing thickness changes of Domino and Gray Laminated; (**B**) Model for development of thicker Domino characteristic of the higher-grade Copperwood deposit. Buried faults are proposed to lie under the thicker area of Domino and Gray Laminated. Progressively differential, occasional movements along buried faults resulted in local thickening of the Domino and, to the northeast, of the Gray Laminated.

7. Conclusions

Low-energy, finer-grained sediments, within which TOC and S are sufficiently elevated to accommodate sequestration of Cu from passing fluids, are host to chalcocite that replaced diagenetic pyrite in two discrete tabular copper deposits at Western Syncline. A minimum 2 m-thickness of >0.9% Cu in the favorable host rocks, dark-gray shales and siltstones, is not laterally continuous due to facies changes; thus, sedimentology/stratigraphy is a first-order control on potential ore. The second-order control on potential orebodies is the lithification process as it eventually occludes upward fluid flow, thus impeding the introduction of Cu into the favorable host rocks. A fixed volume of Cu-bearing fluids passed vertically through the sediment pile as the Top Cu Zone transgresses lithologic boundaries, which is a function of suitability of potential host rocks to sequester Cu as the fluids ascended. Syn-sedimentary faulting, likely along pre-existing structures, are a third-order control as the thickness of host rocks is enhanced under such conditions; these buried faults would have focused fluid flow upwards into the Nonesuch Formation. A thorough understanding of these geologic controls will enhance the mine sequencing, and thus the economics, of the proposed mine on the Western Syncline deposits.

Author Contributions: W.C.W. was the Chief Executive Officer and T.J.B. a retained consultant of OMC during the development of the project between 2008 and 2013 [7], at which time the concepts presented herein were conceptualized and methodologies defined. The application of software, validation of data and ideas, formal analyses, the investigation, resources, data curation were a joint effort. W.C.W. prepared the original draft of the manuscript and Bornhorst, as well as representatives of Highland Copper Company Inc. and the United State Geological Survey, reviewed and edited various versions prior to submittal. The visualization, supervision, and project administration were a joint effort. In 2014, the authors participated in the sampling of $\frac{1}{4}$ core and pulps from the USMR and OMC drilling samples, respectively. The interpretations and conclusions presented herein are based on our logging of drill core supplemented by legacy drill logs as well as geochemical data. All authors have read and agreed to the published version of the manuscript.

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