

1 **Concerning Tetrahedrites: How Much to Lump and How Far to Split?**

2 Word counts Total: 3182 Abstract, text, acknowledgements and references:
3 3123

4 Revision #1

6 **Neil E. Johnson**

7 Department of Geosciences, Virginia Tech

8 4044 Derring Hall, 926 West Campus Drive Blacksburg, VA 24061

10 **Abstract**

11 Currently there are two related but distinct approaches to the classification of
12 minerals. The traditional time-independent classification uses rules specified by the
13 IMA-CNMNC that can carefully split mineral species, but may elide valuable information
14 about their formation. In contrast, an emerging time-dependent classification appears to
15 be able to add to our knowledge about planetary evolution, yet may lump minerals into
16 broadly defined kinds even if important distinctions should be made. An examination of
17 the tetrahedrite group provides valuable insights on both approaches. As newly
18 redefined by Biagioni, et al. (2020), the generalized tetrahedrite formula
19 ($A_6(B_4C_2)D_4X_{12}Z_1$) has six sites that can accommodate substitutions and a systematic
20 splitting of all possibilities could lead to more than 200 unique species. In contrast,
21 applying guidelines for lumping largely as suggested by Hazen, et al. (2022) could lead

22 to a single kind. Deciding how much to lump and how far to split may ultimately depend
23 on the intentions of the observer.

24

25 **E-mail:** johnsonne@vt.edu

26 **Keywords:** philosophy of mineralogy, tetrahedrite, nomenclature, classification

27

28

Introduction

29 The name tetrahedrite is well known in mineralogy, it being the most common
30 sulfosalt mineral. But an abundance of additional names have been used and/or
31 proposed as a result of its complicated chemistry and history as a source of copper and
32 silver. From the *argentum rude album* of Agricola (1546) through the grey ores (*fahlerz*
33 and *cuivre gris*) of the 18th century, numerous variants in the 19th century (Palache, et
34 al., 1944), to modern work, perhaps never in the field of mineralogy has a single mineral
35 been split so often by so many. But despite the complexity of its nomenclature, the
36 structure of tetrahedrite is straightforward. It can be considered as a sulfide analogue to
37 the framework aluminosilicate sodalite (Barth, 1932), with transition metal - sulfur
38 tetrahedra in place of the (Al, Si)O₄ tetrahedra. The 'cage' generated by this framework
39 is generally collapsed down onto a transition metal - sulfur octahedron (rather than
40 hosting a large anion or polyanion), and alternating rings of the framework are spanned
41 by four semimetal - sulfur trigonal pyramids (Biagioni, et al., 2020).

42 Two factors have complicated mineralogical and material science research on
43 tetrahedrite. First, the variety of possible chemical substitutions emphasized the
44 inadequacy of the historical nomenclature and made a redefinition sorely needed.
45 Formal work on this was initiated by the IMA-COM (Möelo, et al., 2008) and culminated
46 with the application of current IMA-CNMNC guidelines to the tetrahedrite group
47 (Biagioni, et al., 2020). The second factor lies in the promise tetrahedrite has shown as
48 a thermoelectric material. As a semiconductor, tetrahedrite has a relatively high
49 electrical conductivity, but vibrations of metal atoms within the cage and the lone

50 electron pairs of the semi-metals result in a poor thermal conductivity. This produces the
51 'phonon glass, electron crystal' (PGEC) phenomenon (Beekman, et al., 2015) that
52 generates electricity. Over the last two decades this research has curiously left many of
53 the known tetrahedrite compositions poorly investigated. The focus has largely been on
54 the Sb-dominant compositions (tetrahedrites *sensu stricto*) synthesized with
55 substitutions for the framework cations, including some unlikely to occur naturally, such
56 as Al (Tippireddy, et al., 2020), or Mg (Levinsky, et al., 2018). Part of this focus is due to
57 the lower toxicity of Sb-bearing phases compared with other thermoelectric materials
58 like Bi₂Te₃ or PbTe (Suekuni, et al., 2013; Makin, et al., 2022). But it is also likely due in
59 part to unfamiliarity with the nomenclature, owing (for non-mineralogists) to the
60 bewildering assortment of names.

61 The recent re-examination of the structure and chemistry of tetrahedrite (*sensu lato*)
62 by Biagioni, et al. (2020) resulted in a formal redefinition and a number of named series
63 and species, and their Table 2 included all extant and a number of probable, but not yet
64 formally recognized, species. With its complicated chemistry and tangled history of
65 names, such a review and redefinition was long overdue and Biagioni, et al. (2020)
66 accomplished this in a manner both thorough and thoughtful. It should come as no
67 surprise, however, that even such a detailed review might leave some aspects of the
68 mineral group unaddressed or incompletely considered:

69 •The nature of the classification requires very careful chemical analyses and, in
70 some cases, structural analyses to determine Z-site occupancies, which precludes any
71 use in the field or routine petrographic study. This contrasts with the approach taken for

72 the eudialyte group wherein the contents of the X-sites are ignored in assigning an
73 appropriate mineral name owing to difficulties in determining Cl, F, OH, O, CO₃, H₂O
74 and vacancies during routine analyses. (Johnsen, et al., 2003).

75 •It defines a freibergite series while eliminating the eponymous mineral itself and
76 combines within this series minerals with both occupied and vacant Z-sites, inconsistent
77 with previous IMA recommendations for the classification of alkali-group, calcic-group
78 and X-vacant group tourmalines (Henry, et al., 2011).

79 •It discusses Z-site vacancies solely in the context of kenoargentotetrahedrite-(Fe),
80 despite long standing questions about the presence or absence of a 13th sulfur atom in
81 tetrahedrite (effectively an occupied or unoccupied Z-site, Johnson, et al. 1986, Sack, et
82 al. 2022). The subsequent discoveries of kenorozhdestvenskayaite-(Zn) (Qu, K., et al.,
83 in press a), and kenorozhdestvenskayaite-(Fe) (Qu, K., et al., in press b) suggests that
84 this may be a topic requiring further consideration.

85 •It does not address similarities between the tetrahedrite group and the galkhaite
86 group (Chen and Szymanski, 1981; Kasatkin, et al., 2018), which are also made up of a
87 sodalite-like framework of transition metal - sulfur tetrahedra (in the case of galkhaite,
88 HgS₄), but with each cage occupied by an atom of Cs or Tl instead of a transition metal
89 - sulfur octahedron. The subsequent discovery of posepnyite (Skacha, et al., 2020),
90 where the dominant cation in the B site is Hg instead of Cu suggests a connection
91 between the two groups which may also require additional consideration.

92 •It speculates on the possibility of new tellurian species arsenogoldfieldite and
93 stibiogoldfieldite, both of which have now been reported (Sejkora, et al., 2022; Biagioni,

94 et al., 2022), but only briefly mentioned the possibility of cations other than copper in the
95 framework. This likely due to Makovicky and Karup-Moller (2017) who found
96 substitution, omission and exchange calculations on natural tellurian tetrahedrites
97 (*sensu lato*) to be hindered by poor or incomplete data.

98 The redefinition has also predictably rekindled a debate, since it can be argued that
99 it is a template for excessive splitting (Nikischer, 2020) or that it presents opportunities
100 to more precisely characterize new species (such as the 15 new Sb-dominant minerals
101 since the publication of Biagioni, et al. 2020). But regardless of any weaknesses or
102 perspective, their Table 2 only lists minerals by formula rather than indicating which
103 sites accommodate which substitutions in which series or species. A more
104 comprehensive table could both clarify areas for future research and uniquely illuminate
105 the lumping vs. splitting question, thereby impacting a current philosophical discussion
106 in mineralogy.

107 Hazen (2019) proposed a new type of mineralogical classification, one very different
108 than that which currently exists and driven by the need to interpret data collected during
109 planetary exploration missions. This was termed an evolutionary (i.e. time-dependent)
110 system to contrast it with the current time-independent IMA guidelines. He
111 demonstrated that a time-independent classification may elide important contextual
112 information on mineral formation, illustrating this with a discussion of different diamond
113 morphologies and properties that arise from different parageneses. Hazen & Morrison
114 (2022) surveyed mineral formation environments and identified a series of 57 unique
115 paragenetic modes which could be used to classify minerals in this evolutionary

116 scheme. Following this, Hazen, et al. (2022) explored the lumping and splitting of
117 minerals in this context, providing criteria for determining when to lump or split. They
118 suggest lumping minerals only if part of a continuous solid solution, if they are
119 isostructural or part of a homologous series, and form in the same paragenetic mode.
120 Splitting should occur only if they form via two or more paragenetic modes, and/or
121 cluster analyses reveal multiple and distinct sets of attributes. To stress test these
122 criteria, they examined eight mineral groups in detail (cancrinite, eudialyte, hornblende,
123 jahnsite, labuntsovite, sartorite, tetradymite, tourmaline) in which 20 or more current
124 species could be lumped together into natural kinds. Obviously, the present work also
125 addresses this debate, albeit from a different perspective, and raises the question if the
126 newly defined tetrahedrite group could provide additional insight.

127

128 **Lumping vs Splitting: Speculation *ad Absurdum*?**

129 As shown above, a time-dependent classification might be considered more closely
130 tied to mineral lumping whereas a time-independent one could be thought skewed
131 towards mineral splitting. To apply this to the tetrahedrite group, let us first speculate as
132 to how much lumping could occur. All of the tetrahedrite minerals are isostructural and
133 to date, there is no evidence of anything but complete solid solution across all
134 compositions. The lumping question then comes down to the number of observed
135 paragenetic modes. An examination of the RRUFF database (<https://rruff.info/ima>;
136 accessed 3 July 2023, Downs, 2006) finds (as of this writing) 28 extant tetrahedrites
137 (*sensu lato*) with listed paragenetic modes . Of these, all have PM33 (hydrothermal

138 metal deposits) as a paragenetic mode and only three list any others (two with PM32
139 (Ba-Mn-Pb-Zn metamorphics) and one with PM37 (layered igneous deposits)). Clearly,
140 most tetrahedrites would meet all the criteria for lumping, and relaxing the paragenetic
141 mode criterion only slightly could allow for complete lumping. This extreme case would
142 then turn the tetrahedrite group into a single natural mineral kind - tetrahedrite.

143 But what of maximal splitting? Table 1 is a version of Table 2 of Biagioni, et al.
144 (2020), focusing only on Sb-dominant compositions, but describing other substitutions
145 more exhaustively. It includes the extant series and species (as of this writing), adds a
146 number of speculative series and species (in italics), and specifies which of the six
147 structural sites accommodates which substitutions following the conventions used by
148 Biagioni, et al. (2020). It must be emphasized that these speculative series and species
149 are just that, speculations for the purpose of exploring this debate and not a ‘back-door’
150 attempt to further redefine the tetrahedrite group without IMA-CNMNC sanction. For
151 compactness sake, the tetrahedrite series is the only one completely filled out with eight
152 unique species; the rest can be completed in an analogous fashion. The table also:

153 •Speculates about a Cu-rich series with the Z-site unoccupied. Following the
154 convention established by Biagioni, et al. (2020) this series is referred to as
155 “kenotetrahedrite”.

156 •Abandons the freibergite series of Biagioni, et al. (2020), dividing it into separate
157 speculative series “argentotetrahedrite” and “kenoargentotetrahedrite”.

158 •Speculates about a “kenohakite” series, an “argentohakite” series, and a
159 “kenoargentohakite” series in direct analogy with the matching series - extant and
160 speculative - for tetrahedrite.

161 •Speculates about a “kenorozhdestvenskayaite” series to accommodate the newly
162 discovered kenorozhdestvenskayaite-(Fe) (Qu, K., et al., in press b).

163 •Speculates about an “unnamed series 1” and “kenounnamed series 1” as the
164 Se-dominant analogs of the rozhdestvenskayaite and “kenorozhdestvenskayaite”
165 series.

166 •Leaves out any discussion of posepnyite due to the ambiguity discussed above.

167 The result of this splitting speculation is twelve separate series, each with eight
168 unique species, for a total of 96 possible tetrahedrites. Accommodating these
169 characteristics as well as speculative Se - S ordering and the As-dominant and
170 Te-significant (2 or more atoms per formula unit) minerals, could result in more than 200
171 unique mineral species.

172

173 **Implications**

174 With a potential range of one kind to more than 200 species, at what point are we
175 lumping that which should be split or splitting that which should be lumped? As noted by
176 Hazen, et al. (2022), Darwin originated the terminology but could offer no definitive
177 guidance and Santana (2019) suggests the development of a hard-and-fast rule may be
178 neither useful nor necessary. The contrast between splitting minerals into narrowly
179 defined species or lumping them together into broader kinds resembles past

180 developments in both taxonomy and igneous petrology. Advances in DNA sequencing
181 now allow for species splitting when morphological characteristics might suggest
182 lumping (Bickford, et al., 2007) and the IUGS classifications of igneous rocks
183 (Streckesien, 1976) allow for lumped field classifications and split laboratory
184 classifications based on modal analyses (QAPF).

185 Consider whether the Fe, Mn, Ni, and Zn tetrahedrite variants should be lumped into
186 a single kind or split into separate species as they currently are. From the perspective of
187 a mining company, these are truly distinctions without a difference, since their interests
188 are solely in the amounts of available Cu and Ag in the mineral. Contrast this with the
189 utility of tetrahedrite as a thermoelectric material. Figure 1 is a plot of the dimensionless
190 thermoelectric figure of merit (ZT) as a function of temperature for synthetic
191 tetrahedrite-(Fe), tetrahedrite-(Mn), tetrahedrite-(Ni), and tetrahedrite-(Zn) (Heo, et al.,
192 2014; Wang, 2016; Weller, 2018). The significant differences between these ZT values
193 make the trivial distinction of the mining industry into a serious research question for
194 condensed matter physics. It would seem that sometimes lumping is the better choice,
195 whereas in others splitting is preferable, and which path should be chosen is entirely
196 dependent on the aim of the research.

197

198 **Acknowledgements**

199 This work began as an exploration of the tetrahedrite name space, inspired by Tony
200 Nikischer and furthered by a discussion with Shauna Morrison. It relies heavily on the
201 extraordinary work on proposal IMA 18-K by Cristian Biagioni and coauthors, and the

202 equally extraordinary work by Bob Hazen and collaborators on the ideas of mineral
203 evolution. Exceptionally helpful comments and discussion were provided by Mickey
204 Gunter, Igor Pekov and an anonymous reviewer.
205
206

207

References

208 Agricola, G. (1546) *De Natura Fossilium* (Textbook of Mineralogy), translated from the
209 first Latin edition of 1546 in 1955 by Mark Chance Bandy and Jean A. Bandy for the
210 Mineralogical Society of America, 240 p. Geological Society of America Special Paper
211 63, New York, NY.

212

213 Barth, T.F.W. (1932) The structure of the minerals of the sodalite family. *Zeitschrift für*
214 *Kristallographie*, 83, 405-414.

215

216 Beekman, M., Morelli, D.T., and Nolas, G.S. (2015) Better thermoelectrics through
217 glass-like crystals. *Nature Materials*, 14, 1182-1185.

218

219 Biagioni, C., George, L.L., Cook, N.J., Makovicky, E., Moëlo, Y., Pasero, M., Sejkora, J.,
220 Stanley, C. J., Welch, M. D., and Bosi, F. (2020) The tetrahedrite group: Nomenclature
221 and classification. *American Mineralogist*, 105, 109-122.

222

223 Chen T. T., and Szymanski J T (1981) The structure and chemistry of galkhaite, a
224 mercury sulfosalt containing Cs and Tl. *Canadian Mineralogist*, 19, 571-581.

225

226 Downs, R.T. (2006) The RRUFF project: An integrated study of the chemistry,
227 crystallography, Raman and infrared spectroscopy of minerals. Program and Abstracts
228 of the 19th General Meeting of the International Mineralogical Association in Kobe,

229 Japan O03-13.

230

231 Hazen, R.M. (2019) An evolutionary system of mineralogy: Proposal for a classification
232 based on natural kind clustering. American Mineralogist, 104, 810-816.

233

234 Hazen, R.M., and Morrison, S.M. (2022) On the paragenetic modes of minerals: A
235 mineral evolution perspective. American Mineralogist, 107, 1262-1287.

236

237 Hazen, R.M., Morrison, S.M., Krivovichev, S.V., and Downs, R.T. (2022) Lumping and
238 splitting: Towards a classification of mineral natural kinds. American Mineralogist, 107,
239 1288-1301.

240

241 Henry, D.J., Novak, M, Hawthorne, F.C., Ertl, A., Dutrow, B.L., Uher, P., and Pezzotta,
242 F. (2011) Nomenclature of the tourmaline-supergroup minerals. American Mineralogist,
243 96, 895-913.

244

245 Heo, J., Laurita, G., Muir, S., Subramanian, M.A., and Keszler, D. A. (2014) Enhanced
246 thermoelectric performance of synthetic tetrahedrite. Chemistry of Materials, 26,
247 2047-2051.

248

249 Johnsen, O., Ferraris, G., Gault, R.A., Grice, J.D., Kampf, A.R., and Pekov, I.V. (2003)
250 The nomenclature of eudialyte-group minerals, Canadian Mineralogist, 41, 785-794.

251

252 Johnson, N.E., Craig, J.R.,s and Rimstidt, J.D. (1986) Compositional trends in
253 tetrahedrite. Canadian Mineralogist, 24, 385-397.

254

255 Kasatkin, A.V., Nestola, F., Agakhanov, A.A., Skoda, R., Karpenko, V.Y., Tsyganko,
256 M.V., and Plášil, J. (2018) Vorontsovite, $(\text{Hg}_5\text{Cu})\text{S}_6\text{TlAs}_4\text{S}_{12}$, and ferrovorontsovite,
257 $(\text{Fe}_5\text{Cu})\text{S}_6\text{TlAs}_4\text{S}_{12}$: The Tl- and Tl-Fe-analogues of galkhaite from the Vorontsovskoe
258 Gold Deposit, Northern Urals, Russia. Minerals, 8, 185-197.

259

260 Levinsky, P., Candolfi, C., Dauscher, A., Lenoir, B., and Hejtmanek, J. (2018) Influence
261 of magnesium doping on thermoelectric properties of tetrahedrite. In Osmá studentská
262 vedecká konference fyziky pevných látek a materiálu, 46-48.

263

264 Makin, F., Alam, F., Buckingham, M.A., and Lewis, D.J. (2022) Synthesis of ternary
265 copper antimony sulfide via solventless thermolysis or aerosol assisted chemical vapour
266 deposition using metal dithiocarbamates. Scientific Reports, 1-12.

267

268 Moëlo, Y., Makovicky, E., Mozgova, N.N., Jambor, J.L., Cook, N., Pring, A., Paar, W.H.,
269 Nickel, E.H., Graeser, S., Karup-Møller, S., and others. (2008) Sulfosalt systematics: a
270 review. Report of the sulfosalt sub-committee of the IMA Commission on Ore
271 Mineralogy. European Journal of Mineralogy, 20, 7-46.

272

- 273 Nikischer, T. (2020) Redefinitions of tennantite and tetrahedrite groups: A new
274 Zn-analog of argentotetrahedrite-(Fe) found? Mineral News, 36, 6.
275
- 276 Palache, C., Berman, H., and Frondel, C. (1944) The System of Mineralogy of James
277 Dwight Dana and Edward Salisbury Dana, Yale University 1837-1892, 7th edition,
278 Volume I: Elements, Sulfides, Sulfosalts, Oxides, 834 p. Wiley, New York.
279
- 280 Qu, K., Sima, X., Gu, X., Sun, W., Fan, G., Hou, Z., Ni, P., Wang, D., Yang, Z., and
281 Wang, Y. (2021) Kenoargentotetrahedrite-(Zn), IMA 2020-075. CNMNC Newsletter 59,
282 European Journal of Mineralogy, 33, 139-143. <https://doi.org/10.5194/ejm-33-139-2021>
283
- 284 Qu, K., Sun, W., Gu, X., Yang, Z., Sima, X., Tang, C., Fan, G., and Wang, Y.:
285 Kenorozhdestvenskayaite-(Fe), IMA 2022-001. CNMNC Newsletter 67, European
286 Journal of Mineralogy, 34, <https://doi.org/10.5194/ejm-34-359-2022>, 2022.
287
- 288 Sack, R.O., Lyubimtseva, N.G., Bortnikov, N.S., Anikina, E.Y., and Borisovsky, S.E.
289 (2022) Sulfur vacancies in fahlores from the Ag-Pb-Zn Mangazeyskoye ore deposit
290 (Sakha, Russia). Contributions to Mineralogy and Petrology, 177,
291 <https://doi.org/10.1007/s00410-022-01942-5>
292
- 293 Santana, C. (2019) Mineral misbehavior: Why mineralogists don't deal in natural kinds.
294 Foundations of Chemistry, 21, 333-343.

295

296 Sejkora, J., Biagioni, C., Dolnicek, Z., and Voudouris, P. (2022) Aresnogoldfieldite, IMA
297 2022-84. CNMNC Newsletter 70, European Journal of Mineralogy, 34,
298 <https://doi.org/10.5194/ejm-34-591-2022>

299

300 Skacha, P., Sejkora, J., Plasil, J., and Makovicky, E. (2020) Posepnyite, a new Hg-rich
301 member of the tetrahedrite group from Pribam, Czech Republic. Journal of
302 Geosciences, 65, 173-186.

303

304 Suekuni, K., Tsuruta, K., Kunji, M., Nishiate, H., Nishibori, E., Maki, S., Ohta, M.,
305 Yamamoto, A., and Koyano, M. (2013) High-performance thermoelectric mineral
306 $\text{Cu}_{12-x}\text{Ni}_x\text{Sb}_4\text{S}_{13}$ tetrahedrite. Journal of Applied Physics 113, 043712-043717.

307

308 Tippireddy, S., Ghosh, S., Biswas, R., Dasgupta, T., Rogl, G., Rogl, P., Bauer, E., and
309 Malik, R. C. (2020) Thermoelectric properties of Al substituted tetrahedrite. Journal of
310 Applied Physics, 127, 035105-1 - 035105-14.

311

312 Wang, J., Li, X., and Bao, Y. (2016) Thermoelectric properties of Mn doped
313 $\text{Cu}_{12-x}\text{Mn}_x\text{Sb}_4\text{S}_{13}$ tetrahedrite. Materials Science Forum, 847, 161-165.

314

315 Weller, D.P. (2018) Novel synthetic approaches and doping strategies for facile and
316 versatile synthesis of tetrahedrite thermoelectrics. 154 p. Ph.D. thesis, Michigan State
317 University.

318

319

320

321

Figure captions

322

323 **Figure 1.** Plot of the dimensionless thermoelectric figure of merit (ZT) versus
324 temperature for synthetic C-site substituted tetrahedrites.

325

326 **Table 1. Listing of maximally split Sb-dominant tetrahedrite series and species**

327

328

329 **Dominant site occupant**

330 **Series** **A site (6)** **B site (4)** **C site (2)** **D site (4)** **Y site (12)** **Z site (1)**

331 **Tetrahedrite** **Cu** **Cu** **Variable** **Sb** **S** **S**

332 Tetrahedrite-(Cd)* Cu Cu Cd Sb S S

333 Tetrahedrite-(Cu)* Cu Cu Cu Sb S S

334 Tetrahedrite-(Fe) Cu Cu Fe Sb S S

335 Tetrahedrite-(Hg)* Cu Cu Hg Sb S S

336 Tetrahedrite-(In)* Cu Cu In Sb S S

337 Tetrahedrite-(Mn)* Cu Cu Mn Sb S S

338 Tetrahedrite-(Ni)* Cu Cu Ni Sb S S

339 Tetrahedrite-(Zn) Cu Cu Zn Sb S S

340

341 **Kenotetrahedrite** **Cu** **Cu** **Variable** **Sb** **S** **Vacant**

342

343 **Argentotetrahedrite** **Ag** **Cu** **Variable** **Sb** **S** **S**

344 Argentotetrahedrite-(Cd)* Ag Cu Cd Sb S S

345 Argentotetrahedrite-(Fe) Ag Cu Fe Sb S S

346 Argentotetrahedrite-(Hg)* Ag Cu Hg Sb S S

347 Argentotetrahedrite-(Zn)* Ag Cu Zn Sb S S

348

349 **Kenoargentotetrahedrite** **Ag** **Cu** **Variable** **Sb** **S** **Vacant**

350 Kenoargentotetrahedrite-(Fe)* Ag Cu Fe Sb S Vacant

351 Kenoargentotetrahedrite-(Zn)* Ag Cu Zn Sb S Vacant

352

353 **Hakite** **Cu** **Cu** **Variable** **Sb** **Se** **Se**

354 Hakite-(Cd)* Cu Cu Cd Sb Se Se

355 Hakite-(Fe)* Cu Cu Fe Sb Se Se

356 Hakite-(Hg) Cu Cu Hg Sb Se Se

357 Hakite-(Zn)* Cu Cu Zn Sb Se Se

358

359 ***Kenohakite*** Cu Cu Variable Sb Se Vacant

360

361

362

363 ***Argentohakite*** Ag Cu Variable Sb Se Se

364

365 ***Kenoargentohakite*** Ag Cu Variable Sb Se Vacant

366

367 ***Rozhdestvenskayaite*** Ag Ag Variable Sb S S

368 Rozhdestvenskayite-(Zn) Ag Ag Zn Sb S S

369

370 ***Kenorozhdestvenskayaite*** Ag Ag Variable Sb S Vacant

371 Kenorozhdestvenskayite-(Fe)* Ag Ag Fe Sb S Vacant

372

373 ***Unnamed Series 1*** Ag Ag Variable Sb Se Se

374

375 ***Kenounnamed Series 1*** Ag Ag Variable Sb Se Vacant

376

377 Extant series and species are in plain text. Speculative series and species are in italics.

378 Species noted with an "*" are newly described - either in print or in press - since the

379 redefinition by Biagioni, et al. (2020).

380

381

382

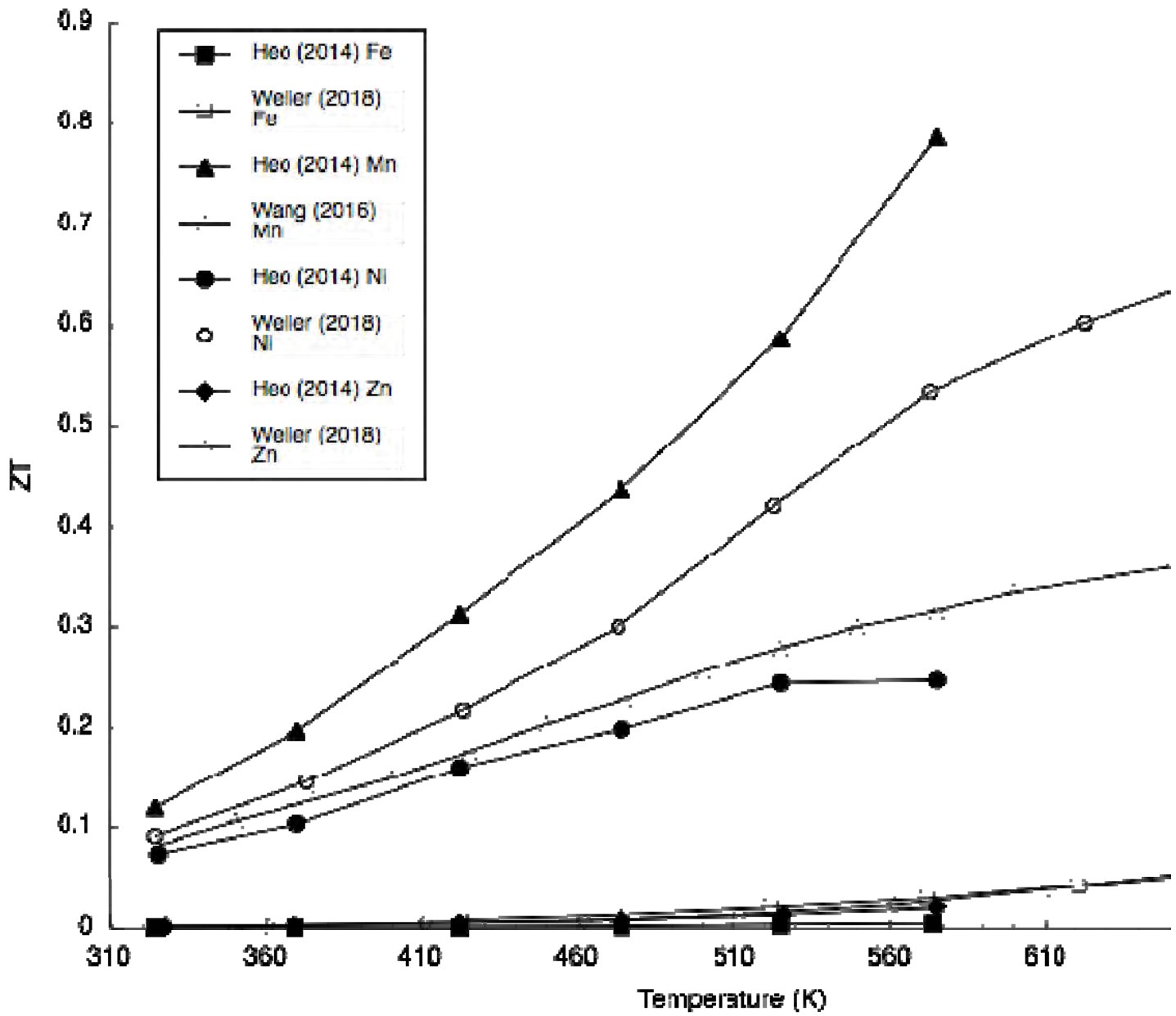
383

384

385

386

Figure 1



387