

MCR-GeoChem: A harmonized, quality-flagged open compilation of whole-rock and mineral geochemistry for the 1.1 Ga Midcontinent Rift in Michigan, Minnesota, and Wisconsin

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MCR-GeoChem: A harmonized, quality-flagged open compilation of whole-rock and mineral geochemistry for the 1.1 Ga Midcontinent Rift in Michigan, Minnesota, and Wisconsin

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Nickel, copper, cobalt, and the platinum-group metals are all on the final 2025 U.S. List of Critical Minerals, and the 1.1-billion-year-old Midcontinent Rift around Lake Superior hosts some of the largest domestic resources of them. The rock chemistry needed to study these systems is public but fragmented: it is spread across the U.S. Geological Survey (USGS) National Geochemical Database, project-level USGS data releases, the GEOROC compilation, and individual EarthChem datasets, each with its own units, method codes, and conventions for values below or above analytical limits. We present MCR-GeoChem v1.0.0, an open, versioned, reproducible compilation of 3,524 Midcontinent Rift samples and 168,748 geochemical determinations (88 analytes) from Michigan, Minnesota, and Wisconsin. Every value is converted to a common unit scheme (oxides in wt%, trace elements in ppm, Au and platinum-group elements in ppb) while retaining its original form; censored values are decoded into an explicit qualifier and limit; 89 source method codes are mapped to a common vocabulary of technique, digestion, and completeness; and each sample carries a rift-membership label tied to the USGS State Geologic Map Compilation. An open checker, `mcrqa`, adds value- and sample-level flags for below-detection results, uninformative detection limits, semi-quantitative and partial-digestion methods, unit errors, oxide-total problems, likely post-magmatic alteration, coordinate quality, and cross-source duplicates. The compilation shows that 27% of determinations derive from legacy semi-quantitative emission spectrography, that 501 of 1,304 platinum results are below-detection values whose limits are too high to constrain the rock, and that 488 of 2,821 igneous whole-rock samples carry at least one alteration flag. The full pipeline rebuilds the release from public sources with identical results. The dataset, the method and detection-limit crosswalk, and the checker are released under open licenses to support critical-mineral research in the Lake Superior region.

Keywords: Midcontinent Rift, Keweenaw, Duluth Complex, critical minerals, platinum-group elements, geochemical data harmonization, detection limits, data quality

I. INTRODUCTION

Critical-mineral policy in the United States has turned attention back to old geological provinces whose resource potential was characterized decades ago with the analytical tools of the time. The final 2025 U.S. List of Critical Minerals, released by the U.S. Geological Survey (USGS) in November 2025, contains 60 commodities and includes nickel, cobalt, platinum, palladium, and, for the first time, copper [1]. The 1.1 Ga Midcontinent Rift (MCR) of the Lake Superior region is one of the few places in the conterminous United States where all of these commodities occur in significant concentrations: magmatic Cu–Ni–platinum-group element (PGE) sulfide mineralization at the base of the Duluth Complex and in smaller conduit intrusions such as Eagle [2], native copper in the Keweenaw Peninsula lavas and interflow conglomerates [3], and sediment-hosted stratiform copper in the Nonesuch Shale at White Pine and Copperwood [4]. The USGS Earth Mapping Resources Initiative (Earth MRI) funds new geologic, geophysical, and geochemical mapping in such regions [5], and USGS Midcontinent Rift projects have recently released new drill-core geochemistry for the Duluth Complex [6].

Every one of these efforts begins with the same step: assembling the existing rock chemistry. That chemistry is public, but it is fragmented. The USGS National Geochemical Database (NGDB) now publishes 1.5 million samples analyzed between 1962 and 2023 [7]; project data releases add newer analyses in their own formats [6, 8, 9]; the GEOROC compilation, now being rebuilt as GEOROC 2.0 [10], holds published analyses grouped by tectonic province and mineral [11, 12]; and individual studies deposit their own tables in repositories such as the EarthChem Library [13]. Each source uses its own units (element percent versus oxide weight percent, ppm versus ppb), its own codes for analytical methods, and its own conventions for values below a detection limit or above an upper limit. In the NGDB, for example, a value of -0.5 means “less than 0.5,” and a value of 10.11111 means “greater than 10” [7]. A user who joins these sources without decoding such conventions will silently treat a detection limit as a measured concentration, or an upper limit as a typing error.

These problems are well recognized in geochemistry. Community reviews call for machine-readable data with explicit units, methods, uncertainties, and provenance [14], in line with the FAIR principles [15]. Statistical treatment of censored (below-detection) data is a mature field [16], and the USGS “best value” approach provides a ranked choice among multiple determinations of the same element in one sample [17]. What has been

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missing for the MCR is a single open table that applies these practices across the major public sources, documents every decision, and flags rather than hides the quality problems that remain.

This paper describes MCR-GeoChem v1.0.0, built to fill that gap. Its contributions are: (i) a harmonized compilation of 3,524 samples and 168,748 determinations from 6 public sources, restricted to Midcontinent Rift rocks in Michigan, Minnesota, and Wisconsin by a documented membership rule; (ii) a crosswalk that maps 89 analytical-method codes to a common vocabulary, with a method-by-analyte detection-limit table; (iii) an open quality-assurance checker, *mcrqa*, usable on any geochemistry table; and (iv) a reproducible pipeline and provenance log that rebuild the release from the public sources.

The paper is organized as follows. Sec. II summarizes the geological setting and scope. Sec. III describes the sources. Sec. IV sets out the harmonization, membership, crosswalk, best-value, and QA methods. Sec. V describes the resulting dataset. Sec. VI reports technical validation. Sec. VII gives usage notes, Sec. VIII lists limitations, and Sec. IX concludes.

II. GEOLOGICAL SETTING AND SCOPE

The Midcontinent Rift is a failed intracontinental rift that formed around 1.1 Ga and extends more than 2000 km from Kansas through the Lake Superior basin and south through Michigan [18, 19]. Seismic reflection profiling beneath Lake Superior imaged a very thick succession of rift volcanic and sedimentary rocks [18], and it has been proposed that the rift was part of a larger plate-boundary system [19]. Exposed rift rocks in the three study states comprise four broad groups [20]: (1) flood basalts and associated felsic volcanic rocks, including the Portage Lake Volcanics of the Keweenaw Peninsula, the Porcupine Volcanics and Powder Mill Group of Michigan and Wisconsin, the Chengwatana Volcanic Group, and the North Shore Volcanic Group of Minnesota; (2) large mafic intrusions, above all the Duluth Complex, together with the Beaver Bay Complex, the Mellen Complex, and numerous sills and dikes; (3) rift-basin sedimentary rocks of the Oronto Group (Copper Harbor Conglomerate, Nonesuch Shale, Freda Sandstone) and their equivalents; and (4) late- to post-rift sandstones of the Bayfield Group and Jacobsville Sandstone. Basalt geochemistry has been correlated across the rift to identify multiple mantle sources [21], and U-Pb geochronology shows that the Duluth Complex was emplaced during the main magmatic stage around 1.1 Ga [22], with much of its volume intruded rapidly [23].

The scope of v1.0.0 is the rift as exposed or drilled in Michigan, Minnesota, and Wisconsin. Rift rocks in Ontario and the buried southern segment of the rift are outside the study area by design. Following the economic relevance of the province, all rift rocks are included, not

only igneous rocks, and each sample carries a class label (rift igneous, rift sedimentary, or post-rift sedimentary) so users can select the subset they need.

III. DATA SOURCES

Table I lists the sources, their licenses, and the number of samples read, located in the study states, and retained. All are openly accessible. Sources S1, S2, S3, and S7 are USGS data releases in the U.S. public domain; S4–S6 are licensed CC BY-SA 4.0.

S1, USGS NGDB 1962–2023. The NGDB release of Granitto *et al.* [7] (published January 2026) covers 1,524,014 samples within U.S. boundaries. Since its November 2025 file update the ScienceBase bulk files (geodatabase, GeoPackage, Parquet) require a ScienceBase login; the same release is served by a public USGS ArcGIS feature service linked from the USGS Geochemical Data Portal. We queried its Rock, Mineral, and Geologic-material layers for state IN ('MI', 'MN', 'WI'), which returned 6,496 samples. Each record carries one “best value” per species with its method code, and, where several determinations exist, a text field listing every value and method.

S2, USGS Duluth Complex release. Parks *et al.* [6] report 390 drill-core and hand samples from the Duluth Complex and its footwall, with qualifier, numeric, and method columns for every element and a method dictionary.

S3, USGS Earth MRI geochemistry v12.0. The Earth MRI release [9] contains 777 rock samples in the three states. None are rift rocks (they are Archean, Paleoproterozoic, or Paleozoic), so S3 contributes no samples to v1.0.0; it remains in the pipeline so that later versions are screened automatically.

S4, GEOROC Continental Flood Basalts, Midcontinent Rift System–Keweenaw. The GEOROC precompiled file (generated 1 September 2026) [11] holds 1,357 published whole-rock analyses from the whole rift, including Ontario; 718 fall in the three study states.

S5, GEOROC Minerals. The 19 global GEOROC mineral files [12] (about 2.4 million analyses) were each downloaded, filtered to a box around the study region or to locations naming the rift, and discarded, leaving 4,450 analyses for screening.

S6, EarthChem Library dataset 1501. Davis, Collins, and Rooney [13] report XRF and LA-ICP-MS analyses of 55 Portage Lake Volcanics samples with IGSN identifiers and a method metadata sheet.

S7, USGS Duluth Complex basal contact. Woodruff [8] reports 42 bedrock samples from three watersheds that cross the basal contact of the Duluth Complex, with an analytical-method and lower-limit table.

Supporting sources. Rift membership uses the USGS State Geologic Map Compilation (SGMC) [24]; method definitions come from the method and parameter tables

TABLE I. Sources of MCR-GeoChem v1.0.0. “Read”: samples read from the source; “MI/MN/WI”: located in the study states; “Kept”: retained as Midcontinent Rift samples; “Determinations”: values retained before the derived Fe_2O_3^T values are added. PD: U.S. public domain.

ID	Source	License	Read	MI/MN/WI	Kept	Determinations
S1	USGS NGDB 1962–2023 [7]	PD	6,496	6,496	2,237	125,952
S2	USGS Duluth Complex [6]	PD	390	390	331	27,267
S3	USGS Earth MRI v12.0 [9]	PD	777	777	0	0
S4	GEOROC CFB: MCR–Keweenawan [11]	CC BY-SA	1,357	718	661	10,310
S5	GEOROC Minerals (region) [12]	CC BY-SA	4,450	974	204	1,091
S6	EarthChem 1501 [13]	CC BY-SA	55	55	55	2,255
S7	USGS Woodruff (2019) [8]	PD	42	42	36	1,614
Total			13,567	9,452	3,524	168,489

of the USGS Alaska Geochemical Database version 4 (AGDB4) [25], which use the same method-code system as the NGDB; state assignment uses U.S. Census Bureau TIGER/Line 2023 state boundaries [26].

IV. METHODS

A. Acquisition and provenance

A single script downloads every input and appends, for each file, the source identifier, file name, URL, access date, size in bytes, SHA-256 checksum, license, and full citation to a provenance log. Feature-service queries are paged and stored as JSON together with the query text and retrieval time. The provenance log is published with every release and rendered as a human-readable page with row counts.

B. Data model

The compilation has three linked tables. The *samples* table has one row per sample (or per mineral analysis spot) with location, coordinate quality, sample type (whole rock, mineral grain, mineral separate), rock class, stratigraphy as given by the source, rift-membership class, and QA results. The *long* table has one row per determination: sample identifier, analyte, harmonized value, unit, censoring qualifier, detection limit, method, a best-value indicator, and the original analyte name, unit, and value exactly as written in the source. The *wide* table holds one row per sample with best values as columns, for convenience. Each sample has a permanent identifier of the form MCRG-`<source>-<source sample id>`.

C. Unit harmonization

Target units are oxide wt% for major elements, loss on ignition (LOI), and volatiles; ppb for Au, Pt, Pd, Rh, Ru, Ir, Os, and Re; and ppm for all other elements. Sources

TABLE II. Gravimetric conversion factors f_{ox} of Eq. (1) applied to element-basis major elements.

Reported	Converted to	f_{ox}
Si	SiO_2	2.1393
Ti	TiO_2	1.6681
Al	Al_2O_3	1.8895
Fe	Fe_2O_3^T	1.4297
Mn	MnO	1.2912
Mg	MgO	1.6583
Ca	CaO	1.3992
Na	Na_2O	1.3480
K	K_2O	1.2046
P	P_2O_5	2.2914
FeO^T	Fe_2O_3^T	1.1113

that report major elements on an element basis (the USGS sources report Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P in percent) are converted to oxides with gravimetric factors,

$$c_{\text{ox}} = f_{\text{ox}} c_{\text{el}}, \quad f_{\text{ox}} = \frac{M_{\text{ox}}}{n M_{\text{el}}}, \quad (1)$$

where M are molar masses and n is the number of cation atoms per oxide formula unit. The factors used are listed in Table II. Total iron is expressed as Fe_2O_3^T . FeO^T is converted with $f = 1.1113$, and where only Fe_2O_3 and FeO are reported,

$$\text{Fe}_2\text{O}_3^T = \text{Fe}_2\text{O}_3 + 1.1113 \text{FeO}, \quad (2)$$

recorded as a derived value (259 samples). In GEOROC files a lone FE203 column (no FeO or FeO^T in the same sample) holds total iron in practice and is labeled Fe_2O_3^T ; the rule is recorded with the value. Unit changes between ppm, ppb, and wt% use exact powers of ten. Non-chemical fields (density, pH, sample weights) are not carried.

D. Censored values

Each determination is stored as a triple (v, q, L) of value, qualifier, and limit:

$$(v, q, L) = \begin{cases} (x, \emptyset, \emptyset) & \text{measured,} \\ (\emptyset, <, L_{lo}) & \text{below lower limit,} \\ (\emptyset, >, L_{hi}) & \text{above upper limit.} \end{cases} \quad (3)$$

The NGDB qualified-value convention is decoded as follows: a negative number $-x$ becomes $(<, x)$, and a number whose fractional part is 0.1111 becomes $(>, \lfloor x \rfloor)$ [7]. Earth MRI uses the same negative-value convention [9]. Text values such as <0.5 , >10000 , and $bd1$ are parsed directly. The limit is converted to the target unit with the same factor as the value, so a censored Si result becomes a censored SiO_2 result with a converted limit. In the wide table, below-limit values are written as the negative of the limit, following the USGS convention, so that the file stays numeric.

E. Rift membership

A sample is retained only if (a) its coordinates fall in Michigan, Minnesota, or Wisconsin (TIGER/Line state polygons, including Great Lakes waters), and (b) a membership rule assigns it to the rift. We extracted all 77 Mesoproterozoic SGMCM map units in the three states and labeled each as rift igneous, rift sedimentary, post-rift sedimentary, or excluded (Table III). Excluded units are the Wolf River batholith, Wausau and Stettin plutons (about 1.47–1.56 Ga, older than the rift) and the Minnesota unit of mafic intrusions of unknown age. For each sample, let P be the text of its primary unit fields (stratigraphy, unit names), S the text of secondary fields (deposit, project, locality), A its geologic-age label, and m the SGMCM class at its location. With $R(\cdot)$ a match against a list of rift unit and locality names and $N(\cdot)$ a match against non-rift units and ages, the decision is

$$\text{MCR} = \begin{cases} \text{yes (text)} & R(P) \wedge \neg N(P), \\ \text{no} & N(P) \vee N(A), \\ \text{yes (map)} & m \in \text{rift classes}, \\ \text{yes (context)} & R(S) \wedge \neg N(S), \\ \text{no} & \text{otherwise,} \end{cases} \quad (4)$$

evaluated in that order. Membership classes are then refined: a sample whose source names a post-rift or rift-basin sedimentary unit takes that class, and an igneous rock on a sedimentary map polygon (a dike, or a mapping-scale effect) is labeled rift igneous. Each sample records how it was matched, so that users can drop the lower-confidence “map” and “context” matches. Every excluded sample is written to a separate table with its reason.

TABLE III. Rift-membership classes of the 77 Mesoproterozoic SGMCM map units in the study states, with examples and the number of retained samples per class. Match types of retained samples: map 443, map+context 6, text 671, text+map 2,404.

Class	Units	Examples	Samples
Excluded	15	Wolf River batholith; Wausau and Stettin plutons	–
Post-rift sedimentary	5	Jacobsville Sandstone; Bayfield Group	34
Rift igneous	46	Portage Lake Volcanics; Duluth Complex units (Y3); Mellen Complex	3,076
Rift sedimentary	11	Nonesuch Shale; Copper Harbor Conglomerate; Freda Sandstone	414

F. Method crosswalk and detection limits

Each source method code is mapped to a record giving the technique, the digestion or preparation, and an *extent* class: total, near-total, partial, semi-quantitative, or unknown. For the NGDB the code grammar (technique prefix, digestion suffix, and a $_P$ partial marker) is combined with the AGDB4 method dictionary, which supplies descriptions, digestions, and references for 51 of the 54 NGDB codes present; three rarely used codes are classified from the grammar alone. Codes from S2, S6, and S7 are mapped from each release’s own method table. GEOROC precompiled files do not carry per-value methods and are marked “not reported.” The detection-limit table records, for each source, method, and analyte, the number of determinations, the number and share censored, the minimum and maximum limits actually reported with censored values, the documented lower limit of determination where available, and the USGS best-value rank of the method.

G. Best values

Where a sample has several determinations of one analyte, exactly one is marked as the best value. If the source designates a best value (NGDB, S2), it is kept. Otherwise determinations are ranked lexicographically by

$$\text{rank} = (\mathbb{1}[\text{censored}], e, L), \quad (5)$$

where e orders extents as total $<$ near-total $<$ unknown $<$ partial $<$ semi-quantitative, and L is the detection limit. A measured value therefore wins over a censored one, a total digestion over a partial one, and a lower limit over a higher one.

H. Quality-assurance checker

The `mcrqa` package adds flags; it never changes values. Its thresholds are defaults with stated bases and can be overridden by a JSON file.

Value-level flags. BDL marks $q = <$; BDL_UNINFORMATIVE marks censored values with $L > \tau_a$, where τ_a is an analyte-specific threshold near typical rock abundance (for example 10 ppb for Pt, Pd, and Au, and 50 ppm for Ni and Cu); ABOVE_UPPER_LIMIT marks $q = >$; SEMI_QUANTITATIVE, PARTIAL_DIGESTION, and METHOD_NOT_REPORTED follow the crosswalk extent; IMPLAUSIBLE_VALUE marks negative values (LOI excepted down to -5 wt%), values above 100 wt%, or above 10^6 ppm; POSSIBLE_UNIT_ERROR marks whole-rock values above generous ceilings for unmineralized rock (for example 5000 ppm Ni or Cu, 2000 ppb Pt) unless the sample has ≥ 1 wt% S; and ZERO_VALUE marks exact zeros.

Oxide totals. When SiO_2 , Al_2O_3 , Fe_2O_3^T , MgO , CaO , Na_2O , and K_2O are all measured and at least eight of the ten major oxides are present,

$$\Sigma = \sum_{i \in \text{majors}} c_i + \text{LOI}, \quad (6)$$

with $\text{H}_2\text{O} + \text{CO}_2$ substituted when LOI is missing. Totals outside 96–102.5 wt% are flagged, except that low totals are not flagged when $S \geq 1$ wt%, since sulfide-rich samples are not oxide-dominated. Requiring measured SiO_2 matters: HF-based digestions lose Si, and totals computed without it are meaningless. An igneous SiO_2 between 15 and 32 wt% is flagged as a possible element-for-oxide error, because Si in a basalt is about 22–24 wt%.

Alteration. For igneous whole rocks, three indices are computed from best values. The Chemical Index of Alteration [27] is

$$\text{CIA} = 100 \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O}}, \quad (7)$$

in molar proportions, with $\text{CaO}^* = \text{CaO} - \frac{10}{3}\text{P}_2\text{O}_5 - \text{CO}_2$ (molar, floored at zero) to remove apatite and calcite. The Ishikawa alteration index [28, 29] is

$$\text{AI} = 100 \frac{\text{MgO} + \text{K}_2\text{O}}{\text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}}, \quad (8)$$

in wt%. A sample is flagged ALTERED_LOI if LOI > 3 wt%, ALTERED_CIA if CIA > 60 , ALTERED_AI if AI lies outside 20–65 (the least-altered field of the alteration box plot [29]), and ALTERED_SOURCE if the source describes alteration. The summary indicator `altered_likely` is true if any of these is set.

Coordinates. Samples are flagged COORD_MISSING, COORD_APPROXIMATE (one decimal place, or the centroid of a GEOROC latitude–longitude box wider than 0.01°), or COORD_STATE_MISMATCH.

I. Cross-source duplicates

The same physical sample can appear in more than one source, for example a Duluth Complex drill-core interval in both the NGDB and the 2025 USGS release. Two samples j, k from different sources are linked if

$$\max(|\Delta\varphi|, |\Delta\lambda|) \leq 0.005^\circ \wedge [\text{ID}_j = \text{ID}_k \vee (\delta_{\text{SiO}_2} \leq 1\% \wedge \delta_{\text{MgO}} \leq 1\%)], \quad (9)$$

where φ, λ are latitude and longitude, ID is the field or laboratory identifier normalized to upper-case alphanumeric, and δ is the relative difference. Linked samples are grouped by union-find. Duplicates are flagged and given a group identifier, not removed.

J. Author corrections

The pipeline changes no source value except by documented unit conversion and by corrections listed in a corrections file, each with the original value, the corrected value, the reason, the decision maker, and the date. One correction was applied in v1.0.0: USGS sample MCRG-S2-1002826 is reported with Pd = 123,000 ppb and Pt = 123 ppb, a Pd/Pt ratio near 1000; the authors judged the Pd value a transcription error and normalized it to 123 ppb. The original value is kept in the long table, and the row carries the flag AUTHOR_CORRECTED. We note that several other samples from the same deposit area (NorthMet, west pit) also show Pd far in excess of Pt, so Pd–Pt decoupling in Cu-rich sulfide cannot be excluded; confirmation has been requested from the data release authors, and users can recover the published value from `value_source` or by setting aside the corrections file.

K. Software and reproducibility

The pipeline is a set of numbered Python scripts using pandas [30], GeoPandas, Shapely, and Matplotlib. A run-all script downloads the sources, builds and checks the tables, draws the figures, renders every number in the documentation from a statistics file written by the pipeline, and packages the release. The `mcrqa` checker is an installable package with a command-line interface for long-format tables and for ordinary wide spreadsheets, and with 14 automated tests.

V. RESULTS

A. Dataset composition

MCR-GeoChem v1.0.0 contains 3,524 samples: 1,695 in Minnesota, 1,057 in Michigan, and 772 in Wisconsin.

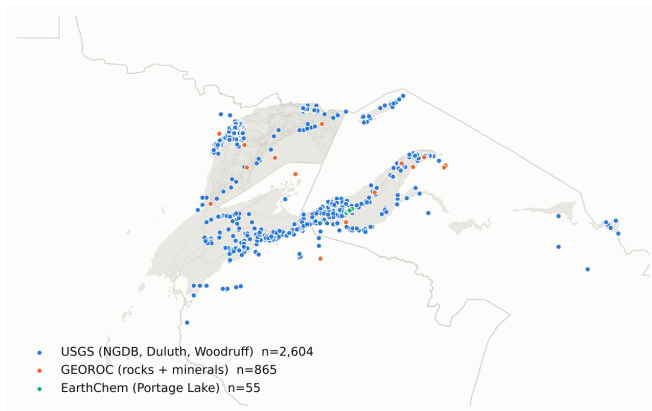


FIG. 1. Locations of the 3,524 MCR-GeoChem v1.0.0 samples, grouped by source family, over the Mesoproterozoic rift map units of the USGS State Geologic Map Compilation used for membership (gray). State outlines are U.S. Census TIGER/Line 2023 boundaries, which include Great Lakes waters.

(Fig. 1). Of these, 3,320 are whole-rock analyses and 204 are in-situ mineral analyses from GEOROC, dominated by zircon (119) with plagioclase, clinopyroxene, olivine, and sulfides. By rift class, 3,076 samples are rift igneous, 414 rift sedimentary, and 34 post-rift sedimentary; by rock class, 1,690 are intrusive and 1,310 volcanic. Drill core supplies 1,173 samples and natural outcrop 869. The long table holds 168,748 determinations of 88 analytes, of which 145,596 are best values; 26.3% of best values are below detection. The NGDB supplies most samples (2,237), followed by GEOROC rock analyses (661), the 2025 USGS Duluth release (331), GEOROC minerals (204), EarthChem (55), and the Woodruff release (36).

Membership was decided by a named rift unit in the source for 3,075 samples (2,404 of them also on a rift map unit), and by the map alone for 443 samples (Table III). Of all samples read, 10,043 were excluded, most commonly because the source names a non-rift unit (for example Michigamme Slate, Biwabik Iron Formation, or Giants Range Granite) or a non-rift age, or because the coordinates fall outside the three states (most GEOROC rift samples outside the study area are in Ontario).

B. Analytical methods and detection limits

After crosswalk harmonization the determinations fall into 83,735 total, 25,044 near-total, 1,934 partial, 46,375 semi-quantitative, and 11,401 unknown-method records (Table IV). The single largest technique family is DC-arc emission spectrography (Fig. 2), the screening method of USGS geochemical surveys from the 1960s through the 1980s. Its results are reported in steps and carry high limits for precious metals. The “not reported” family consists entirely of GEOROC values.

TABLE IV. Method codes and determinations by crosswalk extent class.

Extent	Codes	Determinations	Share (%)
total	53	83,735	49.7
near-total	20	25,044	14.9
partial	13	1,934	1.1
semi-quantitative	1	46,375	27.5
unknown	2	11,401	6.8

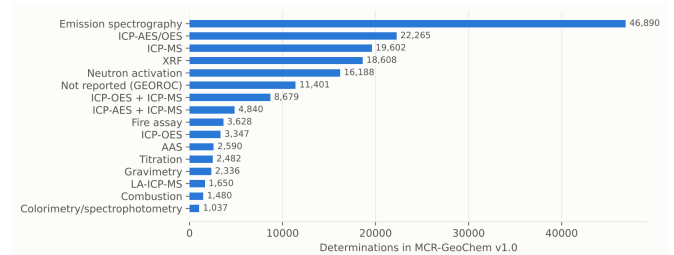


FIG. 2. Determinations by analytical technique family after crosswalk harmonization (families with at least 500 determinations). The code-level mapping of all 89 method codes is released as `method_crosswalk.csv`.

C. Critical metals

Table V and Fig. 3 summarize best values for the critical base and precious metals. Nickel, copper, and cobalt are measured in 95%, 98%, and 99% of the samples that report them, with median measured values of 120, 108, and 47 ppm. The precious metals are a different story. Of 1,304 samples with a platinum best value, only 579 are measured; of the 725 below-detection results, 501 have limits above 10 ppb, most from emission spectrography with limits of 1000–50,000 ppb. Palladium (648 of 1,304 measured; 502 uninformative) and gold (922 of 2,243; 818 uninformative) follow the same pattern. For these elements, a “below detection” entry in the legacy record says almost nothing about whether a rock is enriched, and treating it as zero, or as half the limit, would bias any regional assessment.

D. Quality-assurance outcomes

Table VI lists the flag counts and Fig. 4 the sample-level flags. At the value level, the most common flags are SEMI_QUANTITATIVE (46,375), BDL (42,788), BDL_UNINFORMATIVE (16,361), and METHOD_NOT_REPORTED (11,401). Only 161 values exceed the unit-error ceilings; inspection shows most are genuine ore samples (for example native-copper and chalcocite ore from the Nonesuch Shale) in which sulfur was not reported, so the sulfide exemption could not apply.

Of the 1,828 samples with a computable oxide total,

TABLE V. Best values for critical metals. “Uninf.”: below-detection results with limits above the mcrqa threshold; “Median”: median of measured best values.

Metal	Unit	<i>n</i>	Measured	BDL	Uninf.	Median
Ni	ppm	2,782	2,650	115	0	120
Cu	ppm	2,667	2,601	34	0	108
Co	ppm	2,733	2,693	40	0	47
Pt	ppb	1,304	579	725	501	16
Pd	ppb	1,304	648	656	502	12
Au	ppb	2,243	922	1,321	818	5

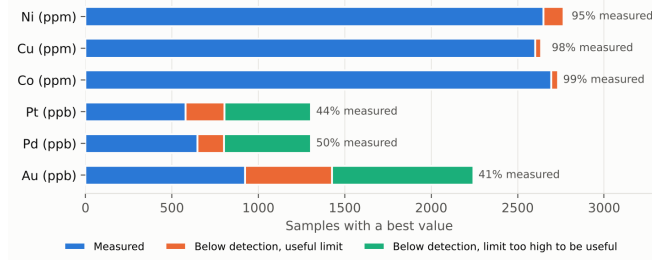


FIG. 3. Best values for critical metals, split into measured results, below-detection results with a useful limit, and below-detection results whose limit exceeds the mcrqa threshold (for example 10 ppb for Pt, Pd, and Au). Labels give the measured share.

1,396 fall within 96–102.5 wt% (median 99.62 wt%). At the sample level, 750 samples have approximate coordinates (nearly all from GEOROC), and 239 samples in 110 groups are probable cross-source duplicates. Among igneous whole rocks, 488 of 2,821 (17%) carry an alteration flag. The Ishikawa index fires most often (283), followed by LOI (184), source descriptions (87), and CIA (39). Fig. 5 shows that flagged samples are concentrated at low alkali contents in mafic and ultramafic cumulates and at scattered positions off the main magmatic trend, as expected for samples whose alkalis were mobilized after crystallization.

VI. TECHNICAL VALIDATION

Reproducibility. The complete pipeline was rerun in an empty folder, downloading every source again. The rerun reproduced every headline count (samples, determinations, best values, analytes, method codes, exclusions, state totals, alteration and duplicate counts, and critical-metal statistics) and produced byte-identical samples, wide, and crosswalk tables. The single author correction (Sec. IV) is applied deterministically from the corrections file after harmonization, so it does not affect reproducibility.

Spot checks against the sources. Values chosen to include easy cases, hard cases, and extremes from every source were compared with the original records

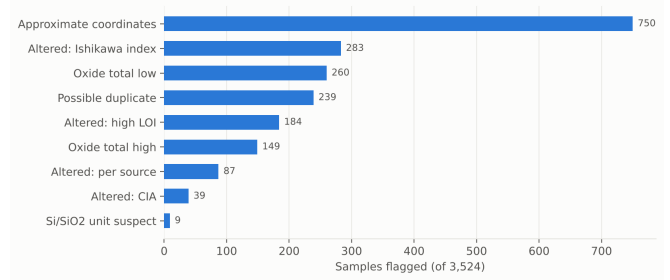


FIG. 4. Sample-level flags from mcrqa for the 3,524 samples. A sample can carry several flags.

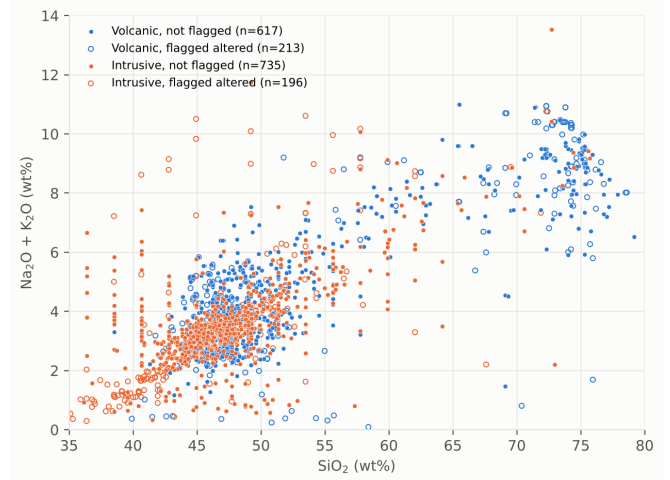


FIG. 5. Total alkali versus silica for 1,761 rift igneous whole rocks with measured SiO₂, Na₂O, and K₂O (best values). Open symbols carry at least one mcrqa alteration flag (LOI > 3 wt%, CIA > 60, Ishikawa AI outside 20–65, or a source description of alteration).

(Table VII). All matched after the documented conversions; for example, NGDB Si = 22.3% becomes SiO₂ = 47.71 wt% by Eq. (1), and an NGDB Pt value of −30 ppm is decoded as Pt < 30,000 ppb. The same review flagged the Duluth palladium value corrected in Sec. IV, whose Pd/Pt ratio near 1000 was implausible. A verification checklist distributed with the release adds five randomly selected best values (fixed random seed) and a review of excluded samples for independent checking by users.

Checker tests. The 14 unit tests of mcrqa cover the element-to-oxide and FeO^T conversions, PGE unit changes, decoding of the USGS negative and .11111 conventions, text qualifiers, every value-level flag, oxide totals, the three alteration indices on fresh and altered basalt compositions, coordinate flags, duplicate grouping, and the wide-spreadsheet mode.

Internal consistency. Every determination links to exactly one sample and one crosswalk record; exactly one best value exists per sample and analyte; and every excluded sample has a reason. The median oxide total of 99.62 wt% indicates that the unit conversions and the

TABLE VI. Flag counts from mcrqa: value-level flags (left) over 168,748 determinations and sample-level flags (right) over 3,524 samples.

Value flag	Count	Sample flag	Count
SEMI_QUANTITATIVE	46,375	COORD_APPROXIMATE	750
BDL	42,788	ALTERED_AI	283
BDL_UNINFORMATIVE	16,361	MAJOR_TOTAL_LOW	260
METHOD_NOT_REPORTED	11,401	POSSIBLE_DUPLICATE	239
PARTIAL_DIGESTION	1,934	ALTERED_LOI	184
ZERO_VALUE	452	MAJOR_TOTAL_HIGH	149
ABOVE_UPPER_LIMIT	294	ALTERED_SOURCE	87
POSSIBLE_UNIT_ERROR	161	ALTERED_CIA	39
AUTHOR_CORRECTED	1	SI_ELEMENT_SUSPECT	9

TABLE VII. Spot checks of harmonized values against the source records. All matched after the documented conversion. Identifiers omit the MCRG- prefix.

Sample	Analyte	MCR-GeoChem	Source value	Source method
S1-W210634	Pt	4,600 ppb	4.6 ppm	ES_SQ
S1-W210634	Pd	<1,000 ppb	-1.0 ppm	ES_SQ
S1-W210634	Cu	24 ppm	24.0 ppm	EDX
S1-W210634	Ni	30 ppm	30.0 ppm	AA_F_HF
S1-C100666	SiO ₂	47.71 wt%	22.3 pct	WDX_Fuse
S1-C100666	MgO	7.346 wt%	4.43 pct	WDX_Fuse
S1-C100666	Fe ₂ O ₃ T	11.8 wt%	8.25 pct	WDX_Fuse
S1-W175024	Cu	125,000 ppm	125000.0 ppm	AA_F_HF
S1-AHK811	Pt	<30,000 ppb	-30.0 ppm	ES_SQ
S1-AHK811	Au	<20 ppb	-0.02 ppm	AA_F_HBr
S2-1002841	Pd	10,200 ppb	10200 ppb	C_FA_TRACE_AU-PD-PT
S2-1002841	Pt	<5 ppb	<5 ppb	C_FA_TRACE_AU-PD-PT
S2-1002841	Cu	192,000 ppm	192000 ppm	C_ICPOES_MS-60
S4-104473	SiO ₂	67.5 wt%	67.5 wt%	not reported (GEOROC p
S4-104473	TiO ₂	0.95 wt%	0.95 wt%	not reported (GEOROC p
S4-104473	Zr	600 ppm	600 ppm	not reported (GEOROC p
S6-9550	SiO ₂	46.21 wt%	46.21 WT%	ECL1501-1:XRF
S6-9550	Fe ₂ O ₃ T	12.81 wt%	12.81 WT%	ECL1501-1:XRF
S6-9550	Ni	235.1 ppm	235.1 PPM	ECL1501-1:ICP:MS-LA
S7-C-392223	Cu	141 ppm	141.0 ppm	ICPAES_MS
S7-C-392223	Ni	296 ppm	296.0 ppm	ICPAES_MS
S7-C-392223	Al ₂ O ₃	17.04 wt%	9.02 wt%	ICPAES_MS
S5-OLIVINES-2150	MgO	30.4 wt%	30.4 wt%	not reported (GEOROC p
S5-OLIVINES-2150	SiO ₂	36.83 wt%	36.83 wt%	not reported (GEOROC p

Fe₂O₃^T convention are applied consistently.

VII. USAGE NOTES

For regional statistics, keep one sample per duplicate_group, use is_best_value = True, and decide explicitly how to treat censored values; methods for censored environmental data [16] apply directly. For precious metals, exclude BDL_UNINFORMATIVE values or treat them as missing rather than as small concentrations. For igneous petrogenesis, filter on altered_likely = False, on extent in {total, near-total}, and on mcr_match

in {text, text+map}. For mineral-potential work, retain semi-quantitative data as presence/absence screening evidence but do not mix them with quantitative data in averages. The checker can be applied to new data before merging: `mcrqa wide table.csv -id-col Sample -out qa/` reads USGS-style, GEOROC-style, or simple column headers and writes the flags and a summary.

VIII. LIMITATIONS

(1) State geological survey releases are not yet included; in October 2026 no machine-readable state chemistry

table for rift rocks was found, and candidate reports are listed for v1.1. (2) The NGDB was taken from the public feature service, which lacks per-determination laboratory names and dates. (3) GEOROC precompiled files lack per-value methods and limits (11,401 values) and often give approximate coordinates. (4) 27% of determinations are semi-quantitative. (5) Rift membership is algorithmic; 443 samples rest on the 1:500,000-scale map alone, and contact-zone hornfels such as the Virginia Formation are excluded although they matter for sulfide genesis. (6) Alteration indices were designed for volcanic and fresh igneous rocks; cumulates and sulfide-bearing rocks can trip them. (7) Mineral chemistry is limited to 204 GEOROC analyses. (8) 452 GEOROC values are exact zeros, kept and flagged. (9) NGDB depths often lack units and are not converted.

IX. CONCLUDING REMARKS

MCR-GeoChem v1.0.0 provides, for the first time to our knowledge, an open, documented, and quality-flagged geochemistry table for the Midcontinent Rift in Michigan, Minnesota, and Wisconsin. It assembles 3,524 samples and 168,748 determinations from six public sources, decodes their units and censoring conventions, maps 89 method codes to a common vocabulary, and labels every sample's rift membership and quality. The compilation makes visible what is otherwise hidden when sources are merged naively: more than a quarter of the record is semi-quantitative; most below-detection precious-metal results cannot constrain the rocks; about one igneous sample in six shows signs of alteration; and the same drill core appears in more than one federal release. Because every flag is explicit and every decision documented, users can apply their own filters rather than inherit hidden ones. Version 1.1 will add state-survey tables, GEOROC methods from the GEOROC 2.0 interface, and additional mineral chemistry; the open checker can be applied to any of these additions, and to other provinces, before they are merged.

DATA AND CODE AVAILABILITY

The MCR-GeoChem v1.0.0 dataset, with its code-book, provenance log, and QA report, is archived on Zenodo at doi:10.5281/zenodo.23501580. The method and detection-limit crosswalk is archived at doi:10.5281/zenodo.23501707, and the mcrqa checker with the full pipeline at doi:10.5281/zenodo.23501711. The development repository is <https://github.com/bkdanso/mcr-geochem> (release v1.0.0). Data are licensed CC BY-SA 4.0, as required by the share-alike terms of the GEOROC and EarthChem inputs; code is MIT-licensed; documentation is CC BY 4.0. Users should also cite the original sources [6–9, 11–13].

AUTHOR CONTRIBUTIONS

B.K.D.: Conceptualization, Data curation, Methodology, Software, Validation, Writing - original draft. S.A.: Validation (cross-checking of the geophysical aspects) and Visualization (review of the sample map and plotted figures). All authors approved the final manuscript.

USE OF AI TOOLS

AI assistance (Claude, Anthropic) was used for code development and text drafting. The authors reviewed and edited all content, verified the results, and take full responsibility for the work.

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Appendix A: Column dictionary

Table VIII lists the core columns of the samples and long tables. The full codebook, including the wide, crosswalk, detection-limit, and exclusion tables, is distributed with the data.

TABLE VIII. Core columns of the samples and long tables.

Table	Column(s)	Meaning
samples	mcr_uid	Permanent identifier, MCRG-<source>-<source id>
samples	source_id, source_sample_id	Source and the identifier used by the source
samples	latitude, longitude, coord_quality	Decimal degrees; reported, approximate, range_centroid, state_mismatch, missing
samples	state	MI, MN, or WI from TIGER/Line 2023 polygons
samples	sample_type	whole_rock, mineral_grain, mineral_separate
samples	rock_class, rock_name	Harmonized class; rock name as given by the source
samples	stratigraphy, geologic_age_source	Unit hierarchy and age label as given by the source
samples	sgmc_label, sgmc_unit_name	SGMC map unit at the sample point
samples	mcr_class, mcr_match, mcr_reason	Rift class; how membership was decided (Eq. 4); reason
samples	major_oxide_total, loi_wt	Eq. 6; LOI or H ₂ O+CO ₂ (wt%)
samples	cia, ai_ishikawa	Eqs. 7 and 8
samples	altered_likely, altered_criteria	Any ALTERED flag; the criteria that fired
samples	duplicate_group, qa_flags	Cross-source duplicate group (Eq. 9); sample flags
long	analyte, value, unit	Harmonized analyte, value, and unit (wt%, ppm, ppb)
long	censor, detection_limit	Qualifier and limit of Eq. 3
long	is_best_value, best_value_basis	One best value per sample and analyte (Eq. 5)
long	method_id, technique, digestion, extent	Key into the crosswalk and its harmonized fields
long	analyte_source, unit_source, value_source	Exactly as written in the source
long	harmonize_rule, derived, author_corrected	Conversion applied; calculated value; documented correction
long	qa_flags	Value-level flags

Appendix B: QA flag definitions

Table IX defines every flag emitted by mcrqa v1.0.0, as returned by mcrqa flags.

TABLE IX. Flags emitted by mcrqa.

Flag	Definition
BDL	Below detection limit: value unknown, less than the detection limit.
BDL_UNINFORMATIVE	Below detection, but the detection limit is so high the result says little about the rock.
ABOVE_UPPER_LIMIT	Above the method's upper limit: true value is higher than reported.
SEMI_QUANTITATIVE	Semi-quantitative method (e.g., DC-arc emission spectrography); use for screening only.
PARTIAL_DIGESTION	Partial digestion (e.g., aqua regia): may under-report elements in resistant minerals.
METHOD_NOT_REPORTED	The source file does not give the analytical method.
IMPLAUSIBLE_VALUE	Physically impossible after unit harmonization (negative, >100 wt%, >1,000,000 ppm).
AUTHOR_CORRECTED	Value corrected by the dataset authors; the original is kept in value_source (see docs/corrections.csv).
ZERO_VALUE	Reported as exactly zero; in compilations this usually means 'not detected' with no limit given.
POSSIBLE_UNIT_ERROR	Far above what unmineralized rock contains; check units (ppm vs ppb, element vs oxide).
MAJOR_TOTAL_LOW	Sum of major oxides + LOI below the accepted range.
MAJOR_TOTAL_HIGH	Sum of major oxides + LOI above the accepted range.
SI_ELEMENT_SUSPECT	SiO ₂ in an igneous rock is in the range expected if Si (element) was reported as SiO ₂ .
ALTERED_LOI	Loss on ignition above threshold: likely hydrated or carbonated.
ALTERED_CIA	Chemical Index of Alteration above threshold: feldspar likely weathered to clay.
ALTERED_AI	Ishikawa alteration index outside the least-altered range.
ALTERED_SOURCE	The source describes the sample as altered.
COORD_MISSING	No coordinates.
COORD_APPROXIMATE	Coordinates are approximate (one decimal place, or a locality range centroid).
COORD_STATE_MISMATCH	State given in the source differs from the state at the coordinates.
POSSIBLE_DUPLICATE	Same place and near-identical SiO ₂ and MgO (or same name) as a sample in another source.

Appendix C: Most frequent method codes

Table X shows the 20 method codes with the most determinations and their crosswalk entries.

TABLE X. The 20 most frequent source method codes and their crosswalk classification.

Source	Code	Technique	Digestion	Extent	Determinations
S1	ES_SQ	Emission spectrography, semi-quantitative (DC-arc)	ignition	semi-quantitative	46,375
S1	AES_HF	ICP-AES/OES	HF-HCl-HNO ₃ -HClO ₄	near-total	14,686
S1	NA_LC	Neutron activation (INAA)	none	total	12,267
S1	MS_ST	ICP-MS	Na ₂ O ₂ sinter	total	11,518
S4	not reported (GEOROC pre	Not reported in source file	not reported	unknown	10,310
S1	WDX_Fuse	XRF, wavelength dispersive (WDXRF)	LiBO ₂ /Li ₂ B ₄ O ₇ fusion	total	9,185
S2	C_ICPOES_MS-60	ICP-OES + ICP-MS	sodium peroxide fusion	total	6,866
S1	EDX	XRF, energy dispersive (EDXRF)	none	total	6,591
S1	AES_ST	ICP-AES/OES	Na ₂ O ₂ sinter	total	6,364
S2	FUS_MS	ICP-MS	lithium borate fusion	total	4,480
S1	MS_HF	ICP-MS	HF-HCl-HNO ₃ -HClO ₄	near-total	3,452
S2	C_ICPAES_MS_55	ICP-AES + ICP-MS	sodium peroxide sinter	total	3,364
S2	FUS_ICP	ICP-OES	lithium borate fusion	total	2,557
S2	C_WDXRF-MAJORS	XRF, wavelength dispersive (WDXRF)	lithium borate fusion	total	2,282
S1	NA_SC	Neutron activation (INAA)	none	total	2,123
S2	C_ICPOES_MS-49	ICP-OES + ICP-MS	multi-acid incl. HF (4-acid)	near-total	1,813
S2	INAA	Neutron activation (INAA)	none (solid sample)	total	1,738
S6	ECL1501-1:ICP:MS-LA	LA-ICP-MS	not reported	total	1,650
S1	GV	Gravimetry	heat or combust	total	1,511
S1	FA_MS	Fire assay, ICP-MS finish	NiS fire assay	total	1,486

Appendix D: Excluded samples

Table XI summarizes the 10,043 samples read but not retained, grouped by reason. Every excluded sample is listed individually, with its reason, in `excluded_samples.csv`.

TABLE XI. Excluded samples by reason.

Reason	Samples
outside study states	4,115
non-rift geologic age in source	2,766
non-rift unit named in source	2,433
not on a rift map unit and no rift name in source	529
no chemistry values	200

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