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Tsumeb: Zincolivenite and the Adamite-Olivenite Series

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Abstract

Tsumeb is one of the world's premier localities for arsenate (and arsenite) minerals. At least eighty-four species containing the arsenate (or arsenite) anion groups have been confirmed from Tsumeb, which is the type locality for forty-two of them.

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Tsumeb: Zincolivenite and the adamite-olivenite series

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Tsumeb is one of the world's premier localities for arsenate (and arsenite) minerals. At least 84 species containing the arsenate (or arsenite) anion groups have been confirmed from Tsumeb, which is the type locality for 42 of them (www.tsumeb.com; accessed December 2018).

Minerals of the adamite – olivenite solid solution series are among the most common, most colorful, and best crystallized of Tsumeb's arsenates. They occur with a diversity of other minerals, both common and rare, in parageneses that range from simple to complex, but with associations and colour combinations that are often highly attractive (fig. 1). As such, specimens of adamite – olivenite series minerals are generally desirable, although their precise nomenclature has been problematic, particularly for collectors without access to analytical facilities.

Adamite and Olivenite at Tsumeb; a brief history

Olivenite was recognized at Tsumeb from the earliest years of mining. Schneider (1906) implies that it was somewhat uncommon, occurring either as fine-grained, amorphous aggregates with other secondary minerals and quartz, or in cavities as columnar crystals to 1 mm in length. Maucher (1908) described blackish-green crusts and crystals of olivenite. He also determined that the olivenite is commonly zinc-enriched, with the zinc lending a lighter green colour to the mineral and a tendency to better-formed crystals. In particular, he described the occurrence of leek-green radial hemispheres of zinc-enriched olivenite on crusts of quartz.

Klein (1938) considered olivenite to be very common at Tsumeb, occurring with malachite and azurite to a depth of 100 m (i.e. between the surface and 4 level), and as particularly well-formed crystals between 3 and 4 levels. The Klein Collection (now at Harvard University) boasts 15 olivenite specimens, four of which are from the open pit and the remainder from 4 level (Klein Collection catalog, unpublished, MGMH collection, Harvard University). Klein's open pit specimens include a spectacular example of needle-shaped olivenite crystals (fig. 2), an unusual habit for Tsumeb, on a matrix of massive malachite and olivenite.

Intriguingly, none of the pre-WWII authors appear to have recognized the occurrence of adamite. One reason for this is simply that compositions close to end-member adamite appear to be relatively scarce at Tsumeb and particularly so in the upper levels of the mine (the first oxidation zone). It also appears, however, that what later collectors would call 'cuproadamite' or 'cuprian adamite' was commonly misidentified by pre-war observers. There are, for example, three specimens of 'cuprian adamite' in the Klein Collection, that Klein misidentified as tsumebite (Southwood, Alonso-Perez and Schnaitmann, 2018), while the Karabacek Collection, which was purchased by Harvard University in 1935, includes a specimen that Karabacek believed to be a unique example of veszelyite from Tsumeb, but subsequent analysis (at MGMH) showed to be simply a 'cuprian adamite' (fig. 3).

On the other hand, Karabacek (unpublished collection prospectus (English transcript), circa 1934, MGMH Collection, Harvard University) lists "…one single specimen of cobaltoadamine from Tsumeb with crystals over 0.5 cm in size" (see fig. 4).

The first mention of adamite from Tsumeb in the formal literature is by Strunz, Söhnge and Geier (1958). Their list of minerals from the first oxidation zone (page 92) includes "Olivenite $Cu_2[OH/AsO_4]$ – Adamite $Zn_2[OH/AsO_4]$ (Isomorphic)" suggesting that they recognized the presence of different compositions within the solid solution series. For the second oxidation zone, however, they list (page 94) "Olivenite (epidote-green), Adamite (yellow-brown) and their mixed crystals (blue-green to brown)" indicating, for the first time, the identification of something they believed to be close to end-member adamite and a growing understanding, perhaps, of the relationships of intermediate compositions in the solid solution series.

Strunz (1959) described an occurrence of 'cuproadamite' from 30 level in the second oxidation zone. He presented crystallographic drawings, unit cell parameters and optical data, suggesting that the occurrence was considered a significant novelty.

As mining progressed through the second oxidation zone, however, discoveries of 'cuproadamite' became relatively common (Geier 1973/74). Bartelke (1976) noted the rarity of end-member adamite, but the relative abundance of bright green 'cuproadamite' with varying proportions of zinc and copper that sometimes manifest as color zoning. He described crystals with rhombic, pseudo-octahedral and prismatic habits.

Pinch and Wilson (1977, page18) commented on the rarity of "copper-free adamite" at Tsumeb and their description of 'cuproadamite' as "…supposedly part of a continuous series to olivenite" indicates a continuing uncertainty as to the nature and status of the more common copper-bearing members of the series.

Keller (1977; page 43) made a study of second oxidation zone parageneses and concluded that 'cupriferous adamite' is more common (in the second oxidation zone) than olivenite and that it occurs in more complex associations. Keller identified 19 secondary minerals that occur with 'cupriferous adamite' compared with only nine for olivenite.

In commenting on the best specimens of adamite and 'cuproadamite' from Tsumeb, Key (1977; page 48) inadvertently highlighted the labelling dilemma facing many collectors: "Cuproadamite is a variety of different occurrence from the relatively pure adamite… With the exception of several specimens that are nothing but cuproadamite, the others grade insensibly into zincian olivenite, and cannot be distinguished by eye."

Gebhard (1999; page 157) describes the 1986 discovery of "…probably the finest cuproadamite in existence…" on 30 level, in the second oxidation zone, with crystals up to 5 cm associated with yellow ferrilotharmeyerite and sparse crystals of wulfenite (fig. 5). Cairncross (2000; page 126) refers to this pocket simply as "the Famous Find".

Further discoveries of 'cuproadamite' were made in the third oxidation zone in the early 1990s. One of the most important, on 44 level, yielded several different habits, ranging from stubby, zoned crystals to 2 cm associated with the very rare minerals chudobaite and johillerite to "…tiny, white needle-like crystals" associated with leiteite and legrandite (Gebhard 1999; page 160). These discoveries undoubtedly contributed to the established wisdom among collectors that Tsumeb 'cuproadamite' is often a marker for some of Tsumeb's rarest species and that fresh acquisitions are always worthy of thorough examination under the microscope.

Adamite – Olivenite Series Nomenclature: What are we dealing with?

Adamite, ideally $Zn_2(AsO_4)(OH)$, and olivenite, ideally $Cu_2(AsO_4)(OH)$ have long been recognized as, respectively, the zinc and copper end-members of a solid solution series of basic zinc and copper arsenates. Palache et al. (1951; page 865) noted that copper substitutes for zinc "…up to at least 1:1.33, and a partial series therefore extends towards olivenite", while Guillemin (1956) and Minčeva-Stephanova et al. (1965; cited by Braithwaite, 1983) demonstrated complete compositional solid solution between the two end-members.

Historically, both adamite and olivenite were considered to be orthorhombic. Heritsch (1938) was the first of several workers to propose structures for olivenite based on the assumption of orthorhombic symmetry (space group *Pnnm*), with further refinements by Richmond (1940; space group $P2_12_12_1$), Berry (1951; $Pnmm$) and Walitzi (1963; $Pn2_1m$). Subsequent studies (Toman, 1977; Burns and Hawthorne 1995; Li et al. 2008), however, have solved the olivenite structure on the basis of monoclinic symmetry (space group $P2_1n$;). Toman (1977, 1978) showed that the symmetry change from monoclinic to orthorhombic occurs at approximately 80 mol % copper. Back (2018) lists adamite as orthorhombic, and olivenite as monoclinic.

For many years, collectors and many mineral professionals have used the terms 'cuproadamite', 'cuprian adamite', 'zinc-olivenite', and 'zincian olivenite' to describe intermediate members of the adamite-olivenite series. Commonly, such names have been assigned on the basis of color or habit and without supporting analysis. Braithwaite (1983) lamented nomenclature problems in the adamite-olivenite series and suggested (page 51) that a formal definition of cuproadamite should be introduced to "…include all orthorhombic members of the series containing appreciable copper."

In 2006, the International Mineralogical Association (IMA) approved a new mineral species named zincolivenite (IMA 2006-047; see Chukanov et al. 2007), and the name 'cuproadamite' was formally discredited (Burke, 2006). Zincolivenite, intermediate in composition between adamite and olivenite, ideally has the composition $CuZnAsO_4(OH)$, with a Zn : Cu ratio of 1 : 1. Like adamite, it is orthorhombic, but it is justified as a distinct species according to the ordering of zinc and copper between the two separate cation sites in which the progressive substitution of one metal for the other is believed to be site-specific. Based on the IMA's 'dominant cation' rule, Chukanov et al. (2007) suggested that the species should be defined by a compositional range extending between 25 and 75 mol % copper, or from $Cu_{0.5}Zn_{1.5}AsO_4(OH)$ to $Cu_{1.5}Zn_{0.5}AsO_4(OH)$.

The structure and crystal chemistry of the adamite-olivenite series minerals have been detailed by Chukanov et. al (2007), but a simplified explanation is offered here, together with a structure diagram (fig. 6). All members of the adamite – olivenite series have two distinct cation sites, M1 and M2, that can contain either zinc or copper; however, one of them, M2 (see fig. 6), favors zinc, while the other, M1, favors copper. In pure end-member adamite, both sites are zinc-filled, a situation that can be represented by rewriting the formula as $ZnZn(AsO_4)(OH)$. As copper starts to substitute into the adamite structure, the replacement is site-specific, with copper replacing zinc only in the M1 site. Once copper becomes the dominant cation (i.e. > 50 mol %) in that site, the overall copper ratio (including both cation sites) exceeds 25 mol % and the mineral moves into the compositional range of zincolivenite. Eventually, all of the zinc in the copper-favoring site is replaced by copper, at which point the "ideal" zincolivenite composition of $ZnCu(AsO_4)(OH)$ is reached, containing 50 mol % zinc and 50 mol % copper overall. Thereafter, further substitution of copper occurs in the second, zinc-favoring M2 site. Once copper exceeds 50 mol % in the second site (i.e. > 75 mol % overall), however, the upper limit of copper content by which zincolivenite is defined is exceeded.

Potentially, this introduces a further problem of nomenclature (although not an issue in the context of the current article); zincolivenite is defined as containing between 25 and 75 mol % copper, but in synthetic members of the series the symmetry change from orthorhombic to monoclinic occurs at around 80 mol % copper (Toman 1977, 1978; see fig. 7). What then is the name of a composition in the adamite – olivenite series containing between 75 mol % and 80 mol % copper? Potentially such a composition could be defined as a new species; however, none of the specimens analysed in the course of the current study have mean compositions that fall between 75 and 80 mol % copper and, to date, we are unaware of such compositions in other natural members of the adamite – olivenite series.

In summary, the adamite – olivenite solid solution series now includes three distinct species: adamite (orthorhombic), ideally $Zn_2(AsO_4)(OH)$ in which zinc must be the dominant metal in both cation sites so that the copper content must therefore be less than 25 mol %; zincolivenite (orthorhombic), ideally $ZnCu(AsO_4)(OH)$, in which neither the copper nor the zinc content can exceed 75 mol %; and olivenite (monoclinic), ideally $Cu_2(AsO_4)(OH)$, in which copper must be the dominant metal in both cation sites so that the overall zinc content must be less than 25 mol % (fig. 7). Olivenite can be distinguished from zincolivenite and adamite by X-ray diffraction analysis (XRD), but the diffraction patterns for adamite and zincolivenite are so similar that a quantitative chemical analysis is required for definitive confirmation of these species.

‘Cuproadamite’ is now a discredited name (Burke, 2006) so, following the IMA rules of nomenclature, ‘cuproadamite’ should no longer be used for specimen labels. The current study was undertaken to determine the compositions of a range of adamite – olivenite series minerals from Tsumeb, firstly to determine where they lie in the solid solution series and hence their correct identification as either adamite, zincolivenite, or olivenite, and secondly to assess whether or not these species names can be assigned reliably on the basis of visual properties, notably color and habit.

Experimental

As a first step towards an understanding of the range of compositions in the adamite – olivenite series at Tsumeb, 43 specimens were selected to represent a wide range of colors and habits. 34 of these specimens were from the collection of one of the authors (M. Southwood; denoted as “MS” specimens in tables 1 and 2), and the remainder were from the inventory of Crystal Classics Fine Minerals (“TA” specimens). Single crystals (or parts thereof), typically 1 to 2 mm in size, were removed from each of these specimens, mounted in resin, polished and carbon coated for quantitative electron microprobe analysis.

Analyses of the MS specimens were conducted using wavelength dispersive spectrometry (WDS) at 15 kV, 5-10 mA, with a 3–5 μm beam diameter, on a JEOL JXA-8530F field emission electron probe microanalyser at the Australian National University, in Canberra, Australia. Analyses of the TA specimens were conducted by WDS at 15 kV, 10 nA, with a 5 μm beam diameter, on a Cameca SX 100 electron probe microanalyser at Department of Geological Sciences, Faculty of Science, Masaryk University, in Brno, Czech Republic.

All samples were analysed for the major elements arsenic, copper and zinc, and for minor elements cobalt, iron and phosphorus, with between 3 and 8 analyses per sample. Standards used for analysis of the MS specimens were: As and Co – skutterudite; Cu – cuprite; Fe – hematite; P – apatite and Zn – willemite. Standards used for analysis of the TA specimens were: As and Cu – lammerite; Co – Co metal; Fe – almandine; P – fluorapatite and Zn – gahnite.

Analytical results are presented in Table 1, with the specimens listed in order of increasing mean mol % copper. Calculation of chemical formulae shows that none of the minor elements (P, Co, Fe) substitutes at more than 1 mol % in the relevant sites, and they make little practical difference to the results as far as the determination of mineral species is concerned (figure 8).

Ignoring the very minor presence of iron and cobalt in the two cation sites, the calculated mol % for copper and zinc always sums to 100. Because the boundaries between the species – adamite, zincolivenite and olivenite, are defined by the ratio of Cu:Zn, the molar proportion of copper, MP_{Cu}, expressed as a percentage, [i.e. Cu/(Cu+Zn)*100], provides a practical measure of where each analysis sits in the solid solution series. End-member adamite has MP_{Cu} = 0%, while end-member olivenite has a value for MP_{Cu} of 100%; values for MP_{Cu} between 25% and 75% correspond to zincolivenite.

Figure 9 summarizes the distribution of the 43 specimens in the solid solution series, based on their mean cation proportions. Eight specimens have mean compositions with zinc as the dominant metal in both cation sites (i.e. MP_{Cu} < 25%) and are therefore adamite (see figs. 10 through 17); 28 have mean compositions indicative of zincolivenite (i.e. MP_{Cu} between 25 % and 75 %; figs 18 through 45), while seven specimens with mean values for MP_{Cu} > 75 % are olivenite (figs 46 through 52).

Caution is required in interpreting the distribution of data in figure 9, as the sample (43 specimens) is small and cannot be assumed to reflect the natural abundance of various adamite – olivenite series compositions at Tsumeb. In particular, the impression of a trimodal distribution in figure 9 may be exaggerated because of sampling bias; several specimens visually identified on the basis of habit and color as being close to end-member compositions (both adamite and olivenite) were deliberately included in the study and their weighting in the sample almost certainly exceeds their natural representation. The data distribution does, however, suggest a tendency for both adamite and, to a lesser extent, olivenite specimens to lie close to their respective end member compositions. It should be noted, in this respect, that the two specimens with mean MP_{Cu} values between 15.01 and 25.00 % in figure 9 are 'hybrid' specimens containing both adamite and zincolivenite compositions (see *Compositional Variations*, below).

The interpretation of data within the zincolivenite grouping also requires caution, although apart from the obvious tendency to recover the more colourful and better-formed crystals from the mine in the first place, a sampling bias is less likely among these specimens. The distribution of the zincolivenite analyses supports a preliminary hypothesis that the compositions of Tsumeb zincolivenites are weighted towards the middle of the range of MP_{Cu} values by which the species is defined.

Relationships Between Composition and Visual Properties

The photographs of specimens analysed in this study are arranged in ascending order of copper content (figs. 10 through 52), and represent a progression from adamite, through zincolivenite, to olivenite. A quick review of these figures will show a relationship between the visual properties of the minerals and chemical composition that is mainly dependent on color. A simple summary of the main visual properties (color, transparency (diaphaneity) and habit) for each specimen is provided in Table 2, together with the minimum, mean, and maximum values for MP_{Cu} determined by our analyses.

The description of color in minerals can be very subjective, particularly when attempting to compare or distinguish shades of similar hue among crystals of varying size, habit and transparency. Nevertheless, consideration of our descriptions, and analytical data (Table 2) together with the relevant specimen photographs indicates some clear trends.

- Specimens confirmed by analysis as adamite show considerable variation in color (see figs. 10 through 17). With as little subjectivity as possible, our color descriptions for these specimens (Table 2) include orange-yellow, yellow-green, colorless to brown, pale-yellow and magenta or pink.
- Zincolivenite specimens (as confirmed by analysis) also show variation in color but essentially all such specimens present as greens of varying hue. We have used three main descriptions for the colors of these specimens – spearmint-green (for example fig. 25), emerald-green (for example fig. 34), and bottle-green (for example fig. 44) and we note that the majority of specimens in this color range would probably have been labelled traditionally as ‘cuproadamite’. Spearmint-green (paler) crystals tend to lie towards the zinc-rich end of the zincolivenite range (fig. 25), while a

high proportion of specimens described as emerald-green are close to mid-range in terms of the MP_{Cu} value (fig. 39). Zincolivenite crystals described as bottle-green are usually (though not always) towards the copper-rich end of the zincolivenite range (fig. 44) and may include zones of olivenite composition (fig. 45).

- All of the specimens determined by analysis to be olivenite (on the basis of mean composition) are described as blackish-green.

As far as our limited data set allows us to determine, no useful relationship between the observed diaphaneity (transparency) and composition is apparent, and only tenuous relationships between habit and composition are observed. There is, for example, a loose tendency for adamite compositions to present as equant or tabular crystals, while zincolivenite habits are much more variable, ranging from pseudo-octahedral and short prismatic, through long prismatic and acicular. Radial aggregates and curvilinear “fans” of crystals tend to occur in compositions towards the copper-rich end of the zincolivenite range (figs. 43 and 45) or in olivenite (fig. 47).

Compositional Variations

Several of the specimens analysed include more than one adamite – olivenite series mineral in the paragenesis. In some cases, crystals of different composition are present on the same specimen while in others, compositional zoning occurs within individual crystals. Table 2 shows minimum, mean and maximum values for MP_{Cu} determined for each of the specimens analysed. The table shows that five of the specimens (figs. 16 through 20) include compositions corresponding to both adamite and zincolivenite, while only one specimen (fig. 45) has compositions straddling the zincolivenite – olivenite boundary.

It is interesting to consider some of these ‘hybrid specimens’ more closely:

- Specimen MS 2009.048 (fig. 16) includes two distinct generations comprising (a) elongated and intergrown crystals of magenta adamite that is close to end-member composition (mean MP_{Cu} = 0.18%), and for which the color is probably due to an elevated presence of cobalt (see below), and (b) a banded crust of spearmint-green zincolivenite crystals with a mean MP_{Cu} of 35.46 %.

- By contrast, individual crystals from specimen TA2-6 (fig. 17) are zoned, with compositions close to end-member adamite (mean MP_{Cu} = 1.72 %, and a pale-yellow color) at the base of each crystal, grading to zincolivenite (mean MP_{Cu} = 38.51 %, and emerald-green) at the terminations.
- Specimen MS 2013.002 (fig. 18) also has zoned crystals, but in this case the zoning appears to be concentric; the paler-colored cores have the adamite composition (MP_{Cu} = 11.14 %), while the darker-green sheaths are zincolivenite (MP_{Cu} = 38.69 %).
- Specimen MS 2014.001 (fig. 45) has crystals with a mean composition of zincolivenite (MP_{Cu} = 67.01%) but with a very wide compositional range from near-ideal zincolivenite (MP_{Cu} = 50.11 %) to zinc-rich olivenite (with MP_{Cu} = 79.35%). This is the widest compositional range determined for any of the samples analysed, and yet no visually discernible zoning is apparent in these crystals.

Wide compositional variation, however, does not necessarily straddle species boundaries:

- The MP_{Cu} values determined for specimen MS 2012.011 (fig. 22) range from 29.39 % – 48.86 %, all comfortably within the compositional boundaries of zincolivenite. Surprisingly, perhaps, there is no visually-apparent zoning in the crystals on this specimen.

“Pink” Adamite

Cobalt was determined in each of the specimens studied, specifically because of its probable role as a chromophore in crystals that present with a magenta or ‘pink’ hue. Pink adamite is rare at Tsumeb, and only two specimens (figs. 15 and 16) were available for this study.

The pink crystals from specimen MS 2009.048 (fig. 16) are close to end-member adamite with a value for MP_{Cu} of just 0.18 %, and a cobalt content of 0.054 wt % (average of 3 analyses). The pink zones of crystals from specimen MS 2016.076 (fig. 15) have a value for MP_{Cu} of 1.62 % and contain 0.045 wt % Co (average of 3 analyses).

The pink adamite from both specimens is therefore close to end-member composition, with elevated Co content compared to the average for all specimens analysed of 0.015 wt %.

While these results are by no means conclusive, our working hypothesis is that slightly elevated cobalt levels of as little as c. 0.05 wt % in near end-member adamites may be sufficient to impart a distinctive pink coloration to the crystals, but that the color affect from similar cobalt levels is lost in specimens with higher copper content. For example, specimen MS 2013.002 (fig. 18) has crystals ranging in composition from adamite (MP_{Cu} = 11.14 %) to zincolivenite (MP_{Cu} = 38.69 %) and an average Co tenor of 0.041 wt %, but the bottle-green color of the crystals caused by copper masks the potential effect of the cobalt.

Conclusions

Although olivenite was recognised at Tsumeb at a very early stage of mining (Schneider, 1906), zinc-dominant members of the adamite – olivenite series were often overlooked or mis-identified by early observers. As mining penetrated the second oxidation zone in the 1950s, however, 'cuproadamite' was encountered much more commonly.

The definition of zincolivenite, a new species in the adamite – olivenite solid solution series (Chukanov et al. 2007) and the discreditation of the name 'cuproadamite' (Burke 2006) have important implications for how specimens should be labelled. We perceive a reluctance, however, among collectors and dealers, to use the name zincolivenite, for which we suggest two reasons.

First, there may be a view that since zincolivenite is a relatively recently defined "new" mineral it is probably also a rare mineral. This is simply not so. Based on a modern understanding of crystal chemistry, zincolivenite is a redefined portion of a solid solution between two very well-known end-members (adamite and olivenite); it is not a "new mineral" in the usual sense of species discovery.

Second, even (and especially) with a clear understanding of the relationships between adamite, zincolivenite, and olivenite, definitive identification of these three species requires quantitative chemical analysis, and relatively few collectors have the inclination (or budget) to commission electron microprobe analyses.

Following the approval of zincolivenite as a new species, Braithwaite, Green and Tindle (2009) conducted a study of the distribution of adamite and zincolivenite in the British Isles, noting that the majority of pre-2007 identifications of adamite had been based largely on XRD analysis, which is no longer reliable given the close similarity of the zincolivenite X-ray spectrum. On the basis of over 50 quantitative (WDS) analyses of adamite – olivenite series minerals from a variety of British localities they concluded that zincolivenite is "…a term which for most practical purposes is a synonym of 'cuproadamite'" (Braithwaite, Green and Tindle (2009), page 10) and that "…the adamite to zincolivenite solid solution is one of the cases where colour provides a reasonable guide to composition."

The analytical results from the current study suggest that the same is true at Tsumeb. Quantitative analysis is certainly desirable for definitive discrimination between adamite and zincolivenite, or zincolivenite and olivenite, particularly where zoned crystals are present. The relationship between color and mean composition is such, however, that zincolivenite (spearmint-green, emerald-green, bottle-green) can be distinguished from olivenite (blackish-green) and adamite (colorless, yellow, pink, brown) with reasonable confidence.

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Figures and Tables

			Analysis - Wt % (mean of *n* analyses)							Cations: (mean of *n* analyses)		MP_{Cu} defined as	APFU		
Specimen	**Photo**	***n***	**CuO**	**ZnO**	**FeO**	**CoO**	**P_2O_5**	**As_2O_5**	**Total**	**Cu (mol %)**	**Zn (mol %)**	**Cu/(Cu+Zn)*100**	**Cu**	**Zn**	**Indicated Mineral**
MS 2014.068	Fig. 10	1	0.002	57.220	0.357	0.029	0.002	40.410	98.020	**0.00**	**99.24**	**0.00**	**0.00**	**1.99**	**Adamite**
MS 2014.149	Fig. 11	3	0.337	57.323	0.217	0.021	0.001	40.690	98.590	**0.60**	**98.94**	**0.60**	**0.01**	**1.98**	**Adamite**
MS 2016.072	Fig. 12	3	0.438	56.367	0.357	0.041	0.002	40.433	97.638	**0.78**	**98.43**	**0.79**	**0.02**	**1.97**	**Adamite**
TA2-10	Fig. 13	6	0.593	53.980	1.382	0.046	0.000	39.977	95.978	**1.08**	**96.05**	**1.11**	**0.02**	**1.91**	**Adamite**
MS 2015.065	Fig. 14	3	0.981	55.540	0.103	0.000	0.026	40.170	96.819	**1.77**	**98.02**	**1.77**	**0.04**	**1.95**	**Adamite**
MS 2016.076	Fig. 15	6	3.188	54.938	0.011	0.041	0.027	40.658	98.863	**5.60**	**94.30**	**5.60**	**0.11**	**1.90**	**Adamite**
MS 2009.048	Fig. 16	6	9.973	47.267	0.021	0.030	0.026	40.307	97.623	**17.74**	**82.16**	**17.76**	**0.36**	**1.65**	**Adamite**
TA2-6	Fig. 17	8	12.116	43.383	0.179	0.038	0.063	40.059	95.838	**22.13**	**77.44**	**22.22**	**0.44**	**1.54**	**Adamite**
MS 2013.002	Fig. 18	3	15.160	42.533	0.107	0.041	0.048	39.687	97.576	**26.65**	**73.07**	**26.72**	**0.54**	**1.49**	**Zincolivenite**
MS 2013.014	Fig. 19	3	15.460	41.900	0.272	0.000	0.176	39.570	97.378	**27.26**	**72.21**	**27.41**	**0.55**	**1.47**	**Zincolivenite**
TA1-2	Fig. 20	8	16.423	38.802	0.211	0.000	0.124	40.496	96.056	**30.09**	**69.48**	**30.22**	**0.59**	**1.37**	**Zincolivenite**
MS 2011.084	Fig. 21	2	17.915	39.795	0.006	0.017	0.080	39.830	97.643	**31.52**	**68.43**	**31.54**	**0.64**	**1.39**	**Zincolivenite**
MS 2012.011	Fig. 22	3	21.323	36.187	0.064	0.015	0.085	39.577	97.250	**37.56**	**62.29**	**37.61**	**0.76**	**1.27**	**Zincolivenite**
MS 1986.001	Fig. 23	3	22.737	34.023	0.154	0.021	0.041	40.080	97.055	**40.47**	**59.19**	**40.61**	**0.81**	**1.19**	**Zincolivenite**
TA1-5	Fig. 24	8	22.409	31.195	0.000	0.015	0.152	39.491	93.262	**42.35**	**57.62**	**42.36**	**0.83**	**1.13**	**Zincolivenite**
MS 2018.027	Fig. 25	4	23.805	32.683	0.026	0.022	0.115	39.868	96.518	**42.66**	**57.24**	**42.70**	**0.86**	**1.15**	**Zincolivenite**
MS 2010.189	Fig. 26	3	24.220	32.010	0.058	0.000	0.092	39.700	96.079	**43.59**	**56.30**	**43.64**	**0.88**	**1.13**	**Zincolivenite**
MS 2012.012	Fig. 27	3	24.283	32.010	0.024	0.019	0.083	39.827	96.247	**43.66**	**56.25**	**43.70**	**0.88**	**1.13**	**Zincolivenite**
MS 2016.004	Fig. 28	4	24.775	31.925	0.109	0.008	0.064	39.550	96.431	**44.16**	**55.61**	**44.26**	**0.89**	**1.13**	**Zincolivenite**
TA2-8	Fig. 29	7	24.713	30.715	0.099	0.000	0.102	40.080	95.709	**45.06**	**54.74**	**45.15**	**0.89**	**1.09**	**Zincolivenite**
MS 2015.051	Fig. 30	3	25.453	31.233	0.074	0.038	0.050	40.090	96.939	**45.37**	**54.41**	**45.47**	**0.91**	**1.09**	**Zincolivenite**
MS 2018.056	Fig. 31	3	25.397	30.970	0.106	0.006	0.073	40.053	96.605	**45.52**	**54.26**	**45.62**	**0.91**	**1.09**	**Zincolivenite**
MS 2014.108	Fig. 32	3	25.077	29.893	0.019	0.013	0.141	39.143	94.286	**46.16**	**53.78**	**46.19**	**0.92**	**1.07**	**Zincolivenite**
MS 2010.017	Fig. 33	3	26.420	29.997	0.144	0.019	0.075	39.657	96.311	**47.25**	**52.43**	**47.40**	**0.95**	**1.06**	**Zincolivenite**
MS 2016.075	Fig. 34	6	26.937	29.905	0.063	0.023	0.079	39.792	96.798	**47.88**	**51.95**	**47.96**	**0.97**	**1.05**	**Zincolivenite**
MS 2012.013	Fig. 35	3	27.360	29.183	0.009	0.016	0.124	40.323	97.017	**48.94**	**51.01**	**48.96**	**0.98**	**1.02**	**Zincolivenite**
MS 2005.043	Fig. 36	3	27.473	29.123	0.013	0.004	0.063	39.327	96.003	**49.10**	**50.87**	**49.11**	**1.00**	**1.03**	**Zincolivenite**
MS 2018.058	Fig. 37	4	27.838	28.833	0.010	0.027	0.126	39.933	96.765	**49.66**	**50.27**	**49.69**	**1.00**	**1.01**	**Zincolivenite**
TA1-3	Fig. 38	6	27.476	27.293	0.043	0.000	0.061	40.139	95.012	**50.70**	**49.22**	**50.74**	**1.00**	**0.97**	**Zincolivenite**
MS 2005.044	Fig. 39	3	28.543	27.783	0.013	0.006	0.035	39.907	96.287	**51.23**	**48.73**	**51.25**	**1.03**	**0.98**	**Zincolivenite**
MS 2010.101	Fig. 40	3	28.847	28.033	0.011	0.000	0.036	40.197	97.124	**51.28**	**48.70**	**51.29**	**1.03**	**0.98**	**Zincolivenite**
MS 2016.044	Fig. 41	3	29.330	27.190	0.015	0.009	0.016	39.690	96.250	**52.44**	**47.51**	**52.46**	**1.06**	**0.96**	**Zincolivenite**
TA1-4	Fig. 42	6	29.421	26.404	0.000	0.000	0.013	40.536	96.374	**53.27**	**46.73**	**53.27**	**1.06**	**0.93**	**Zincolivenite**
MS 2017.069	Fig. 43	6	31.057	25.638	0.031	0.013	0.095	39.870	96.703	**55.30**	**44.62**	**55.35**	**1.11**	**0.90**	**Zincolivenite**
MS 2009.064	Fig. 44	3	36.270	20.410	0.101	0.018	0.118	39.900	96.816	**64.37**	**35.40**	**64.52**	**1.30**	**0.71**	**Zincolivenite**
MS 2014.001	Fig. 45	3	37.487	18.880	0.098	0.019	0.069	39.520	96.072	**66.86**	**32.91**	**67.01**	**1.35**	**0.67**	**Zincolivenite**
MS 1985.018	Fig. 46	3	45.903	11.467	0.149	0.026	0.454	39.563	97.562	**80.11**	**19.56**	**80.38**	**1.63**	**0.40**	**Olivenite**
TA2-7	Fig. 47	8	49.016	6.858	0.026	0.000	0.122	40.056	96.078	**87.93**	**12.02**	**87.97**	**1.76**	**0.24**	**Olivenite**
MS 1988.001	Fig. 48	3	52.227	4.087	0.069	0.012	0.184	39.523	96.102	**92.75**	**7.09**	**92.90**	**1.88**	**0.14**	**Olivenite**
MS 1984.043	Fig. 49	4	54.453	1.821	0.078	0.001	0.704	39.295	96.352	**96.69**	**3.16**	**96.84**	**1.94**	**0.06**	**Olivenite**
TA2-9	Fig. 50	6	54.193	1.681	0.000	0.000	0.124	40.275	96.273	**97.06**	**2.94**	**97.06**	**1.94**	**0.06**	**Olivenite**
MS 2017.023	Fig. 51	3	55.453	1.138	0.240	0.001	0.887	38.303	96.022	**97.57**	**1.96**	**98.03**	**1.99**	**0.04**	**Olivenite**
MS 2017.053	Fig. 52	7	55.554	0.928	0.007	0.006	0.735	38.887	96.119	**98.37**	**1.61**	**98.39**	**1.99**	**0.03**	**Olivenite**

Table 1. Mean compositions of adamite – olivenite series minerals, sampled from 43 Tsumeb specimens. Specimen numbers are shown in column 1, and a photograph of each specimen is included in this article according to the figure numbers in column 2. Column 3 shows the number of analyses (*n*) on which the mean composition data (columns 4 through 10) are based. Calculated mol % for copper and zinc are shown in columns 11 and 12; column 13 shows the adjusted mol percent copper (MP_{Cu}; defined as Cu/(Cu+Zn)*100); columns 14 and 15 show the number of copper and zinc atoms per formula unit and column 15 identifies the mineral species on the basis of the MP_{Cu} value (column 13).

	MP_{Cu} = Cu/(Cu+Zn)*100						
	Low	**Mean**	**High**	***n***	**Photo**	**Color / diaphaneity / habit**	**Indicated mineral species and comments**
MS 2014.068	0.00	**0.00**	0.00	1	Fig. 10	Orange-yellow; translucent; equant	**Adamite** (essentially end-member composition)
MS 2014.149	0.32	**0.60**	1.13	3	Fig. 11	Greenish-yellow; translucent; equant	**Adamite** (close to end-member composition)
MS 2016.072	0.03	**0.79**	1.74	3	Fig. 12	Colorless to brown; transparent; equant	**Adamite** (close to end-member composition)
TA2-10	0.02	**1.11**	3.25	6	Fig. 13	Orange-yellow; translucent; long prismatic	**Adamite** (close to end-member composition)
MS 2015.065	0.65	**1.77**	2.82	3	Fig. 14	Pale yellow; opaque; tabular	**Adamite** (close to end-member composition)
MS 2016.076	0.00	**5.60**	18.04	6	Fig. 15	Yellowish brown, pink (zoned); translucent; pseudo-octahedral	**Adamite** (variable composition; locally copper-rich)
MS 2009.048	0.03	**17.76**	36.68	6	Fig. 16	(1) Pink; translucent; elongate; and (2) green; opaque	Adamite / zincolivenite; mean composition is **adamite**
TA2-6	1.72	**22.22**	38.51	8	Fig. 17	Yellow, to green (zoned); translucent; long prismatic	Adamite / zincolivenite; mean composition is **adamite**
MS 2013.002	11.14	**26.72**	38.69	3	Fig. 18	Bottle-green (zoned); translucent; pseudo-octahedral	Adamite / zincolivenite; mean composition is **zincolivenite**
MS 2013.014	16.06	**27.41**	37.87	3	Fig. 19	Emerald-green (zoned); translucent; pseudo-octahedral	Adamite / zincolivenite; mean composition is **zincolivenite**
TA1-2	13.87	**30.22**	41.33	8	Fig. 20	Pale-green (zoned), translucent, short prismatic	Adamite / zincolivenite; mean composition is **zincolivenite**
MS 2011.084	27.72	**31.54**	35.31	2	Fig. 21	Spearmint-green; opaque; equant	**Zincolivenite**
MS 2012.011	29.39	**37.61**	48.86	3	Fig. 22	Emerald-green; transparent; pseudo-octahedral	**Zincolivenite** (wide compositional range)
MS 1986.001	37.87	**40.61**	42.70	3	Fig. 23	Spearmint-green; translucent; equant	**Zincolivenite**
TA1-5	38.73	**42.36**	48.97	8	Fig. 24	Spearmint-green; opaque; short prismatic	**Zincolivenite**
MS 2018.027	40.40	**42.70**	45.36	4	Fig. 25	Spearmint-green; opaque; short prismatic	**Zincolivenite**
MS 2010.189	39.39	**43.64**	43.98	3	Fig. 26	Spearmint-green; opaque; equant	**Zincolivenite**
MS 2012.012	37.29	**43.70**	47.30	3	Fig. 27	Spearmint-green; translucent; elongated / acicular	**Zincolivenite**
MS 2016.004	41.92	**44.26**	46.41	4	Fig. 28	Gray-green; opaque; equant	**Zincolivenite**
TA2-8	43.70	**45.15**	47.75	7	Fig. 29	Spearmint-green; opaque; equant	**Zincolivenite**
MS 2015.051	42.56	**45.47**	48.31	3	Fig. 30	Spearmint-green; opaque; prismatic	**Zincolivenite**
MS 2018.056	44.65	**45.62**	46.88	3	Fig. 31	Spearmint-green; translucent; prismatic	**Zincolivenite**
MS 2014.108	43.86	**46.19**	48.25	3	Fig. 32	Spearmint-green; opaque; prismatic	**Zincolivenite**
MS 2010.017	42.33	**47.40**	51.37	3	Fig. 33	Spearmint-green; opaque; short prismatic	**Zincolivenite**
MS 2016.075	43.69	**47.96**	52.98	6	Fig. 34	Emerald-green; translucent; pseudo-octahedral	**Zincolivenite**
MS 2012.013	45.25	**48.96**	51.75	3	Fig. 35	Emerald-green; translucent; prismatic	**Zincolivenite**
MS 2005.043	47.13	**49.11**	51.36	3	Fig. 36	Emerald-green; translucent; prismatic	**Zincolivenite**
MS 2018.058	47.23	**49.69**	52.01	4	Fig. 37	Emerald-green; translucent; prismatic (acicular)	**Zincolivenite**
TA1-3	46.24	**50.74**	55.13	6	Fig. 38	Emerald-green; translucent; prismatic / radial aggregates	**Zincolivenite**
MS 2005.044	51.13	**51.25**	51.38	3	Fig. 39	Emerald-green; transparent; prismatic	**Zincolivenite** (very narrow compositional range)
MS 2010.101	50.78	**51.29**	51.78	3	Fig. 40	Emerald-green; transparent; prismatic	**Zincolivenite** (very narrow compositional range)
MS 2016.044	51.03	**52.46**	54.40	3	Fig. 41	Emerald-green; translucent; pseudo-octahedral	**Zincolivenite**
TA1-4	50.3	**53.27**	56.26	6	Fig. 42	Emerald-green; translucent; prismatic	**Zincolivenite**
MS 2017.069	49.83	**55.35**	60.37	6	Fig. 43	Emerald-green; transparent; prismatic / radial aggregates	**Zincolivenite**
MS 2009.064	63.57	**64.52**	66.06	3	Fig. 44	Bottle-green; translucent; prismatic / radial aggregates	**Zincolivenite**
MS 2014.001	50.11	**67.01**	79.35	3	Fig. 45	Bottle-green; translucent; composite radial aggregates	Zincolivenite / olivenite; mean composition is **zincolivenite**
MS 1985.018	79.39	**80.38**	80.89	3	Fig. 46	Blackish-green; translucent; 'bow-tie' radial aggregates	**Olivenite**; zinc-enriched
TA2-7	81.16	**87.97**	94.46	8	Fig. 47	Blackish-green; translucent; composite radial aggregates	**Olivenite**; zinc-enriched
MS 1988.001	90.70	**92.90**	95.30	3	Fig. 48	Blackish-green; translucent; prismatic	**Olivenite**; zinc-enriched
MS 1984.043	95.63	**96.84**	98.30	4	Fig. 49	Blackish-green; translucent; short prismatic	**Olivenite**
TA2-9	94.78	**97.06**	97.82	6	Fig. 50	Blackish-green; translucent; long prismatic	**Olivenite**
MS 2017.023	97.23	**98.03**	98.62	3	Fig. 51	Blackish-green; translucent; equant / short prismatic	**Olivenite** (close to end-member composition)
MS 2017.053	97.58	**98.39**	99.13	7	Fig. 52	Blackish-green; translucent; short prismatic	**Olivenite** (close to end-member composition)

Table 2. Copper content (minimum, mean, and maximum values for MP_{Cu}) and simple visual properties for 43 specimens of adamite – olivenite series minerals from Tsumeb, arranged in ascending order of mean copper content. Compositions indicative of adamite are shown in yellow, zincolivenite in lime-green, and olivenite in olive-green.

Figure 1. Crystals of translucent, emerald-green zincolivenite (to 11 mm) associated with aggregates of mustard-yellow ferrilotharmeyerite. 2.6 cm. Malcolm Southwood specimen and photo.

Figure 2. Acicular crystals (to 20 mm) of translucent, olive green olivenite on crystallized malachite lining a vug in a 20 cm boulder of massive malachite and olivenite from the Tsumeb open pit. This habit of olivenite is uncommon at Tsumeb and appears to have occurred only in the near-surface portion of the deposit. The specimen is number 1050 in the collection of Wilhelm Klein. Field of view is 9 cm. Courtesy of the Mineralogical & Geological Museum at Harvard University, Olivenite; MGMH ID# 106045, Tsumeb; Namibia. Malcolm Southwood photo.

Figure 3. Specimen number 2640 from the Karabacek Collection, labelled by its original owner as 'veszelyite', but identified as 'adamite' by X-ray diffraction at Harvard. Field of view is 3.5 cm in a 7.5 cm specimen from the first oxidation zone at Tsumeb. Courtesy of the Mineralogical & Geological Museum at Harvard University, Adamite; MGMH ID# 93856, Tsumeb; Namibia. @ copyright 2012, President and Fellows of Harvard College. All rights reserved. Malcolm Southwood photo.

Figure 4. The famous 'cobaltoan adamite' specimen from the Karabacek Collection (# 4318) at Harvard University. Adamite crystals (to 7 mm) cover one side of the specimen and their terminations are blackish-green in color. Broken surfaces, however, reveal magenta tints attributed to the presence of cobalt. 11 cm specimen, from the first oxidation zone at Tsumeb. Courtesy of the Mineralogical & Geological Museum at Harvard University, Adamite; MGMH ID# 93828, Tsumeb; Namibia. @ copyright 2012, President and Fellows of Harvard College. All rights reserved. Malcolm Southwood photo.

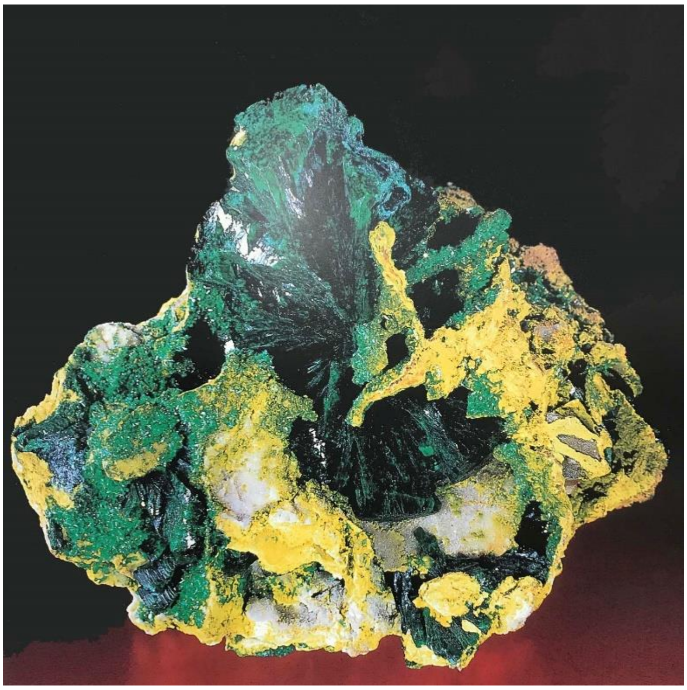

Figure 5. Emerald-green crystals of ‘cuproadamite’ associated with powdery lemon-yellow ferrilotharmeyerite. The specimen was recovered from 30 level in the second oxidation zone in 1986. 10.9 cm. Des Sacco specimen; Bruce Cairncross photo.

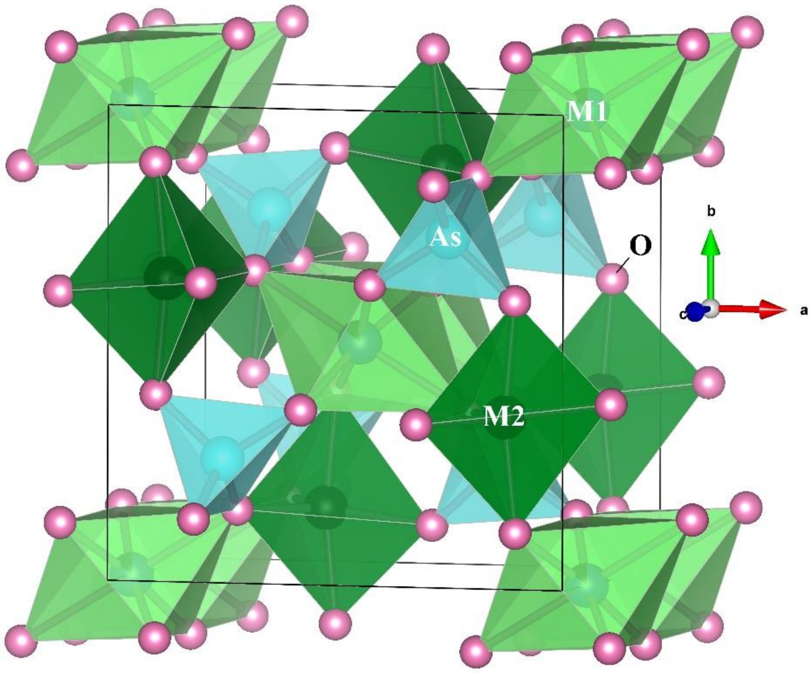

Figure 6. Atomic arrangement of the adamite-olivenite series. The M1 and M2 octahedral sites are indicated by different shades of green. Arsenic resides on the tetrahedral site (blue) and oxygen atoms are indicated by pink spheres. Rendering created with VESTA 3 (Momma and Izumi 2011).

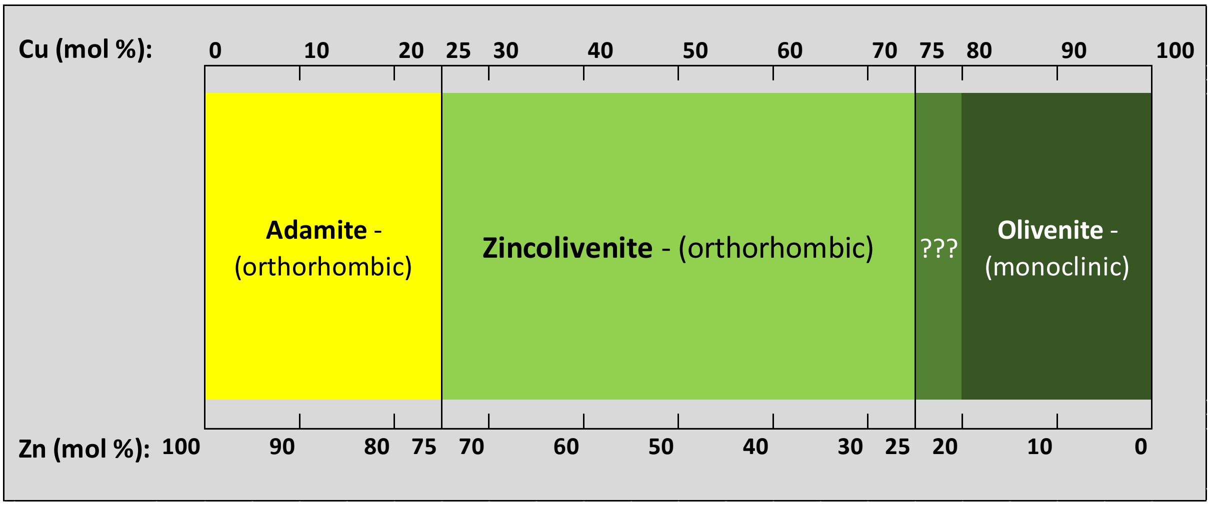

Figure 7. The adamite – olivenite solid solution series includes three mineral species (adamite, zincolivenite and olivenite) defined by the proportions of copper and zinc in each of two ordered cation sites in the crystal structure. Adamite and zincolivenite are both orthorhombic, while olivenite is monoclinic; however, the symmetry change occurs at circa 80 mol % copper, so that the speciation for compositions between 75 mol % and 80 mol % copper is poorly defined. For the purpose of this study we would consider compositions with > 75 mol % copper to be olivenite.

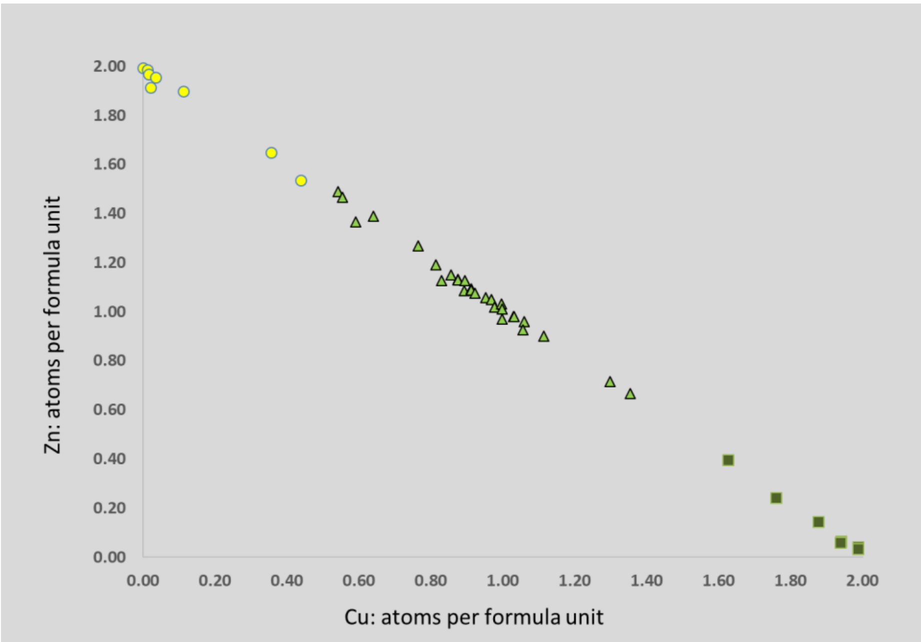

Figure 8. Mean zinc and copper content expressed as atoms per formula unit (APFU) for 43 specimens of adamite – olivenite series minerals from Tsumeb. The (small) deviations from a straight-line (unit) plot are attributable to the minor presence of iron and cobalt in some of the specimens. 8 specimens (with Cu < 0.5 APFU) plot as adamite (yellow circles) while 7 specimens (with Cu > 1.5 APFU) plot as olivenite (olive-green squares). The remaining 28 specimens (green triangles) plot in the compositional field defining zincolivenite, with Cu between 0.5 and 1.5 APFU.

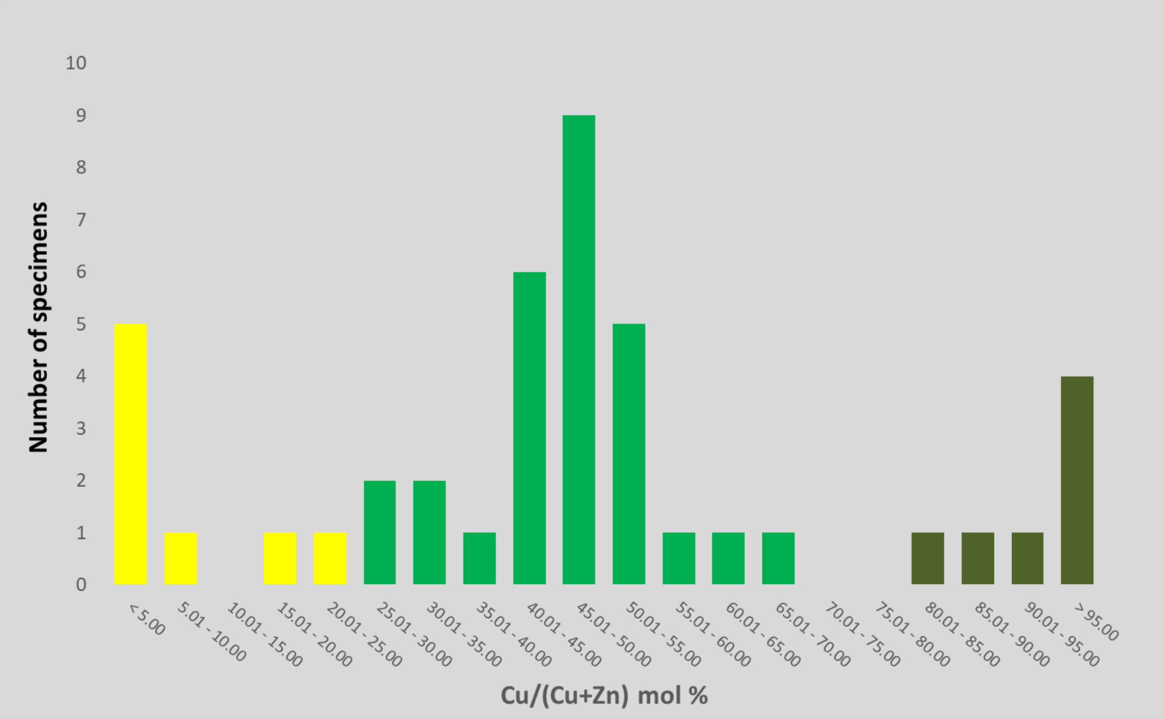

Figure 9. Distribution of mean compositions of 43 specimens of adamite – olivenite series minerals from Tsumeb. Adamite (yellow) specimens appear towards the left of the chart (i.e. lower Cu content); zincolivenite (green) in the center and olivenite (olive-green; higher Cu content) on the right.

Figure 10. Orange-yellow crystals of adamite (to 2 mm) over massive sulfide. This is essentially end-member adamite, with a value for MP_{Cu} of < 0.01%. 3.7 cm. Malcolm Southwood specimen (# MS 2014.068) and photo.

Figure 11. Yellow-green, partly transparent crystals of adamite (to 18 mm) associated with off-white crystals of smithsonite (EDS confirmed). The mean MP_{Cu} value of just 0.60 % (range: 0.32 – 1.13 %) is indicative of near end-member adamite, but it has a distinct greenish color. 6 cm. Malcolm Southwood specimen (# MS 2014.149) and photo.

Figure 12. Equant crystals (to 5 mm) of transparent, colorless to amber-brown adamite, on a siliceous matrix, with goethite. The mean MP_{Cu} is 0.79 % (range: 0.03 – 1.74 %), so the adamite is close to end member composition and, in this case, the minor copper content does not appear to influence the color. 4.5 cm. Malcolm Southwood specimen (# MS 2016.072) and photo.

Figure 13. Long prismatic crystals of orange-yellow adamite on mineralised dolostone. The mean MP_{Cu} is 1.11 % (range: 0.02 – 3.25 %), so the adamite is close to end member composition. 10 cm. Crystal Classics specimen and photo.

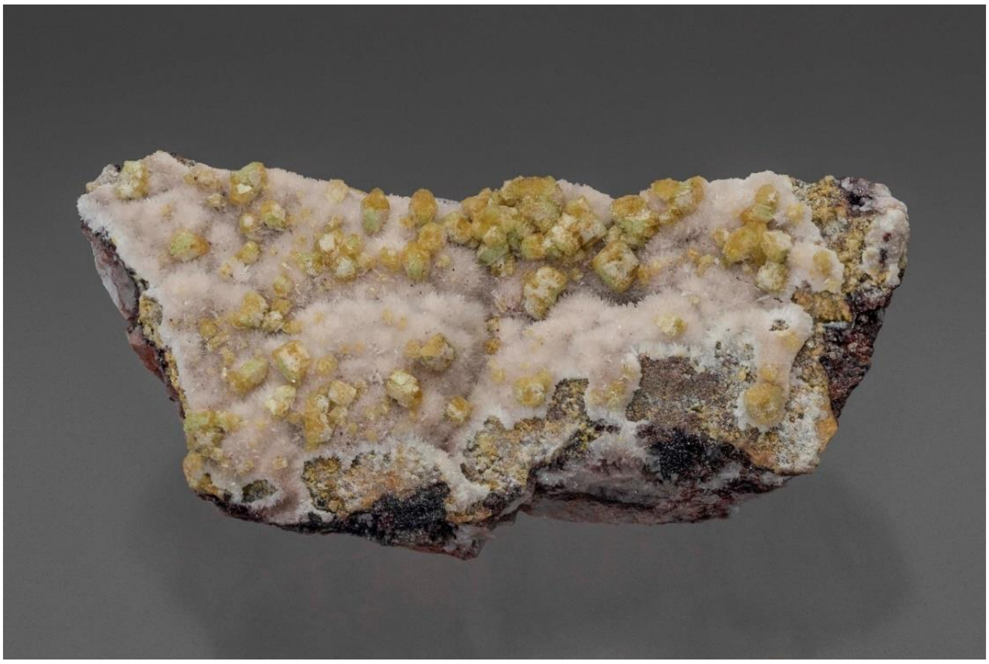

Figure 14. Thick, tabular, crystals of yellow adamite (to 3 mm), on a sub-botryoidal crust of white scalenohedral smithsonite crystals. The mean MP_{Cu} is 1.77 % (range: 0.65 – 2.82 %), so the adamite is close to end member composition. 8.5 cm. Malcolm Southwood specimen (# MS 2015.065) and photo.

Figure 15. This specimen includes adamite – olivenite series minerals of several compositions. The pseudo-octahedral crystals at upper right (as photographed) are yellowish-brown in color, but some have a distinct pinkish blush. The mean MP_{Cu} for the brown crystals is 9.38 % (range: 0.88 – 18.04 %) while the pinkish crystals contain a mean MP_{Cu} of 1.62 % (range: 0.27 – 4.60 %). The mean cobalt content of the pinkish crystals is 0.045 wt % (see text for further details). 9.5 cm. Malcolm Southwood specimen (# MS 2016.076) and photo.

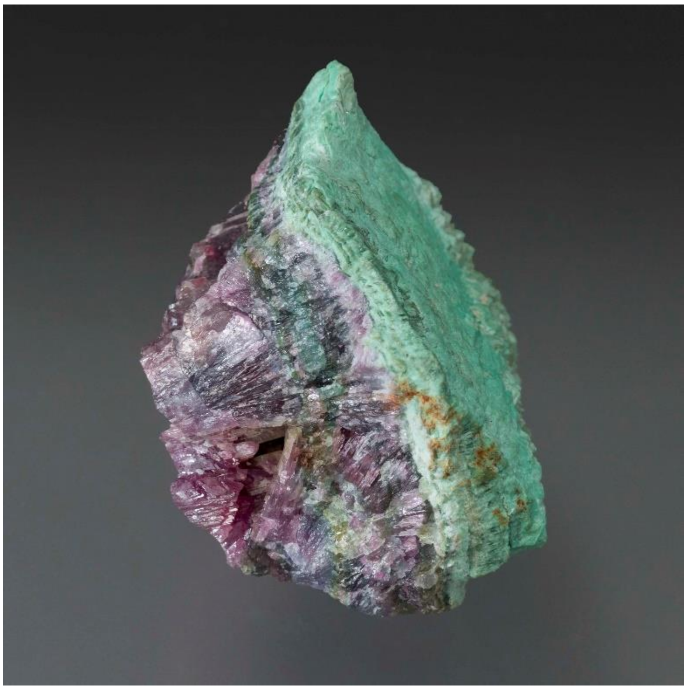

Figure 16. Densely intergrown blades of magenta-coloured adamite crystals (mean MP_{Cu} = 0.18 %), abruptly transitioning to a banded crust of spearmint-green zincolivenite (mean MP_{Cu} = 35.46 %). The mean cobalt content of the magenta crystals is 0.054 wt % (see text for further details). 3.8 cm. Malcolm Southwood specimen (# MS 2009.048) and photo.

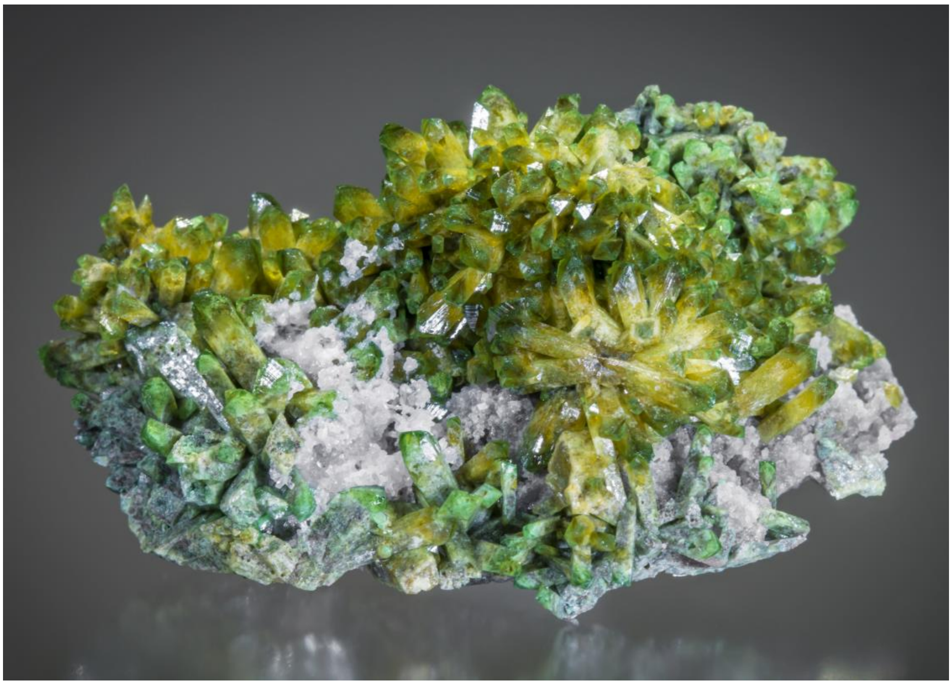

Figure 17. Elongated, prismatic crystals (to 5 mm) with a marked color zoning, ranging in composition from near end-member adamite to zincolivenite. The pale-yellow base of the crystals has a value for MP_{Cu} of 1.72 %, close to end-member adamite, grading up into yellow-green copper-rich adamite, and green terminations with a value for MP_{Cu} of 38.51 % which lies well within the compositional field of zincolivenite. The mean MP_{Cu} is 22.22 %. 5 cm specimen. Crystal Classics specimen; John Schneider photo.

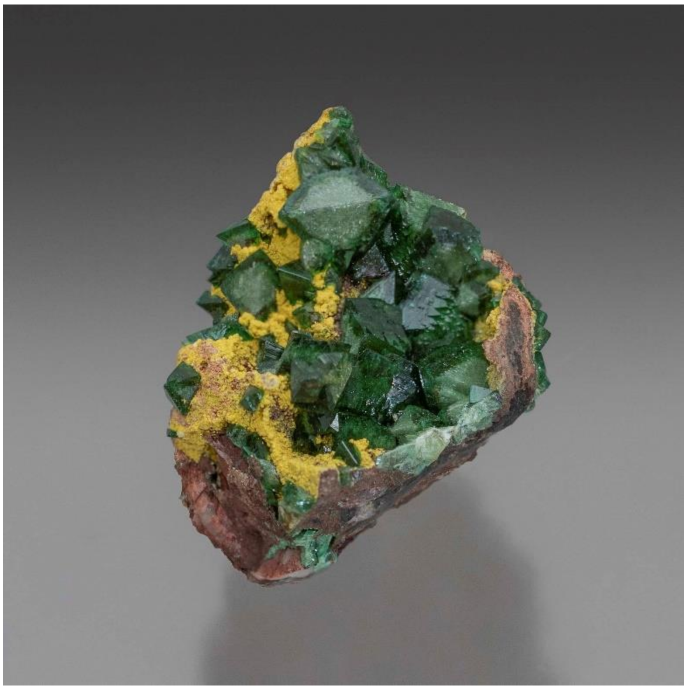

Figure 18. Pseudo-octahedral crystals (to 6 mm) of bottle-green zincolivenite (mean MP_{Cu} = 26.85 %) associated with a yellow micro-botryoidal mineral of the tsumcorite group. The zincolivenite crystals are zoned, with paler, frosted cores. WDS analysis shows that zones of both adamite and zincolivenite are present in these crystals, with MP_{Cu} ranging from 11.14 % to 38.69 %. 3 cm. Malcolm Southwood specimen (# MS 2013.002) and photo.

Figure 19. Equant (pseudo-octahedral) crystals (to 3 mm) of green adamite / zincolivenite (mean MP_{Cu} = 27.41 %). The crystals are zoned, with paler, frosted cores. WDS analysis shows that zones of both adamite and zincolivenite are present in these crystals, with MP_{Cu} ranging from 16.06 % to 37.87 %. 2.5 cm. Malcolm Southwood specimen (# MS 2013.014) and photo.

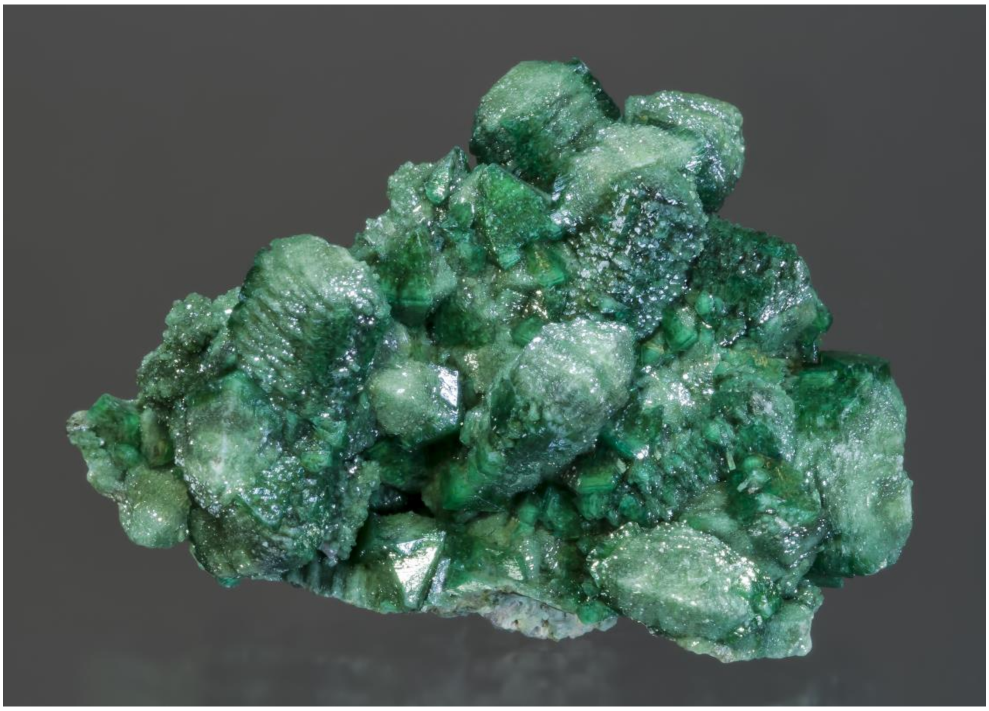

Figure 20. Short, prismatic crystals of adamite / zincolivenite (mean MP_{Cu} = 30.22 %) with pale cores of adamite (MP_{Cu} = 13.87 %) sheathed in darker green zincolivenite (MP_{Cu} = 41.33 %). 4 cm specimen. Crystal Classics specimen; John Schneider photo.

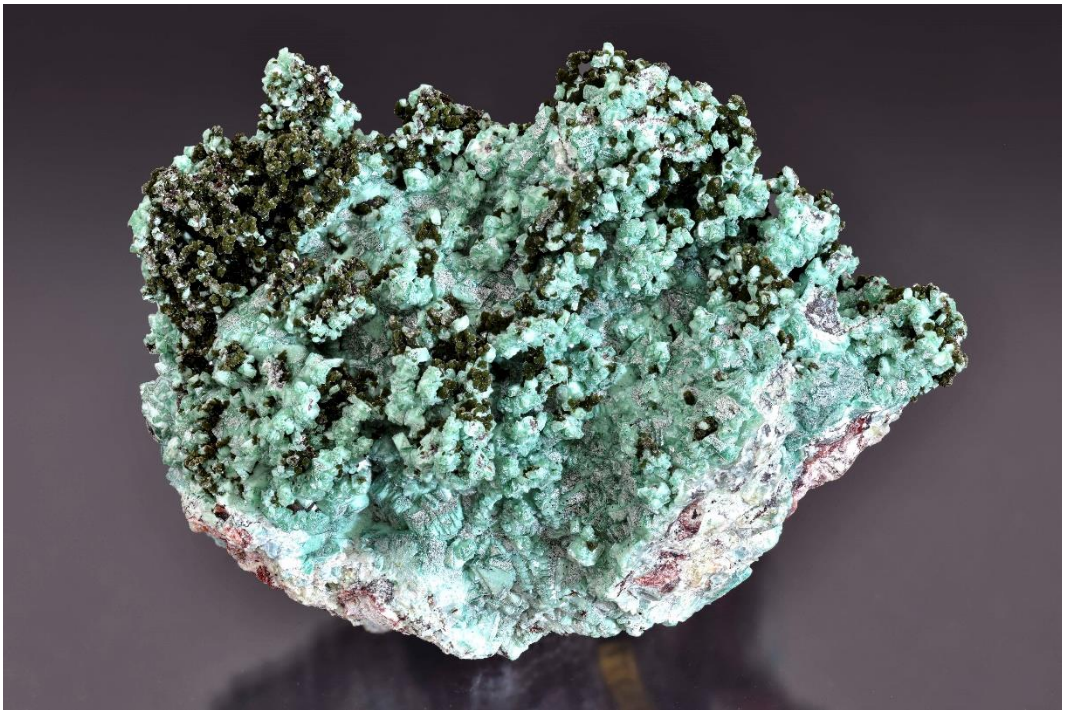

Figure 21. Equant, spearmint-green crystals (to 1 mm) of zincolivenite (mean MP_{Cu} = 31.54 %; range: 27.72 – 35.31 %), overgrowing arborescent aggregates of spheroidal duftite / conichalcite. 7 cm. Malcolm Southwood specimen (# MS 2011.084) and photo.

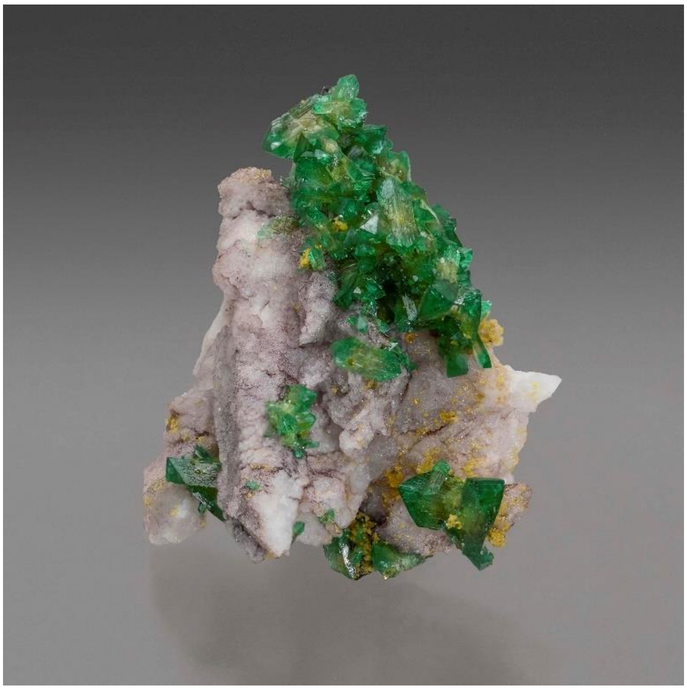

Figure 22. Gemmy crystals (to 3 mm) of emerald-green zincolivenite (mean MP_{Cu} = 37.61 %; range: 29.39 – 48.86 %), many of them doubly terminated, on etched and corroded quartz, with an unidentified (yellow) mineral of the tsumcorite group. The zincolivenite crystals appear zoned, which is consistent with the wide compositional range. 2.5 cm. Malcolm Southwood specimen (# MS 2012.011) and photo.

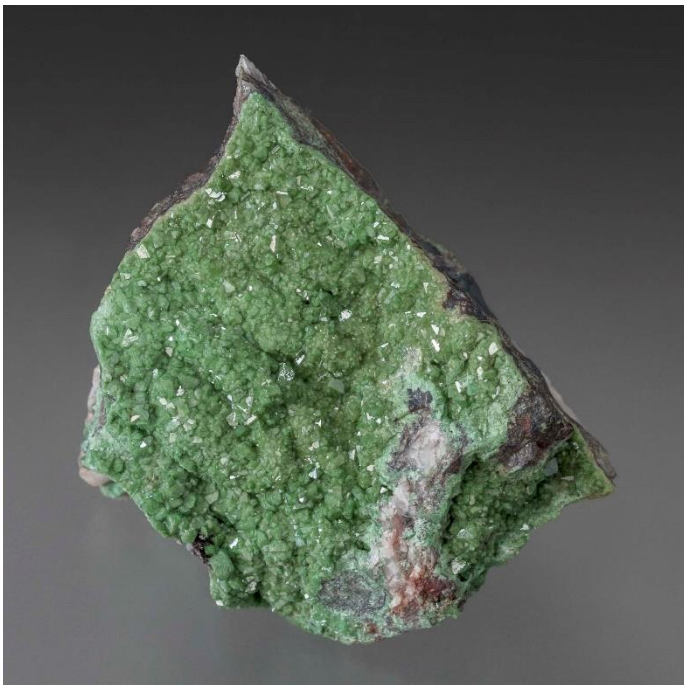

Figure 23. Equant, spearmint-green crystals of zincolivenite (mean MP_{Cu} = 40.61 %; range: 37.87 – 42.70 %) over silicified dolostone. 2.5 cm. Malcolm Southwood specimen (# MS 1986.001) and photo.

Figure 24. A crust of intergrown, short prismatic crystals (to 8 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 42.36 %; range = 38.73 – 48.97 %). 5 cm specimen. Crystal Classics specimen; John Schneider photo.

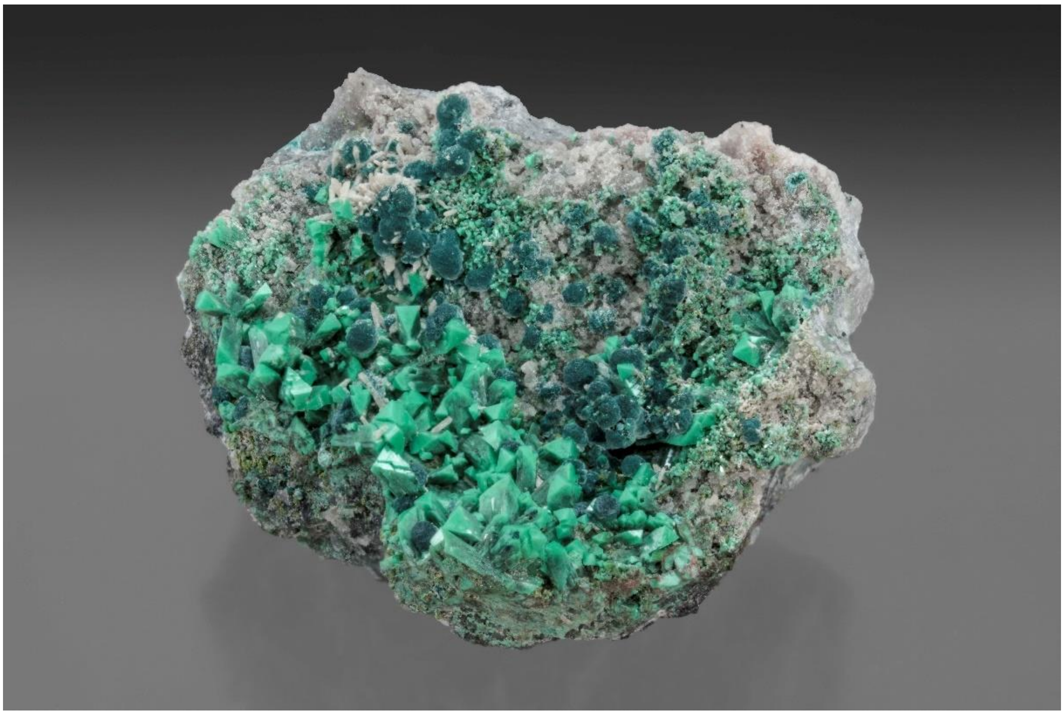

Figure 25. Prismatic crystals (to 4 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 42.70 %; range: 40.40 – 45.36 %), associated with quartz, rosasite and minor duftite / conichalcite. 6 cm. Malcolm Southwood specimen (# MS 2018.027) and photo.

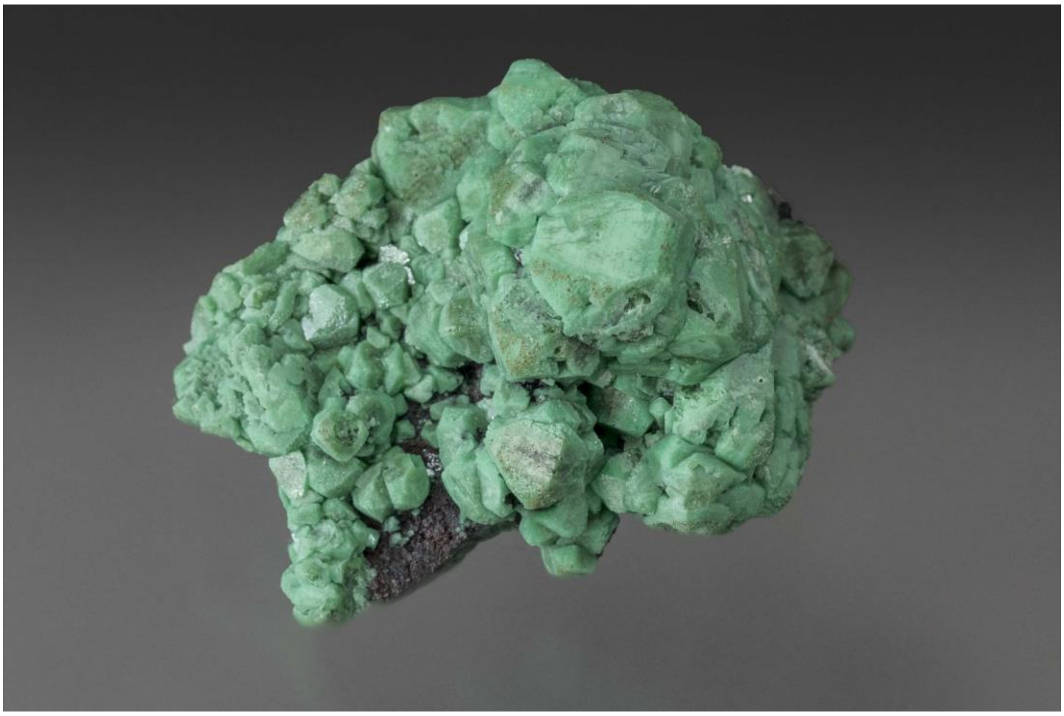

Figure 26. Equant, stubby crystals of spearmint-green zincolivenite (mean MP_{Cu} = 43.64 %; range: 39.39 – 43.98 %) over silicified dolostone. 3 cm. Malcolm Southwood specimen (# MS 2010.189) and photo.

Figure 27. Sprays of elongated blades (to 10 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 43.70 %; range: 37.29 to 47.30 %). 3 cm. Malcolm Southwood specimen (# MS 2012.012) and photo.

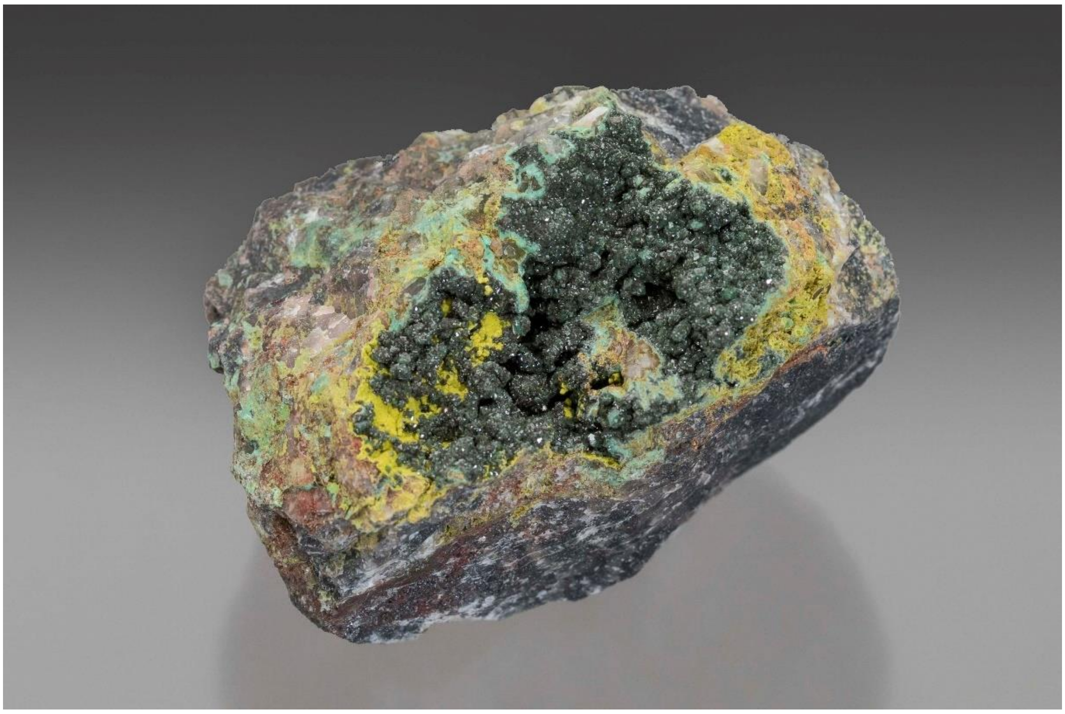

Figure 28. Aggregates of equant, bottle-green crystals (sub-mm) of zincolivenite (mean MP_{Cu} = 44.26 %; range: 41.92 – 44.26 %), in a vug lined with bright yellow zincgartrellite (EDS confirmed). 5.5 cm. Malcolm Southwood specimen (# MS 2016.004) and photo.

Figure 29. Equant, spearmint-green crystals of zincolivenite (mean MP_{Cu} = 45.15 %; range = 43.70 – 47.75 %). 8 cm. Crystal Classics specimen and photo.

Figure 30. Elongated prismatic crystals (to 10 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 45.47 %; range: 42.56 – 48.31 %), on quartz that is partly coated with goethite and sparse tabular crystals of butterscotch-colored wulfenite. This 5.5 cm specimen was collected from the second oxidation zone by the late John Innes, chief mineralogist at Tsumeb in the early 1980s. Malcolm Southwood specimen (# MS 2015.051) and photo.

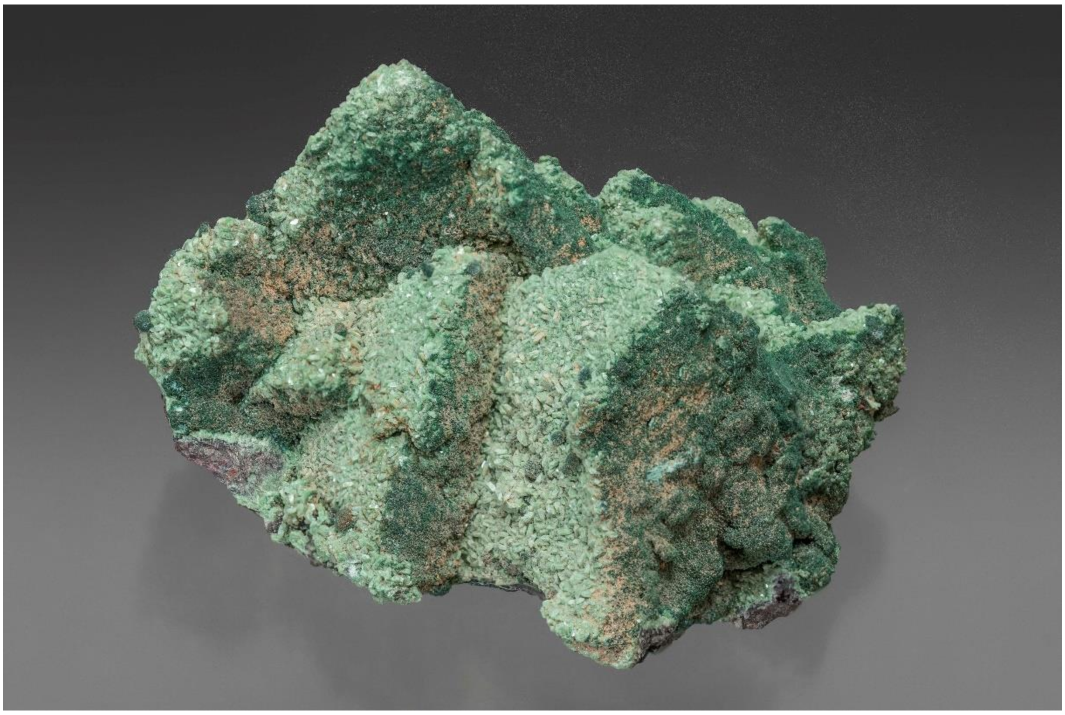

Figure 31. Spearmint-green, intergrown crystals (to 1.5 mm) of zincolivenite (mean MP_{Cu} = 45.62 %; range: 44.65 – 46.88 %) forming a crust over tennantite crystals (to 40 mm). A little malachite is also present. 7 cm. Malcolm Southwood specimen (# MS 2018.056) and photo.

Figure 32. Spearmint-green, elongated crystals (to 8 mm) of zincolivenite (mean MP_{Cu} = 46.19 %; range: 43.86 – 48.25 %) associated with microbotryoidal aggregates of tangeite (XRD/EDS confirmed). 3.5 cm. Malcolm Southwood specimen (# MS 2014.108) and photo.

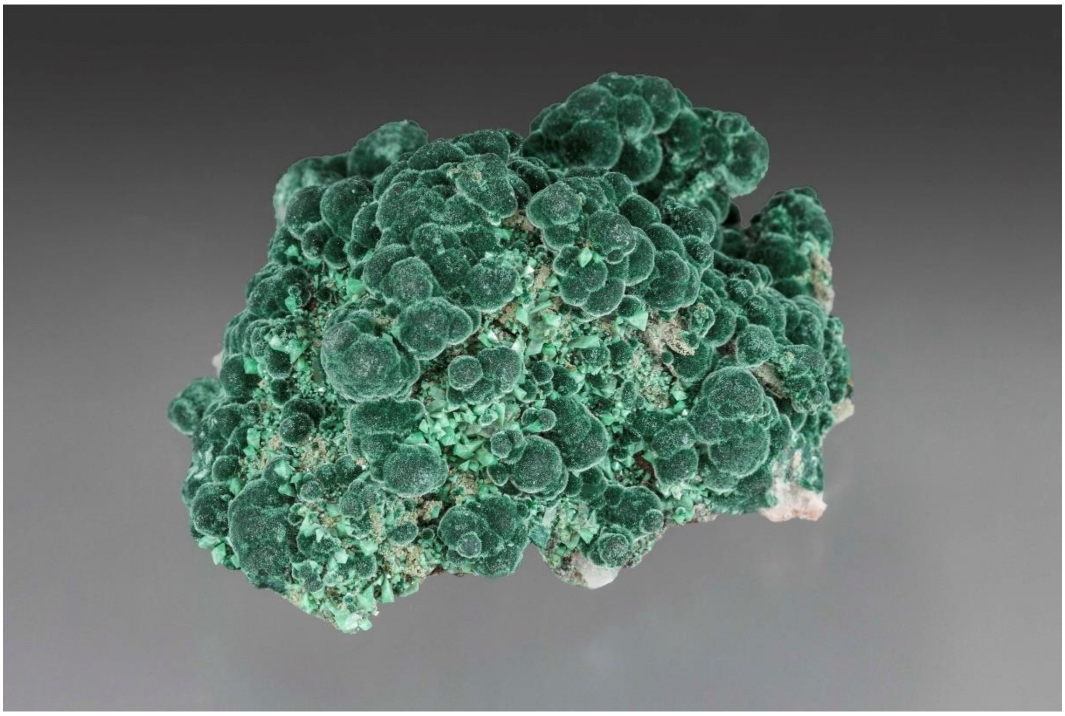

Figure 33. Short, terminated prismatic crystals (to 3 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 47.40 %; range: 42.33 – 51.37 %) associated with botryoids of fibrous malachite, on quartz. 4.5 cm. Malcolm Southwood specimen (# MS 2010.017) and photo.

Figure 34. Pseudo-octahedral crystals (to 1.5 mm) of highly translucent, emerald-green zincolivenite (mean MP_{Cu} = 47.96 %; range: 43.69 – 52.98 %) associated with a powdery yellow mineral of the tsumcorite group. 6 cm. Malcolm Southwood specimen (# MS 2016.075) and photo.

Figure 35. Fans of frosted, pale emerald-green, elongated crystals (to 8 mm) of zincolivenite (mean MP_{Cu} = 48.96 %; range: 45.25 – 51.75 %), peppered with a powdery yellow mineral of the tsumcorite group. 3 cm. Malcolm Southwood specimen (# MS 2012.013) and photo.

Figure 36. Slender prismatic crystals (to 4 mm) of emerald-green zincolivenite (mean MP_{Cu} = 49.11 %; range: 47.13 – 51.36 %) with sub-spherical tufts of acicular olive-green duftite (EDS confirmed). 2.3 cm. Malcolm Southwood specimen (# MS 2005.043) and photo.

Figure 37. Tightly intergrown acicular crystals of emerald-green zincolivenite (mean MP_{Cu} = 49.69 %; range: 47.23 – 52.01 %) forming radial sprays, associated with a powdery yellow mineral of the tsumcorite group. 5.2 cm. Malcolm Southwood specimen (# MS 2018.058) and photo.

Figure 38. Radial fans of long prismatic crystals of emerald-green zincolivenite (mean MP_{Cu} = 50.74 %; range = 46.24 – 55.13 %) on a mineralized, siliceous matrix. 2.5 cm specimen. Crystal Classics specimen; John Schneider photo.

Figure 39. Elongated and striated crystals (to 8 mm) of transparent, emerald-green zincolivenite (mean MP_{Cu} = 51.25 %; range: 51.13 – 51.38 %), associated with drusy sprays of mustard yellow to brown ferrilotharmeyerite, on a matrix of massive sulfide with quartz. 2.7 cm. Malcolm Southwood specimen (# MS 2005.044) and photo.

Figure 40. Pale emerald-green crystals of zincolivenite (mean MP_{Cu} = 51.29 %; range: 50.78 – 51.78 %), associated with colorless-white schultenite, on a matrix of massive sulfide with quartz. 2.1 cm. Malcolm Southwood specimen (# MS 2010.101) and photo.

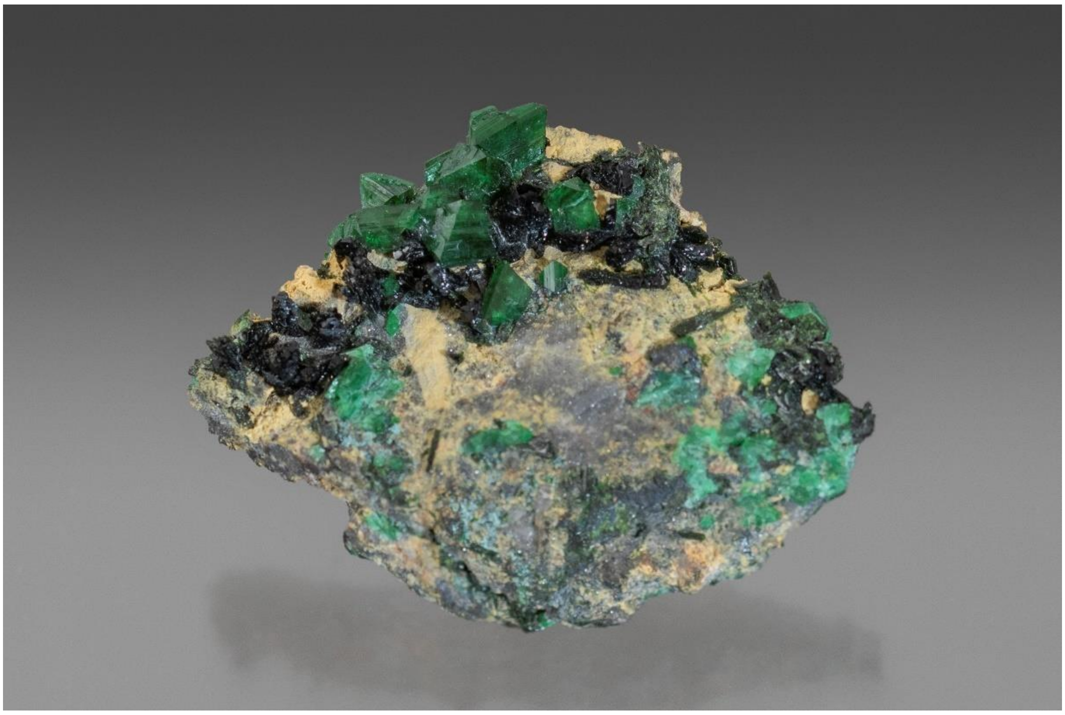

Figure 41. Pseudo-octahedral crystals of emerald-green zincolivenite (mean MP_{Cu} = 52.46 %; range: 51.03 – 54.40 %), associated with blackish-green prismatic crystals of olivenite (EDS analysis only), and a powdery yellow mineral of the tsumcorite group. 4.5 cm. Malcolm Southwood specimen (# MS 2016.044) and photo.

Figure 42. Prismatic crystals of gemmy, emerald-green zincolivenite (mean MP_{Cu} = 53.27 %; range = 49.83 – 60.37 %), associated with minor colorless schultenite, and quartz. 6 cm specimen. Crystal Classics specimen; John Schneider photo.

Figure 43. Fans of curvilinear crystals of emerald-green zincolivenite (mean MP_{Cu} = 55.35 %; range: 49.83 – 60.37 %) forming discoidal aggregates over a carpet of smaller crystals of the same mineral, associated with quartz, goethite and wulfenite. 9.5 cm. Malcolm Southwood specimen (# MS 2017.069) and photo.

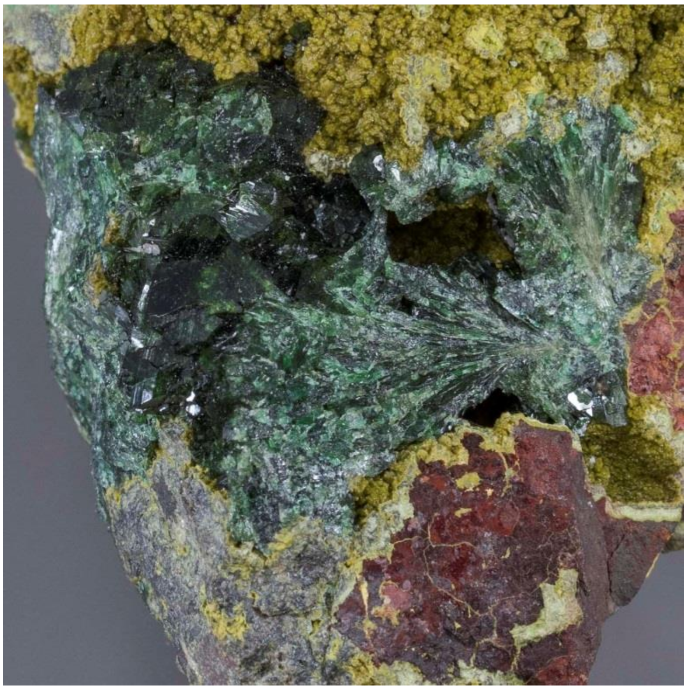

Figure 44. Intergrown crystals of bottle-green zincolivenite (mean MP_{Cu} = 64.52 %; range: 63.57 – 66.06 %) associated with yellow gartrellite (XRD/EDS confirmed). Field of view is 4 cm (in a 9 cm specimen). Malcolm Southwood specimen (# MS 2009.064) and photo.

Figure 45. Curvilinear, fan-shaped crystals of bottle-green zincolivenite (mean MP_{Cu} = 67.01 %; range: 50.11 – 79.35 %) associated with a yellow tsumcorite group mineral. While the mean MP_{Cu} value for this specimen lies within the compositional range of zincolivenite, the maximum value indicates that zones of olivenite are also present. This 4 cm specimen was collected by the late John Innes, chief mineralogist at Tsumeb in the early 1980s, from 35 level north-east, in the second oxidation zone. Malcolm Southwood specimen (# MS 2014.001) and photo.

Figure 46. A 'bow-tie' aggregate of greenish-black olivenite crystals (mean MP_{Cu} = 80.38 %; range: 79.39 – 80.89 %), associated with equant crystals of lighter green duftite / conichalcite and slender individual prisms (to 2.5 mm) of yellow-green olivenite (EDS analysis only) on quartz. 2 cm. Malcolm Southwood specimen (# MS 1985.018) and photo.

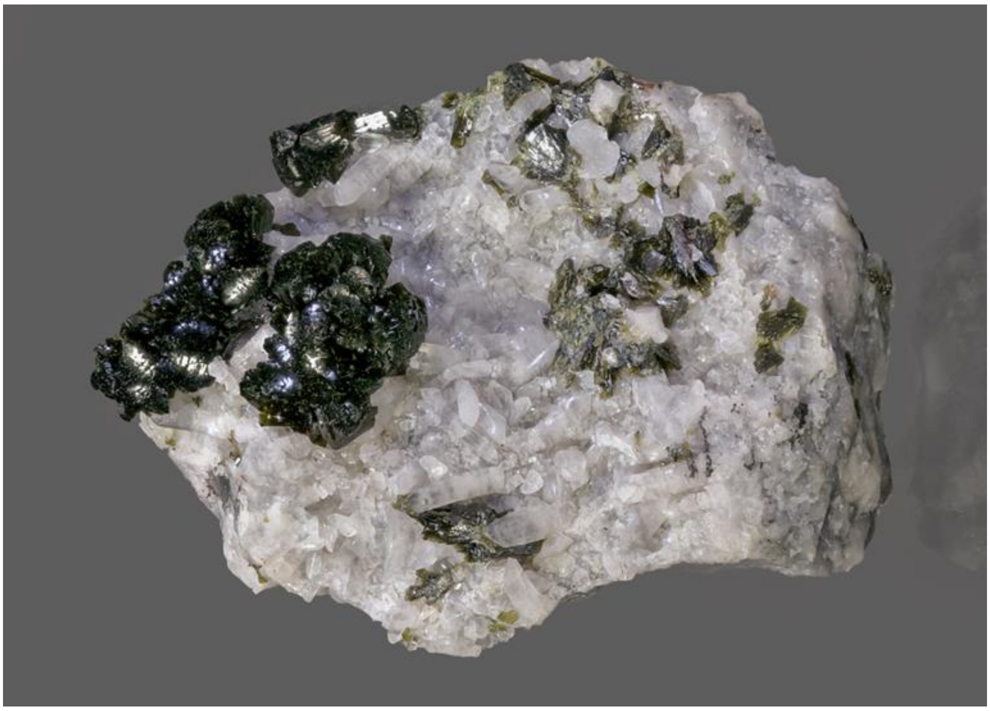

Figure 47. Curvilinear aggregates (to 10 mm) of blackish-green olivenite (mean MP_{Cu} = 87.97 %; range = 81.16 – 87.97 %), on quartz. 5 cm. Crystal Classics specimen; John Schneider photo.

Figure 48. Composite blades of blackish-green olivenite (mean MP_{Cu} = 92.90 %; range: 90.70 – 95.30 %), associated with a partial crust of malachite, over quartz. 3.5 cm. Malcolm Southwood specimen (# MS 1988.001) and photo.

Figure 49. Short prismatic crystals of blackish-green olivenite (mean MP_{Cu} = 96.84 %; range: 95.63 – 98.30 %), overgrown by isolated botryoidal aggregates of fibrous malachite (to 1 mm) in a vug in massive olivenite with relict sulfide. 5.5 cm. Malcolm Southwood specimen (# MS 1984.043) and photo.

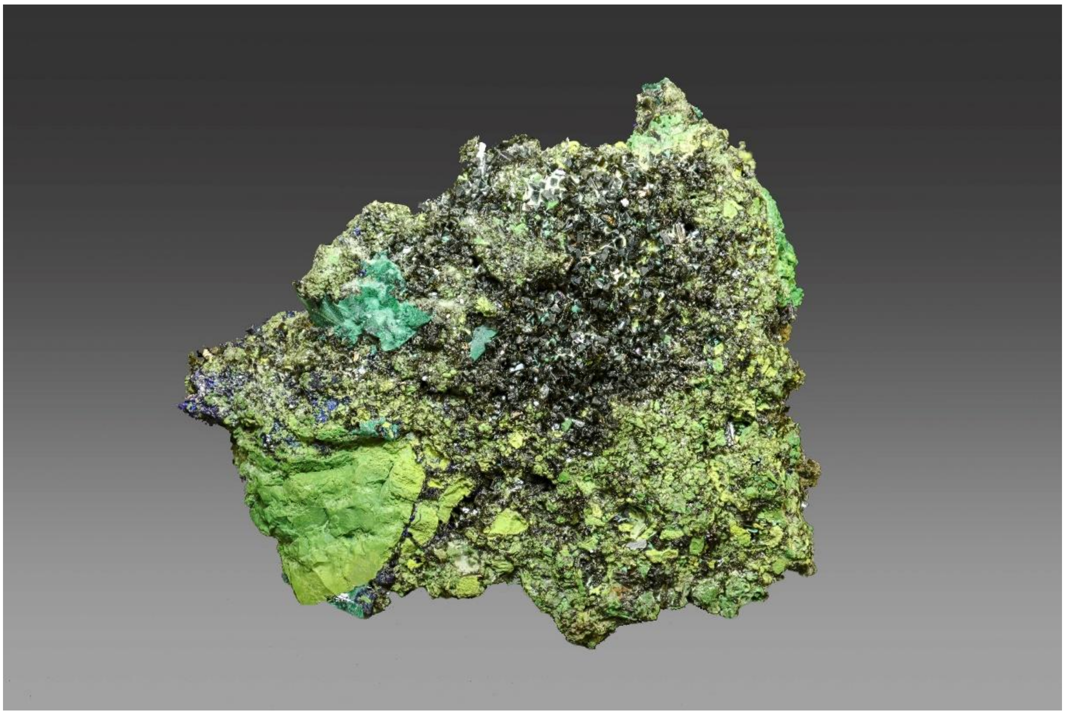

Figure 50. Elongated prismatic crystals of blackish-green olivenite (mean MP_{Cu} = 97.06 %; range: 94.78 – 97.82 %), intergrown in a shallow vug in a matrix of brecciated apple-green arsenates (undetermined) with malachite and minor azurite. 11 cm. Crystal Classics specimen and photo.

Figure 51. Blackish-green crystals (to 2 mm) of olivenite (mean MP_{Cu} = 98.03 %; range: 97.23 – 98.62 %) in a vug in massive olivenite, associated with minor malachite and arsentsumebite. 7 cm. Malcolm Southwood specimen (# MS 2017.023) and photo.

Figure 52. Stout prismatic crystals of bottle-green to blackish-green olivenite (mean MP_{Cu} = 98.39 %; range: 97.58 – 99.13 %), with minor azurite, malachite after azurite, and botryoidal malachite. The olivenite crystals are locally quite gemmy with yellowish-green translucency. 4.5 cm. Malcolm Southwood specimen (# MS 2017.053) and photo.

Figures and Tables

			Analysis - Wt % (mean of *n* analyses)							Cations: (mean of *n* analyses)		MP_{Cu} defined as	APFU		
Specimen	Photo	*n*	CuO	ZnO	FeO	CoO	P_2O_5	As_2O_5	Total	Cu (mol %)	Zn (mol %)	Cu/(Cu+Zn)*100	Cu	Zn	Indicated Mineral
MS 2014.068	Fig. 10	1	0.002	57.220	0.357	0.029	0.002	40.410	98.020	**0.00**	**99.24**	**0.00**	**0.00**	**1.99**	**Adamite**
MS 2014.149	Fig. 11	3	0.337	57.323	0.217	0.021	0.001	40.690	98.590	**0.60**	**98.94**	**0.60**	**0.01**	**1.98**	**Adamite**
MS 2016.072	Fig. 12	3	0.438	56.367	0.357	0.041	0.002	40.433	97.638	**0.78**	**98.43**	**0.79**	**0.02**	**1.97**	**Adamite**
TA2-10	Fig. 13	6	0.593	53.980	1.382	0.046	0.000	39.977	95.978	**1.08**	**96.05**	**1.11**	**0.02**	**1.91**	**Adamite**
MS 2015.065	Fig. 14	3	0.981	55.540	0.103	0.000	0.026	40.170	96.819	**1.77**	**98.02**	**1.77**	**0.04**	**1.95**	**Adamite**
MS 2016.076	Fig. 15	6	3.188	54.938	0.011	0.041	0.027	40.658	98.863	**5.60**	**94.30**	**5.60**	**0.11**	**1.90**	**Adamite**
MS 2009.048	Fig. 16	6	9.973	47.267	0.021	0.030	0.026	40.307	97.623	**17.74**	**82.16**	**17.76**	**0.36**	**1.65**	**Adamite**
TA2-6	Fig. 17	8	12.116	43.383	0.179	0.038	0.063	40.059	95.838	**22.13**	**77.44**	**22.22**	**0.44**	**1.54**	**Adamite**
MS 2013.002	Fig. 18	3	15.160	42.533	0.107	0.041	0.048	39.687	97.576	**26.65**	**73.07**	**26.72**	**0.54**	**1.49**	**Zincolivenite**
MS 2013.014	Fig. 19	3	15.460	41.900	0.272	0.000	0.176	39.570	97.378	**27.26**	**72.21**	**27.41**	**0.55**	**1.47**	**Zincolivenite**
TA1-2	Fig. 20	8	16.423	38.802	0.211	0.000	0.124	40.496	96.056	**30.09**	**69.48**	**30.22**	**0.59**	**1.37**	**Zincolivenite**
MS 2011.084	Fig. 21	2	17.915	39.795	0.006	0.017	0.080	39.830	97.643	**31.52**	**68.43**	**31.54**	**0.64**	**1.39**	**Zincolivenite**
MS 2012.011	Fig. 22	3	21.323	36.187	0.064	0.015	0.085	39.577	97.250	**37.56**	**62.29**	**37.61**	**0.76**	**1.27**	**Zincolivenite**
MS 1986.001	Fig. 23	3	22.737	34.023	0.154	0.021	0.041	40.080	97.055	**40.47**	**59.19**	**40.61**	**0.81**	**1.19**	**Zincolivenite**
TA1-5	Fig. 24	8	22.409	31.195	0.000	0.015	0.152	39.491	93.262	**42.35**	**57.62**	**42.36**	**0.83**	**1.13**	**Zincolivenite**
MS 2018.027	Fig. 25	4	23.805	32.683	0.026	0.022	0.115	39.868	96.518	**42.66**	**57.24**	**42.70**	**0.86**	**1.15**	**Zincolivenite**
MS 2010.189	Fig. 26	3	24.220	32.010	0.058	0.000	0.092	39.700	96.079	**43.59**	**56.30**	**43.64**	**0.88**	**1.13**	**Zincolivenite**
MS 2012.012	Fig. 27	3	24.283	32.010	0.024	0.019	0.083	39.827	96.247	**43.66**	**56.25**	**43.70**	**0.88**	**1.13**	**Zincolivenite**
MS 2016.004	Fig. 28	4	24.775	31.925	0.109	0.008	0.064	39.550	96.431	**44.16**	**55.61**	**44.26**	**0.89**	**1.13**	**Zincolivenite**
TA2-8	Fig. 29	7	24.713	30.715	0.099	0.000	0.102	40.080	95.709	**45.06**	**54.74**	**45.15**	**0.89**	**1.09**	**Zincolivenite**
MS 2015.051	Fig. 30	3	25.453	31.233	0.074	0.038	0.050	40.090	96.939	**45.37**	**54.41**	**45.47**	**0.91**	**1.09**	**Zincolivenite**
MS 2018.056	Fig. 31	3	25.397	30.970	0.106	0.006	0.073	40.053	96.605	**45.52**	**54.26**	**45.62**	**0.91**	**1.09**	**Zincolivenite**
MS 2014.108	Fig. 32	3	25.077	29.893	0.019	0.013	0.141	39.143	94.286	**46.16**	**53.78**	**46.19**	**0.92**	**1.07**	**Zincolivenite**
MS 2010.017	Fig. 33	3	26.420	29.997	0.144	0.019	0.075	39.657	96.311	**47.25**	**52.43**	**47.40**	**0.95**	**1.06**	**Zincolivenite**
MS 2016.075	Fig. 34	6	26.937	29.905	0.063	0.023	0.079	39.792	96.798	**47.88**	**51.95**	**47.96**	**0.97**	**1.05**	**Zincolivenite**
MS 2012.013	Fig. 35	3	27.360	29.183	0.009	0.016	0.124	40.323	97.017	**48.94**	**51.01**	**48.96**	**0.98**	**1.02**	**Zincolivenite**
MS 2005.043	Fig. 36	3	27.473	29.123	0.013	0.004	0.063	39.327	96.003	**49.10**	**50.87**	**49.11**	**1.00**	**1.03**	**Zincolivenite**
MS 2018.058	Fig. 37	4	27.838	28.833	0.010	0.027	0.126	39.933	96.765	**49.66**	**50.27**	**49.69**	**1.00**	**1.01**	**Zincolivenite**
TA1-3	Fig. 38	6	27.476	27.293	0.043	0.000	0.061	40.139	95.012	**50.70**	**49.22**	**50.74**	**1.00**	**0.97**	**Zincolivenite**
MS 2005.044	Fig. 39	3	28.543	27.783	0.013	0.006	0.035	39.907	96.287	**51.23**	**48.73**	**51.25**	**1.03**	**0.98**	**Zincolivenite**
MS 2010.101	Fig. 40	3	28.847	28.033	0.011	0.000	0.036	40.197	97.124	**51.28**	**48.70**	**51.29**	**1.03**	**0.98**	**Zincolivenite**
MS 2016.044	Fig. 41	3	29.330	27.190	0.015	0.009	0.016	39.690	96.250	**52.44**	**47.51**	**52.46**	**1.06**	**0.96**	**Zincolivenite**
TA1-4	Fig. 42	6	29.421	26.404	0.000	0.000	0.013	40.536	96.374	**53.27**	**46.73**	**53.27**	**1.06**	**0.93**	**Zincolivenite**
MS 2017.069	Fig. 43	6	31.057	25.638	0.031	0.013	0.095	39.870	96.703	**55.30**	**44.62**	**55.35**	**1.11**	**0.90**	**Zincolivenite**
MS 2009.064	Fig. 44	3	36.270	20.410	0.101	0.018	0.118	39.900	96.816	**64.37**	**35.40**	**64.52**	**1.30**	**0.71**	**Zincolivenite**
MS 2014.001	Fig. 45	3	37.487	18.880	0.098	0.019	0.069	39.520	96.072	**66.86**	**32.91**	**67.01**	**1.35**	**0.67**	**Zincolivenite**
MS 1985.018	Fig. 46	3	45.903	11.467	0.149	0.026	0.454	39.563	97.562	**80.11**	**19.56**	**80.38**	**1.63**	**0.40**	**Olivenite**
TA2-7	Fig. 47	8	49.016	6.858	0.026	0.000	0.122	40.056	96.078	**87.93**	**12.02**	**87.97**	**1.76**	**0.24**	**Olivenite**
MS 1988.001	Fig. 48	3	52.227	4.087	0.069	0.012	0.184	39.523	96.102	**92.75**	**7.09**	**92.90**	**1.88**	**0.14**	**Olivenite**
MS 1984.043	Fig. 49	4	54.453	1.821	0.078	0.001	0.704	39.295	96.352	**96.69**	**3.16**	**96.84**	**1.94**	**0.06**	**Olivenite**
TA2-9	Fig. 50	6	54.193	1.681	0.000	0.000	0.124	40.275	96.273	**97.06**	**2.94**	**97.06**	**1.94**	**0.06**	**Olivenite**
MS 2017.023	Fig. 51	3	55.453	1.138	0.240	0.001	0.887	38.303	96.022	**97.57**	**1.96**	**98.03**	**1.99**	**0.04**	**Olivenite**
MS 2017.053	Fig. 52	7	55.554	0.928	0.007	0.006	0.735	38.887	96.119	**98.37**	**1.61**	**98.39**	**1.99**	**0.03**	**Olivenite**

Table 1. Mean compositions of adamite – olivenite series minerals, sampled from 43 Tsumeb specimens. Specimen numbers are shown in column 1, and a photograph of each specimen is included in this article according to the figure numbers in column 2. Column 3 shows the number of analyses (*n*) on which the mean composition data (columns 4 through 10) are based. Calculated mol % for copper and zinc are shown in columns 11 and 12; column 13 shows the adjusted mol percent copper (MP_{Cu}; defined as Cu/(Cu+Zn)*100); columns 14 and 15 show the number of copper and zinc atoms per formula unit and column 15 identifies the mineral species on the basis of the MP_{Cu} value (column 13).

	MP_{Cu} = Cu/(Cu+Zn)*100						
	Low	Mean	High	*n*	Photo	Color / diaphaneity / habit	Indicated mineral species and comments
MS 2014.068	0.00	**0.00**	0.00	1	Fig. 10	Orange-yellow; translucent; equant	**Adamite** (essentially end-member composition)
MS 2014.149	0.32	**0.60**	1.13	3	Fig. 11	Greenish-yellow; translucent; equant	**Adamite** (close to end-member composition)
MS 2016.072	0.03	**0.79**	1.74	3	Fig. 12	Colorless to brown; transparent; equant	**Adamite** (close to end-member composition)
TA2-10	0.02	**1.11**	3.25	6	Fig. 13	Orange-yellow; translucent; long prismatic	**Adamite** (close to end-member composition)
MS 2015.065	0.65	**1.77**	2.82	3	Fig. 14	Pale yellow; opaque; tabular	**Adamite** (close to end-member composition)
MS 2016.076	0.00	**5.60**	18.04	6	Fig. 15	Yellowish brown, pink (zoned); translucent; pseudo-octahedral	**Adamite** (variable composition; locally copper-rich)
MS 2009.048	0.03	**17.76**	36.68	6	Fig. 16	(1) Pink; translucent; elongate; and (2) green; opaque	Adamite / zincolivenite; mean composition is **adamite**
TA2-6	1.72	**22.22**	38.51	8	Fig. 17	Yellow, to green (zoned); translucent; long prismatic	Adamite / zincolivenite; mean composition is **adamite**
MS 2013.002	11.14	**26.72**	38.69	3	Fig. 18	Bottle-green (zoned); translucent; pseudo-octahedral	Adamite / zincolivenite; mean composition is **zincolivenite**
MS 2013.014	16.06	**27.41**	37.87	3	Fig. 19	Emerald-green (zoned); translucent; pseudo-octahedral	Adamite / zincolivenite; mean composition is **zincolivenite**
TA1-2	13.87	**30.22**	41.33	8	Fig. 20	Pale-green (zoned), translucent, short prismatic	Adamite / zincolivenite; mean composition is **zincolivenite**
MS 2011.084	27.72	**31.54**	35.31	2	Fig. 21	Spearmint-green; opaque; equant	**Zincolivenite**
MS 2012.011	29.39	**37.61**	48.86	3	Fig. 22	Emerald-green; transparent; pseudo-octahedral	**Zincolivenite** (wide compositional range)
MS 1986.001	37.87	**40.61**	42.70	3	Fig. 23	Spearmint-green; translucent; equant	**Zincolivenite**
TA1-5	38.73	**42.36**	48.97	8	Fig. 24	Spearmint-green; opaque; short prismatic	**Zincolivenite**
MS 2018.027	40.40	**42.70**	45.36	4	Fig. 25	Spearmint-green; opaque; short prismatic	**Zincolivenite**
MS 2010.189	39.39	**43.64**	43.98	3	Fig. 26	Spearmint-green; opaque; equant	**Zincolivenite**
MS 2012.012	37.29	**43.70**	47.30	3	Fig. 27	Spearmint-green; translucent; elongated / acicular	**Zincolivenite**
MS 2016.004	41.92	**44.26**	46.41	4	Fig. 28	Gray-green; opaque; equant	**Zincolivenite**
TA2-8	43.70	**45.15**	47.75	7	Fig. 29	Spearmint-green; opaque; equant	**Zincolivenite**
MS 2015.051	42.56	**45.47**	48.31	3	Fig. 30	Spearmint-green; opaque; prismatic	**Zincolivenite**
MS 2018.056	44.65	**45.62**	46.88	3	Fig. 31	Spearmint-green; translucent; prismatic	**Zincolivenite**
MS 2014.108	43.86	**46.19**	48.25	3	Fig. 32	Spearmint-green; opaque; prismatic	**Zincolivenite**
MS 2010.017	42.33	**47.40**	51.37	3	Fig. 33	Spearmint-green; opaque; short prismatic	**Zincolivenite**
MS 2016.075	43.69	**47.96**	52.98	6	Fig. 34	Emerald-green; translucent; pseudo-octahedral	**Zincolivenite**
MS 2012.013	45.25	**48.96**	51.75	3	Fig. 35	Emerald-green; translucent; prismatic	**Zincolivenite**
MS 2005.043	47.13	**49.11**	51.36	3	Fig. 36	Emerald-green; translucent; prismatic	**Zincolivenite**
MS 2018.058	47.23	**49.69**	52.01	4	Fig. 37	Emerald-green; translucent; prismatic (acicular)	**Zincolivenite**
TA1-3	46.24	**50.74**	55.13	6	Fig. 38	Emerald-green; translucent; prismatic / radial aggregates	**Zincolivenite**
MS 2005.044	51.13	**51.25**	51.38	3	Fig. 39	Emerald-green; transparent; prismatic	**Zincolivenite** (very narrow compositional range)
MS 2010.101	50.78	**51.29**	51.78	3	Fig. 40	Emerald-green; transparent; prismatic	**Zincolivenite** (very narrow compositional range)
MS 2016.044	51.03	**52.46**	54.40	3	Fig. 41	Emerald-green; translucent; pseudo-octahedral	**Zincolivenite**
TA1-4	50.3	**53.27**	56.26	6	Fig. 42	Emerald-green; translucent; prismatic	**Zincolivenite**
MS 2017.069	49.83	**55.35**	60.37	6	Fig. 43	Emerald-green; transparent; prismatic / radial aggregates	**Zincolivenite**
MS 2009.064	63.57	**64.52**	66.06	3	Fig. 44	Bottle-green; translucent; prismatic / radial aggregates	**Zincolivenite**
MS 2014.001	50.11	**67.01**	79.35	3	Fig. 45	Bottle-green; translucent; composite radial aggregates	Zincolivenite / olivenite; mean composition is **zincolivenite**
MS 1985.018	79.39	**80.38**	80.89	3	Fig. 46	Blackish-green; translucent; 'bow-tie' radial aggregates	**Olivenite**; zinc-enriched
TA2-7	81.16	**87.97**	94.46	8	Fig. 47	Blackish-green; translucent; composite radial aggregates	**Olivenite**; zinc-enriched
MS 1988.001	90.70	**92.90**	95.30	3	Fig. 48	Blackish-green; translucent; prismatic	**Olivenite**; zinc-enriched
MS 1984.043	95.63	**96.84**	98.30	4	Fig. 49	Blackish-green; translucent; short prismatic	**Olivenite**
TA2-9	94.78	**97.06**	97.82	6	Fig. 50	Blackish-green; translucent; long prismatic	**Olivenite**
MS 2017.023	97.23	**98.03**	98.62	3	Fig. 51	Blackish-green; translucent; equant / short prismatic	**Olivenite** (close to end-member composition)
MS 2017.053	97.58	**98.39**	99.13	7	Fig. 52	Blackish-green; translucent; short prismatic	**Olivenite** (close to end-member composition)

Table 2. Copper content (minimum, mean, and maximum values for MP_{Cu}) and simple visual properties for 43 specimens of adamite – olivenite series minerals from Tsumeb, arranged in ascending order of mean copper content. Compositions indicative of adamite are shown in yellow, zincolivenite in lime-green, and olivenite in olive-green.

Figure 1. Crystals of translucent, emerald-green zincolivenite (to 11 mm) associated with aggregates of mustard-yellow ferrilotharmeyerite. 2.6 cm. Malcolm Southwood specimen and photo.

Figure 2. Acicular crystals (to 20 mm) of translucent, olive green olivenite on crystallized malachite lining a vug in a 20 cm boulder of massive malachite and olivenite from the Tsumeb open pit. This habit of olivenite is uncommon at Tsumeb and appears to have occurred only in the near-surface portion of the deposit. The specimen is number 1050 in the collection of Wilhelm Klein. Field of view is 9 cm. Courtesy of the Mineralogical & Geological Museum at Harvard University, Olivenite; MGMH ID# 106045, Tsumeb; Namibia. Malcolm Southwood photo.

Figure 3. Specimen number 2640 from the Karabacek Collection, labelled by its original owner as 'veszelyite', but identified as 'adamite' by X-ray diffraction at Harvard. Field of view is 3.5 cm in a 7.5 cm specimen from the first oxidation zone at Tsumeb. Courtesy of the Mineralogical & Geological Museum at Harvard University, Adamite; MGMH ID# 93856, Tsumeb; Namibia. @ copyright 2012, President and Fellows of Harvard College. All rights reserved. Malcolm Southwood photo.

Figure 4. The famous 'cobaltoan adamite' specimen from the Karabacek Collection (# 4318) at Harvard University. Adamite crystals (to 7 mm) cover one side of the specimen and their terminations are blackish-green in color. Broken surfaces, however, reveal magenta tints attributed to the presence of cobalt. 11 cm specimen, from the first oxidation zone at Tsumeb. Courtesy of the Mineralogical & Geological Museum at Harvard University, Adamite; MGMH ID# 93828, Tsumeb; Namibia. @ copyright 2012, President and Fellows of Harvard College. All rights reserved. Malcolm Southwood photo.

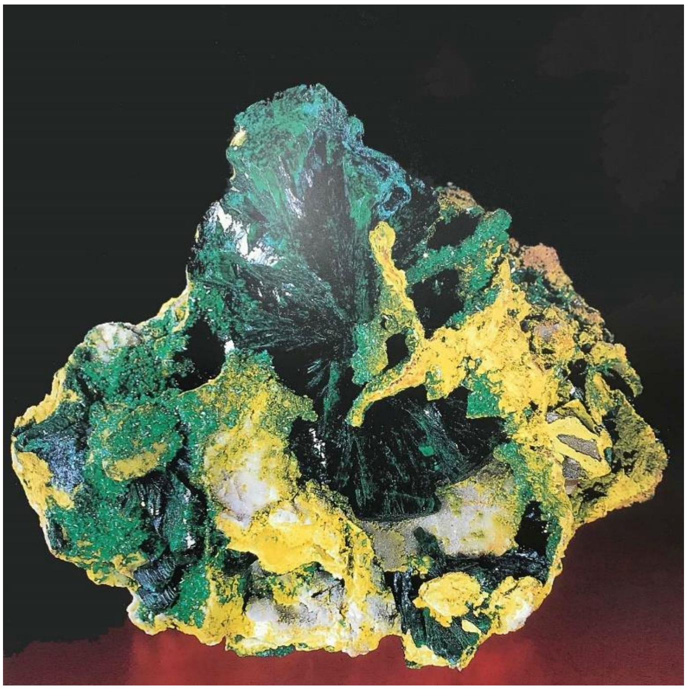

Figure 5. Emerald-green crystals of 'cuproadamite' associated with powdery lemon-yellow ferrilotharmeyerite. The specimen was recovered from 30 level in the second oxidation zone in 1986. 10.9 cm. Des Sacco specimen; Bruce Cairncross photo.

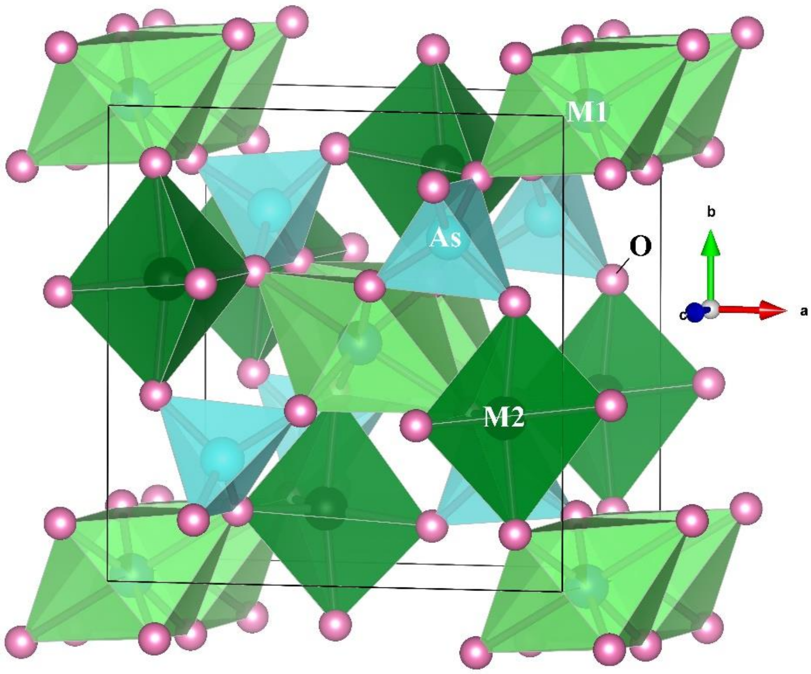

Figure 6. Atomic arrangement of the adamite-olivenite series. The M1 and M2 octahedral sites are indicated by different shades of green. Arsenic resides on the tetrahedral site (blue) and oxygen atoms are indicated by pink spheres. Rendering created with VESTA 3 (Momma and Izumi 2011).

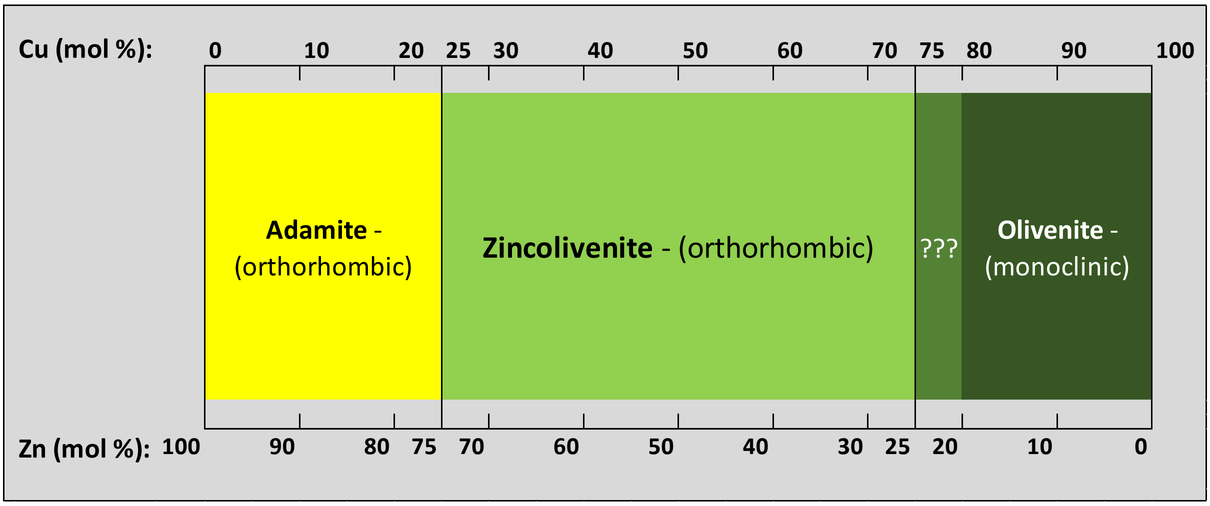

Figure 7. The adamite – olivenite solid solution series includes three mineral species (adamite, zincolivenite and olivenite) defined by the proportions of copper and zinc in each of two ordered cation sites in the crystal structure. Adamite and zincolivenite are both orthorhombic, while olivenite is monoclinic; however, the symmetry change occurs at circa 80 mol % copper, so that the speciation for compositions between 75 mol % and 80 mol % copper is poorly defined. For the purpose of this study we would consider compositions with > 75 mol % copper to be olivenite.

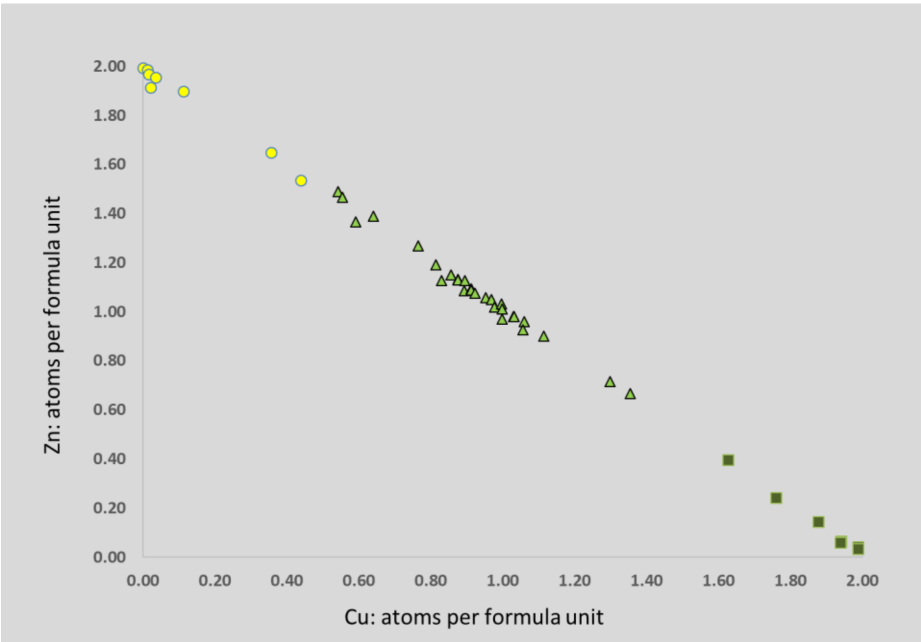

Figure 8. Mean zinc and copper content expressed as atoms per formula unit (APFU) for 43 specimens of adamite – olivenite series minerals from Tsumeb. The (small) deviations from a straight-line (unit) plot are attributable to the minor presence of iron and cobalt in some of the specimens. 8 specimens (with Cu < 0.5 APFU) plot as adamite (yellow circles) while 7 specimens (with Cu > 1.5 APFU) plot as olivenite (olive-green squares). The remaining 28 specimens (green triangles) plot in the compositional field defining zincolivenite, with Cu between 0.5 and 1.5 APFU.

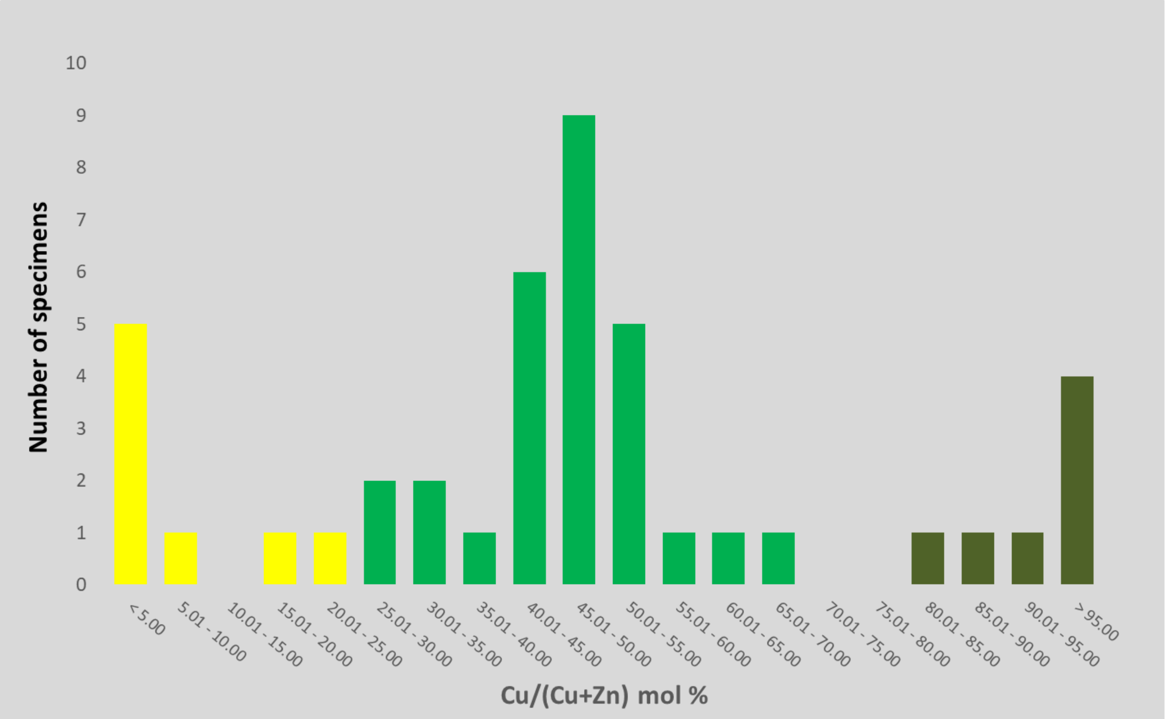

Figure 9. Distribution of mean compositions of 43 specimens of adamite – olivenite series minerals from Tsumeb. Adamite (yellow) specimens appear towards the left of the chart (i.e. lower Cu content); zincolivenite (green) in the center and olivenite (olive-green; higher Cu content) on the right.

Figure 10. Orange-yellow crystals of adamite (to 2 mm) over massive sulfide. This is essentially end-member adamite, with a value for MP_{Cu} of < 0.01%. 3.7 cm. Malcolm Southwood specimen (# MS 2014.068) and photo.

Figure 11. Yellow-green, partly transparent crystals of adamite (to 18 mm) associated with off-white crystals of smithsonite (EDS confirmed). The mean MP_{Cu} value of just 0.60 % (range: 0.32 – 1.13 %) is indicative of near end-member adamite, but it has a distinct greenish color. 6 cm. Malcolm Southwood specimen (# MS 2014.149) and photo.

Figure 12. Equant crystals (to 5 mm) of transparent, colorless to amber-brown adamite, on a siliceous matrix, with goethite. The mean MP_{Cu} is 0.79 % (range: 0.03 – 1.74 %), so the adamite is close to end member composition and, in this case, the minor copper content does not appear to influence the color. 4.5 cm. Malcolm Southwood specimen (# MS 2016.072) and photo.

Figure 13. Long prismatic crystals of orange-yellow adamite on mineralised dolostone. The mean MP_{Cu} is 1.11 % (range: 0.02 – 3.25 %), so the adamite is close to end member composition. 10 cm. Crystal Classics specimen and photo.

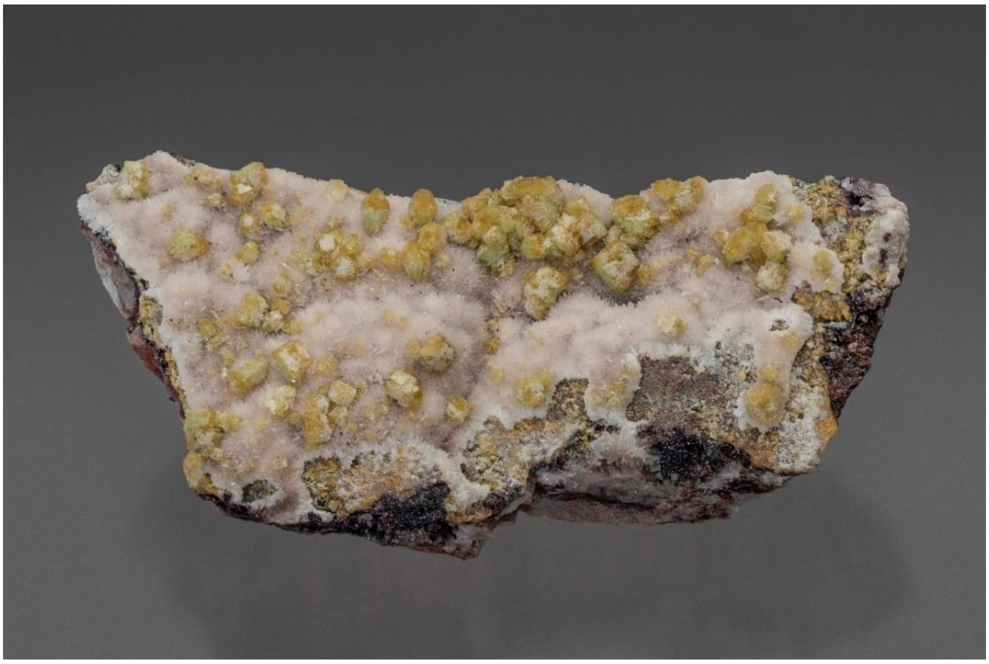

Figure 14. Thick, tabular, crystals of yellow adamite (to 3 mm), on a sub-botryoidal crust of white scalenohedral smithsonite crystals. The mean MP_{Cu} is 1.77 % (range: 0.65 – 2.82 %), so the adamite is close to end member composition. 8.5 cm. Malcolm Southwood specimen (# MS 2015.065) and photo.

Figure 15. This specimen includes adamite – olivenite series minerals of several compositions. The pseudo-octahedral crystals at upper right (as photographed) are yellowish-brown in color, but some have a distinct pinkish blush. The mean MP_{Cu} for the brown crystals is 9.38 % (range: 0.88 – 18.04 %) while the pinkish crystals contain a mean MP_{Cu} of 1.62 % (range: 0.27 – 4.60 %). The mean cobalt content of the pinkish crystals is 0.045 wt % (see text for further details). 9.5 cm. Malcolm Southwood specimen (# MS 2016.076) and photo.

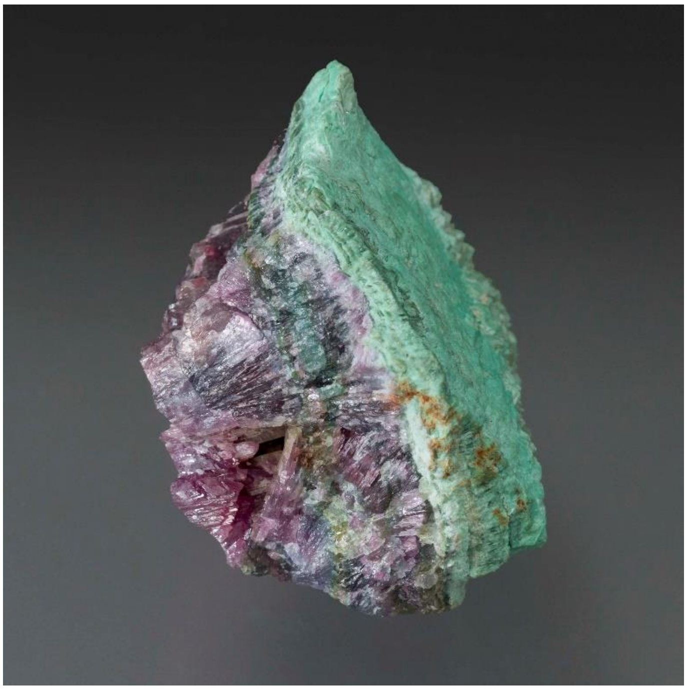

Figure 16. Densely intergrown blades of magenta-coloured adamite crystals (mean MP_{Cu} = 0.18 %), abruptly transitioning to a banded crust of spearmint-green zincolivenite (mean MP_{Cu} = 35.46 %). The mean cobalt content of the magenta crystals is 0.054 wt % (see text for further details). 3.8 cm. Malcolm Southwood specimen (# MS 2009.048) and photo.

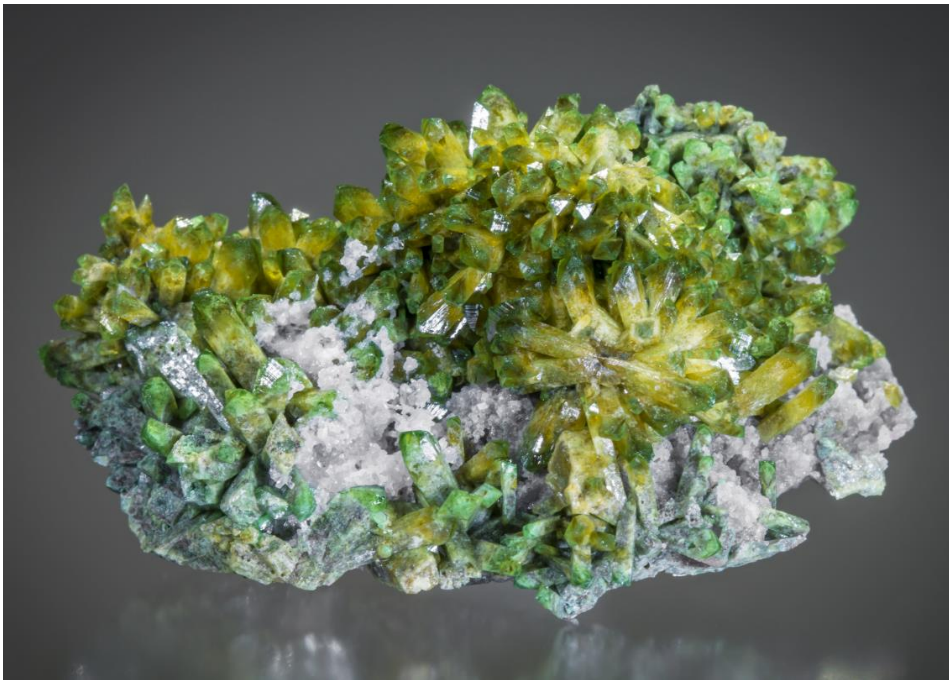

Figure 17. Elongated, prismatic crystals (to 5 mm) with a marked color zoning, ranging in composition from near end-member adamite to zincolivenite. The pale-yellow base of the crystals has a value for MP_{Cu} of 1.72 %, close to end-member adamite, grading up into yellow-green copper-rich adamite, and green terminations with a value for MP_{Cu} of 38.51 % which lies well within the compositional field of zincolivenite. The mean MP_{Cu} is 22.22 %. 5 cm specimen. Crystal Classics specimen; John Schneider photo.

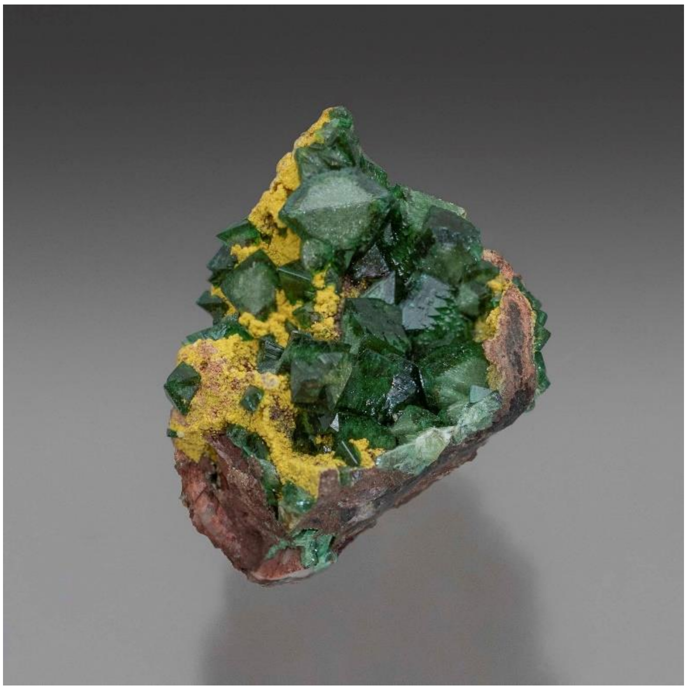

Figure 18. Pseudo-octahedral crystals (to 6 mm) of bottle-green zincolivenite (mean MP_{Cu} = 26.85 %) associated with a yellow micro-botryoidal mineral of the tsumcorite group. The zincolivenite crystals are zoned, with paler, frosted cores. WDS analysis shows that zones of both adamite and zincolivenite are present in these crystals, with MP_{Cu} ranging from 11.14 % to 38.69 %. 3 cm. Malcolm Southwood specimen (# MS 2013.002) and photo.

Figure 19. Equant (pseudo-octahedral) crystals (to 3 mm) of green adamite / zincolivenite (mean MP_{Cu} = 27.41 %). The crystals are zoned, with paler, frosted cores. WDS analysis shows that zones of both adamite and zincolivenite are present in these crystals, with MP_{Cu} ranging from 16.06 % to 37.87 %. 2.5 cm. Malcolm Southwood specimen (# MS 2013.014) and photo.

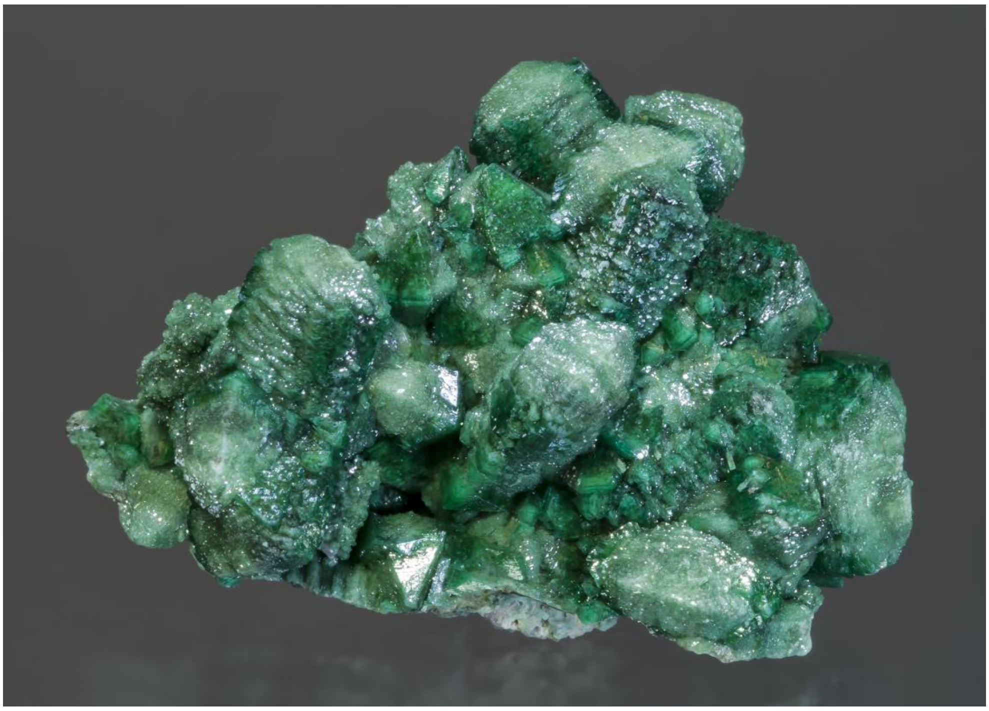

Figure 20. Short, prismatic crystals of adamite / zincolivenite (mean MP_{Cu} = 30.22 %) with pale cores of adamite (MP_{Cu} = 13.87 %) sheathed in darker green zincolivenite (MP_{Cu} = 41.33 %). 4 cm specimen. Crystal Classics specimen; John Schneider photo.

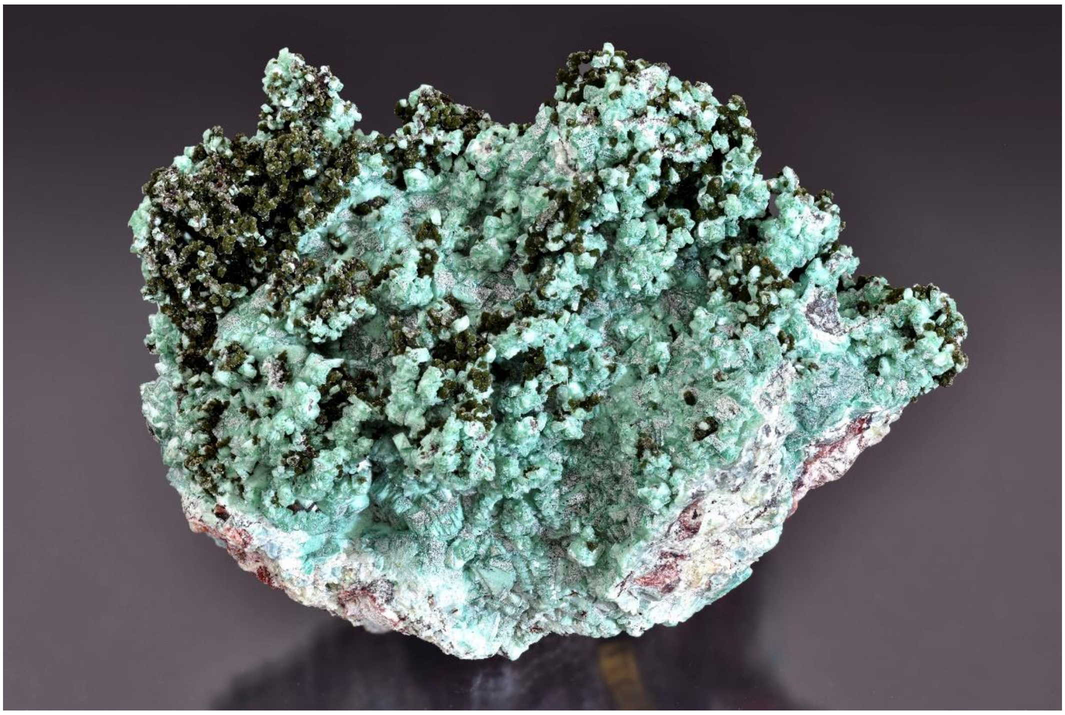

Figure 21. Equant, spearmint-green crystals (to 1 mm) of zincolivenite (mean MP_{Cu} = 31.54 %; range: 27.72 – 35.31 %), overgrowing arborescent aggregates of spheroidal duftite / conichalcite. 7 cm. Malcolm Southwood specimen (# MS 2011.084) and photo.

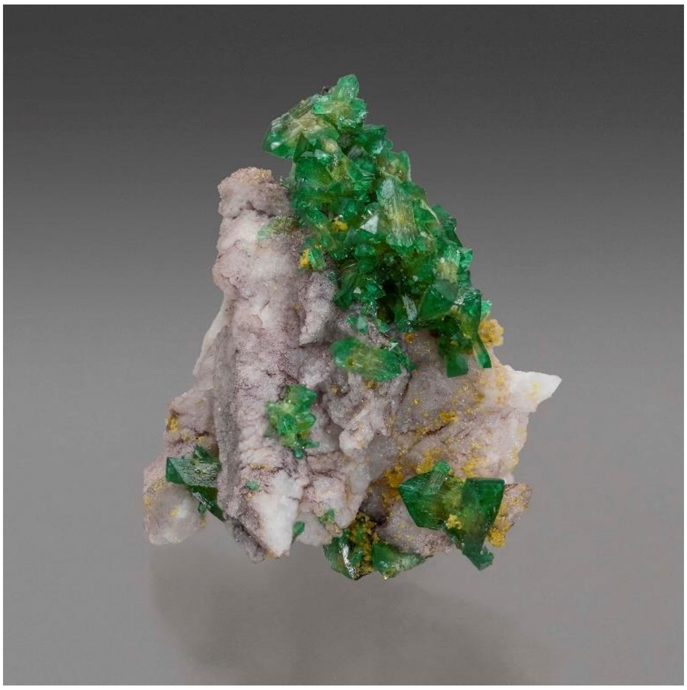

Figure 22. Gemmy crystals (to 3 mm) of emerald-green zincolivenite (mean MP_{Cu} = 37.61 %; range: 29.39 – 48.86 %), many of them doubly terminated, on etched and corroded quartz, with an unidentified (yellow) mineral of the tsumcorite group. The zincolivenite crystals appear zoned, which is consistent with the wide compositional range. 2.5 cm. Malcolm Southwood specimen (# MS 2012.011) and photo.

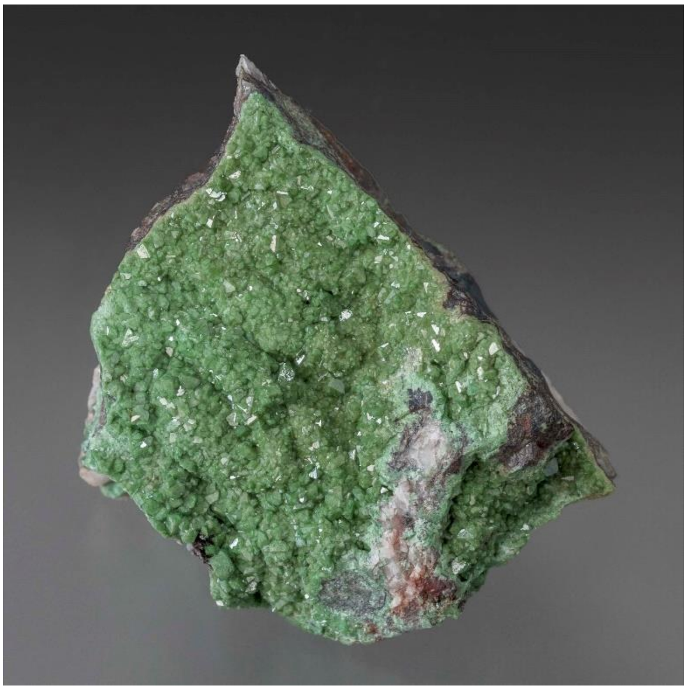

Figure 23. Equant, spearmint-green crystals of zincolivenite (mean MP_{Cu} = 40.61 %; range: 37.87 – 42.70 %) over silicified dolostone. 2.5 cm. Malcolm Southwood specimen (# MS 1986.001) and photo.

Figure 24. A crust of intergrown, short prismatic crystals (to 8 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 42.36 %; range = 38.73 – 48.97 %). 5 cm specimen. Crystal Classics specimen; John Schneider photo.

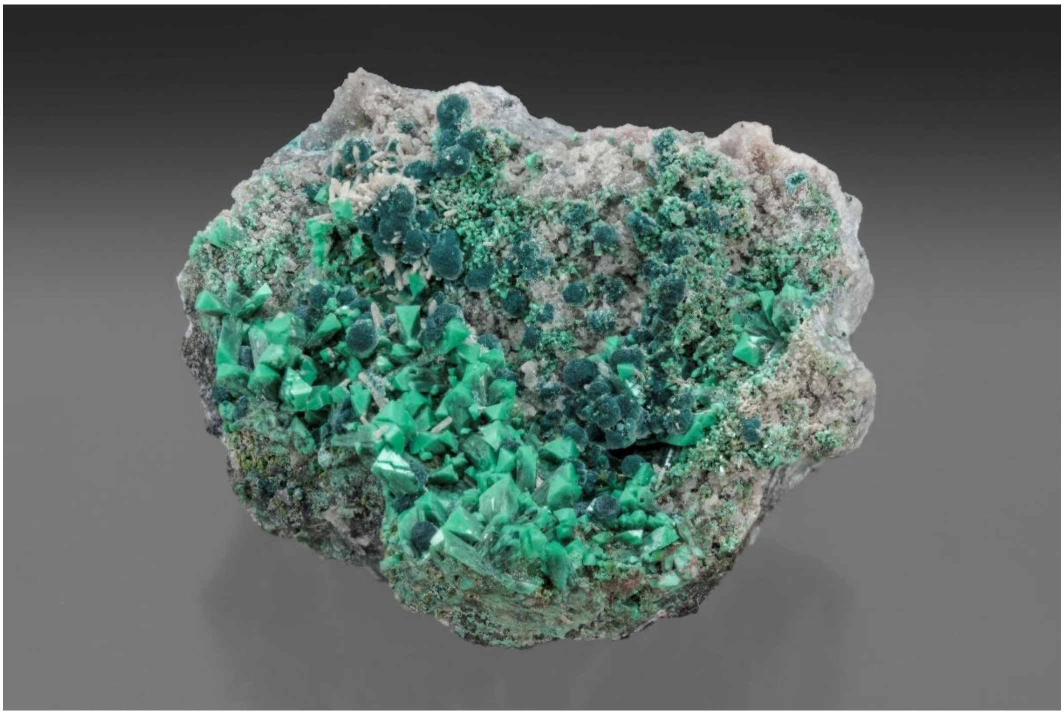

Figure 25. Prismatic crystals (to 4 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 42.70 %; range: 40.40 – 45.36 %), associated with quartz, rosasite and minor duftite / conichalcite. 6 cm. Malcolm Southwood specimen (# MS 2018.027) and photo.

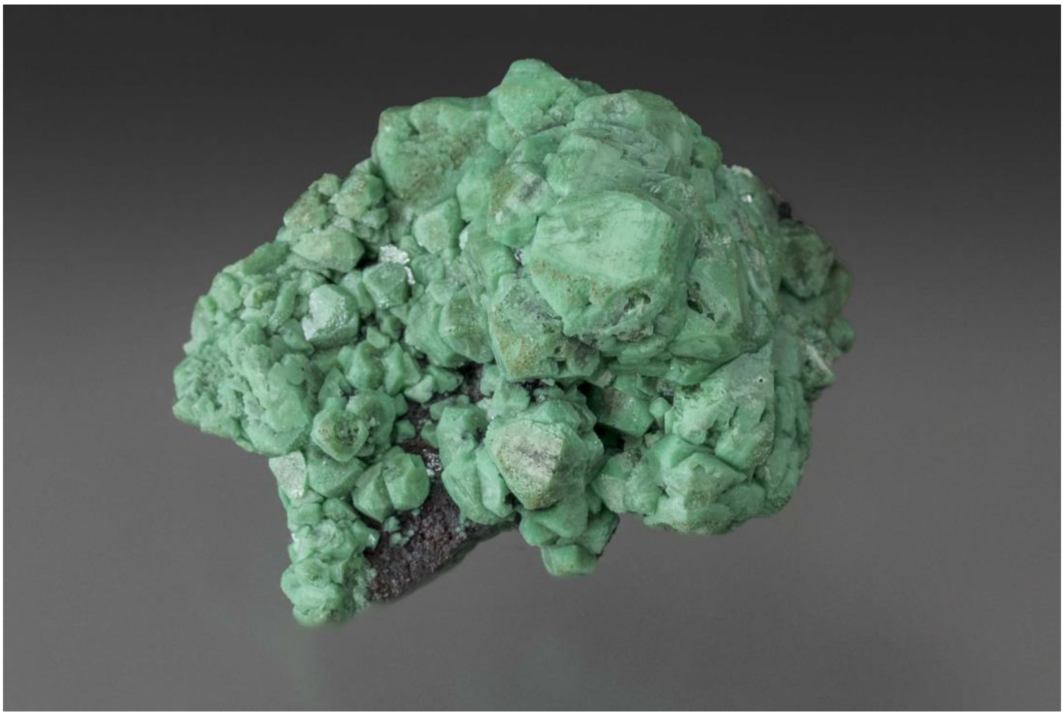

Figure 26. Equant, stubby crystals of spearmint-green zincolivenite (mean MP_{Cu} = 43.64 %; range: 39.39 – 43.98 %) over silicified dolostone. 3 cm. Malcolm Southwood specimen (# MS 2010.189) and photo.

Figure 27. Sprays of elongated blades (to 10 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 43.70 %; range: 37.29 to 47.30 %). 3 cm. Malcolm Southwood specimen (# MS 2012.012) and photo.

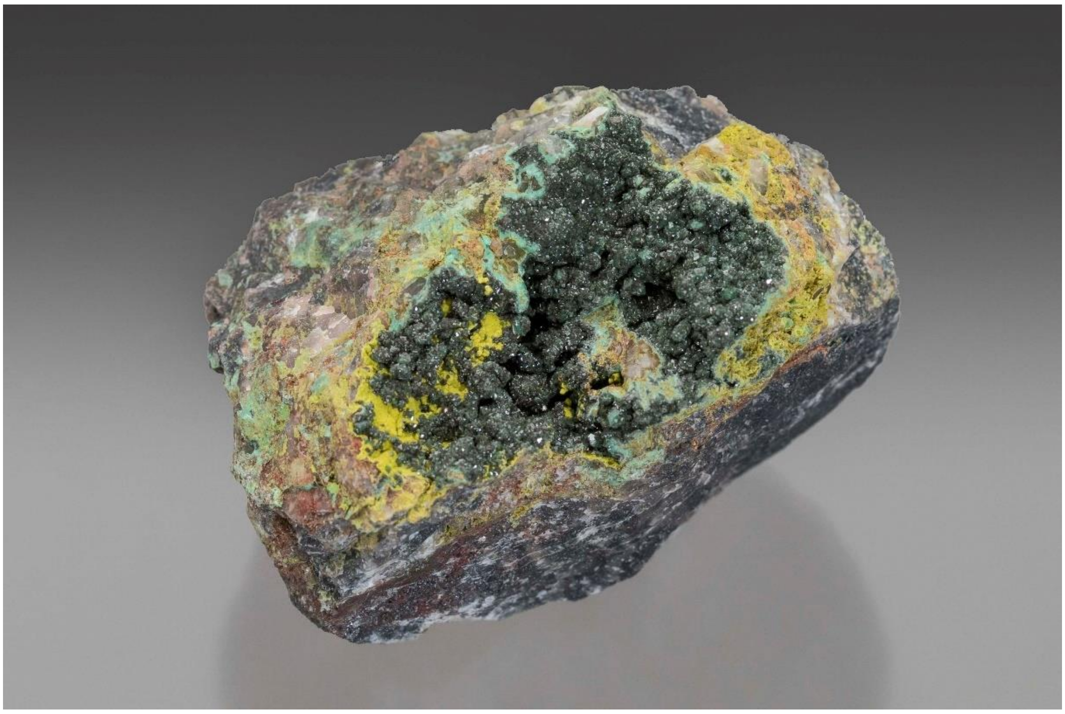

Figure 28. Aggregates of equant, bottle-green crystals (sub-mm) of zincolivenite (mean MP_{Cu} = 44.26 %; range: 41.92 – 44.26 %), in a vug lined with bright yellow zincgartrellite (EDS confirmed). 5.5 cm. Malcolm Southwood specimen (# MS 2016.004) and photo.

Figure 29. Equant, spearmint-green crystals of zincolivenite (mean MP_{Cu} = 45.15 %; range = 43.70 – 47.75 %). 8 cm. Crystal Classics specimen and photo.

Figure 30. Elongated prismatic crystals (to 10 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 45.47 %; range: 42.56 – 48.31 %), on quartz that is partly coated with goethite and sparse tabular crystals of butterscotch-colored wulfenite. This 5.5 cm specimen was collected from the second oxidation zone by the late John Innes, chief mineralogist at Tsumeb in the early 1980s. Malcolm Southwood specimen (# MS 2015.051) and photo.

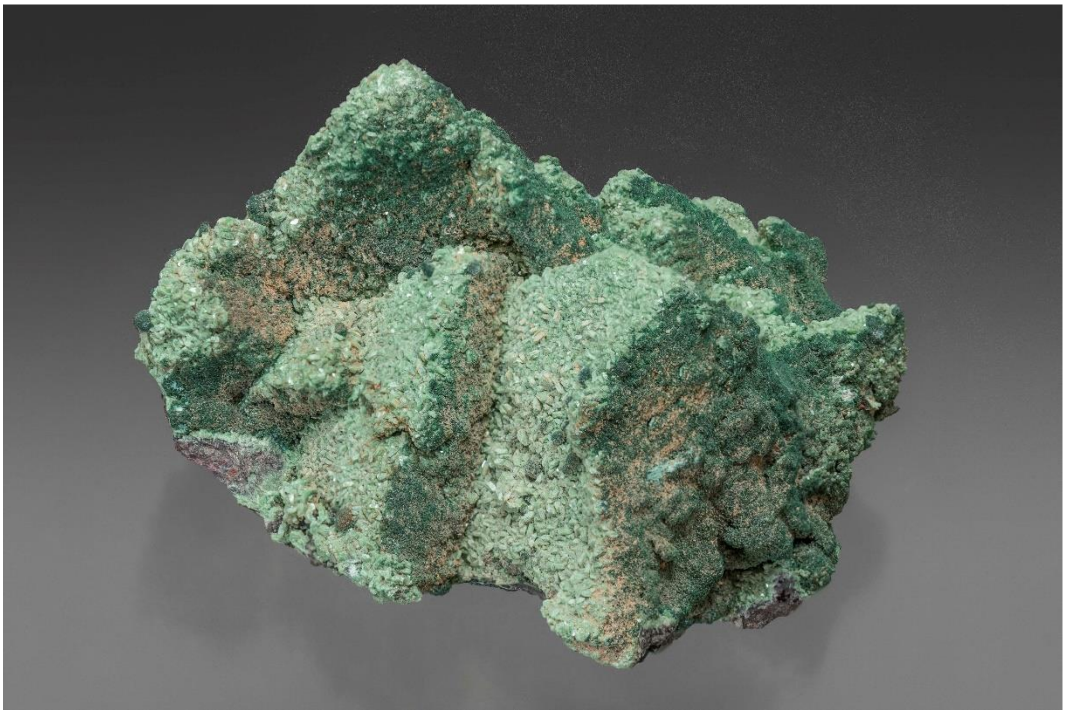

Figure 31. Spearmint-green, intergrown crystals (to 1.5 mm) of zincolivenite (mean MP_{Cu} = 45.62 %; range: 44.65 – 46.88 %) forming a crust over tennantite crystals (to 40 mm). A little malachite is also present. 7 cm. Malcolm Southwood specimen (# MS 2018.056) and photo.

Figure 32. Spearmint-green, elongated crystals (to 8 mm) of zincolivenite (mean MP_{Cu} = 46.19 %; range: 43.86 – 48.25 %) associated with microbotryoidal aggregates of tangeite (XRD/EDS confirmed). 3.5 cm. Malcolm Southwood specimen (# MS 2014.108) and photo.

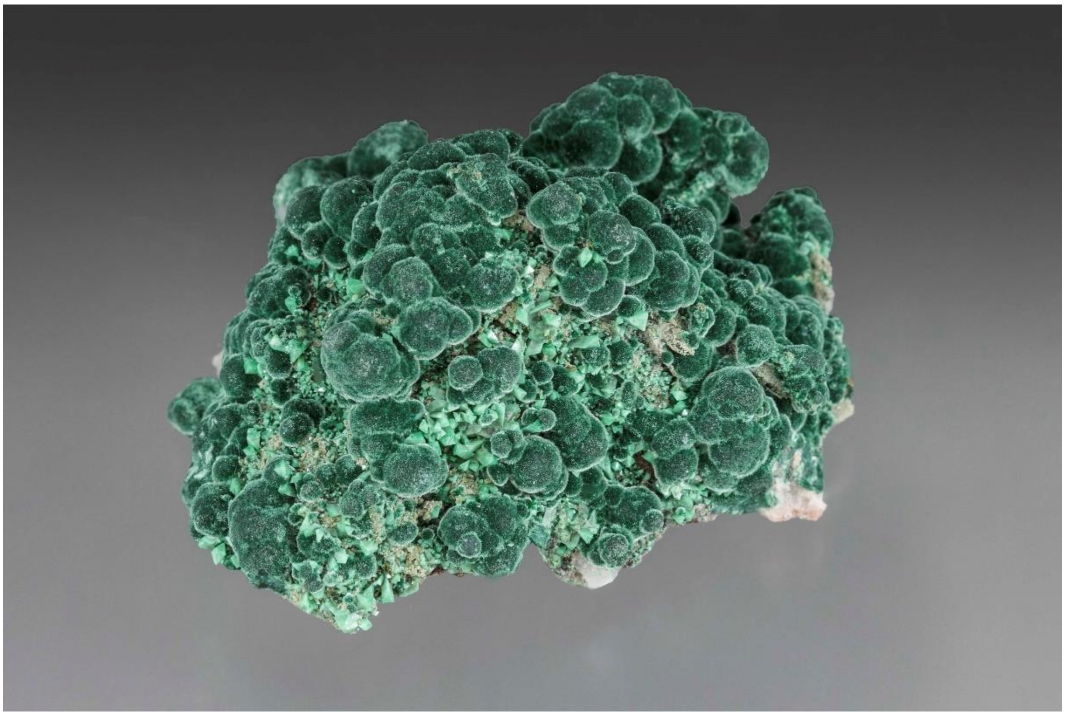

Figure 33. Short, terminated prismatic crystals (to 3 mm) of spearmint-green zincolivenite (mean MP_{Cu} = 47.40 %; range: 42.33 – 51.37 %) associated with botryoids of fibrous malachite, on quartz. 4.5 cm. Malcolm Southwood specimen (# MS 2010.017) and photo.

Figure 34. Pseudo-octahedral crystals (to 1.5 mm) of highly translucent, emerald-green zincolivenite (mean MP_{Cu} = 47.96 %; range: 43.69 – 52.98 %) associated with a powdery yellow mineral of the tsumcorite group. 6 cm. Malcolm Southwood specimen (# MS 2016.075) and photo.

Figure 35. Fans of frosted, pale emerald-green, elongated crystals (to 8 mm) of zincolivenite (mean MP_{Cu} = 48.96 %; range: 45.25 – 51.75 %), peppered with a powdery yellow mineral of the tsumcorite group. 3 cm. Malcolm Southwood specimen (# MS 2012.013) and photo.

Figure 36. Slender prismatic crystals (to 4 mm) of emerald-green zincolivenite (mean MP_{Cu} = 49.11 %; range: 47.13 – 51.36 %) with sub-spherical tufts of acicular olive-green duftite (EDS confirmed). 2.3 cm. Malcolm Southwood specimen (# MS 2005.043) and photo.

Figure 37. Tightly intergrown acicular crystals of emerald-green zincolivenite (mean MP_{Cu} = 49.69 %; range: 47.23 – 52.01 %) forming radial sprays, associated with a powdery yellow mineral of the tsumcorite group. 5.2 cm. Malcolm Southwood specimen (# MS 2018.058) and photo.

Figure 38. Radial fans of long prismatic crystals of emerald-green zincolivenite (mean MP_{Cu} = 50.74 %; range = 46.24 – 55.13 %) on a mineralized, siliceous matrix. 2.5 cm specimen. Crystal Classics specimen; John Schneider photo.

Figure 39. Elongated and striated crystals (to 8 mm) of transparent, emerald-green zincolivenite (mean MP_{Cu} = 51.25 %; range: 51.13 – 51.38 %), associated with drusy sprays of mustard yellow to brown ferrilotharmeyerite, on a matrix of massive sulfide with quartz. 2.7 cm. Malcolm Southwood specimen (# MS 2005.044) and photo.

Figure 40. Pale emerald-green crystals of zincolivenite (mean MP_{Cu} = 51.29 %; range: 50.78 – 51.78 %), associated with colorless-white schultenite, on a matrix of massive sulfide with quartz. 2.1 cm. Malcolm Southwood specimen (# MS 2010.101) and photo.

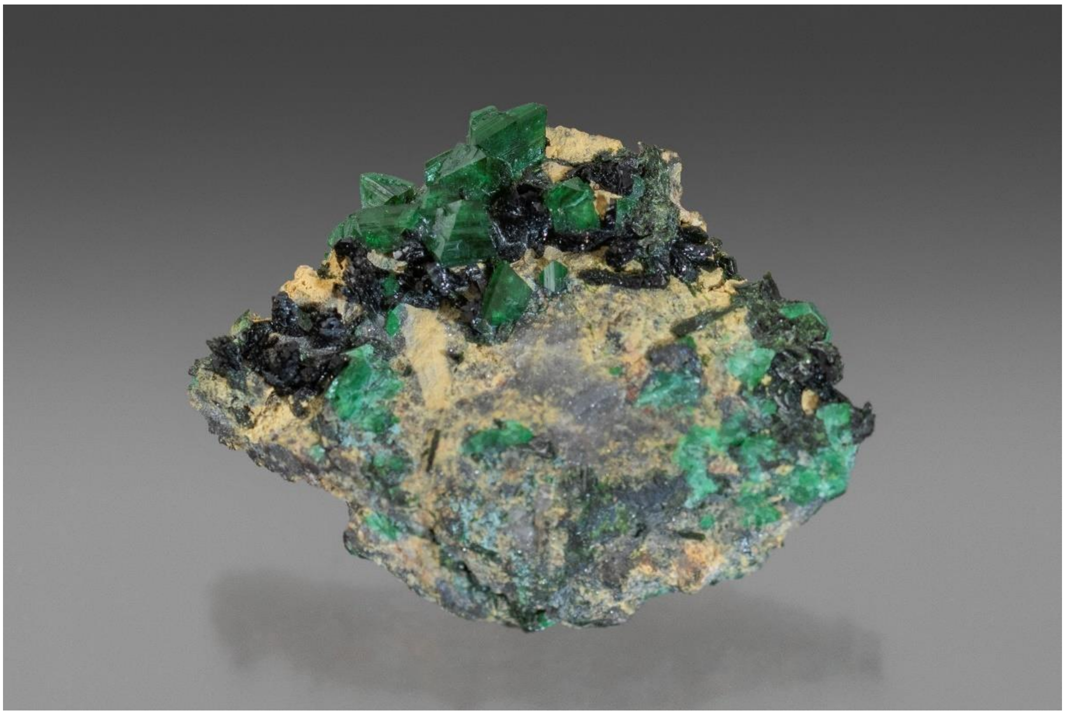

Figure 41. Pseudo-octahedral crystals of emerald-green zincolivenite (mean MP_{Cu} = 52.46 %; range: 51.03 – 54.40 %), associated with blackish-green prismatic crystals of olivenite (EDS analysis only), and a powdery yellow mineral of the tsumcorite group. 4.5 cm. Malcolm Southwood specimen (# MS 2016.044) and photo.

Figure 42. Prismatic crystals of gemmy, emerald-green zincolivenite (mean MP_{Cu} = 53.27 %; range = 49.83 – 60.37 %), associated with minor colorless schultenite, and quartz. 6 cm specimen. Crystal Classics specimen; John Schneider photo.

Figure 43. Fans of curvilinear crystals of emerald-green zincolivenite (mean MP_{Cu} = 55.35 %; range: 49.83 – 60.37 %) forming discoidal aggregates over a carpet of smaller crystals of the same mineral, associated with quartz, goethite and wulfenite. 9.5 cm. Malcolm Southwood specimen (# MS 2017.069) and photo.

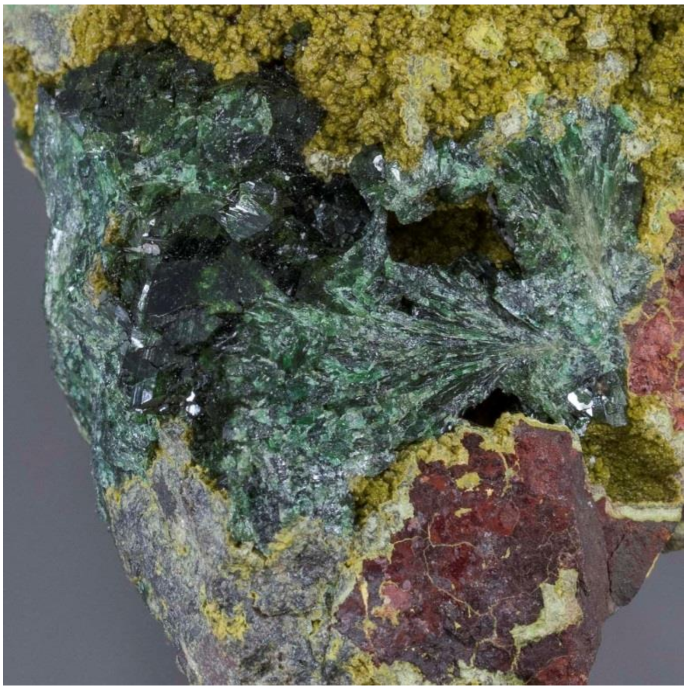

Figure 44. Intergrown crystals of bottle-green zincolivenite (mean MP_{Cu} = 64.52 %; range: 63.57 – 66.06 %) associated with yellow gartrellite (XRD/EDS confirmed). Field of view is 4 cm (in a 9 cm specimen). Malcolm Southwood specimen (# MS 2009.064) and photo.

Figure 45. Curvilinear, fan-shaped crystals of bottle-green zincolivenite (mean MP_{Cu} = 67.01 %; range: 50.11 – 79.35 %) associated with a yellow tsumcorite group mineral. While the mean MP_{Cu} value for this specimen lies within the compositional range of zincolivenite, the maximum value indicates that zones of olivenite are also present. This 4 cm specimen was collected by the late John Innes, chief mineralogist at Tsumeb in the early 1980s, from 35 level north-east, in the second oxidation zone. Malcolm Southwood specimen (# MS 2014.001) and photo.

Figure 46. A 'bow-tie' aggregate of greenish-black olivenite crystals (mean MP_{Cu} = 80.38 %; range: 79.39 – 80.89 %), associated with equant crystals of lighter green duftite / conichalcite and slender individual prisms (to 2.5 mm) of yellow-green olivenite (EDS analysis only) on quartz. 2 cm. Malcolm Southwood specimen (# MS 1985.018) and photo.

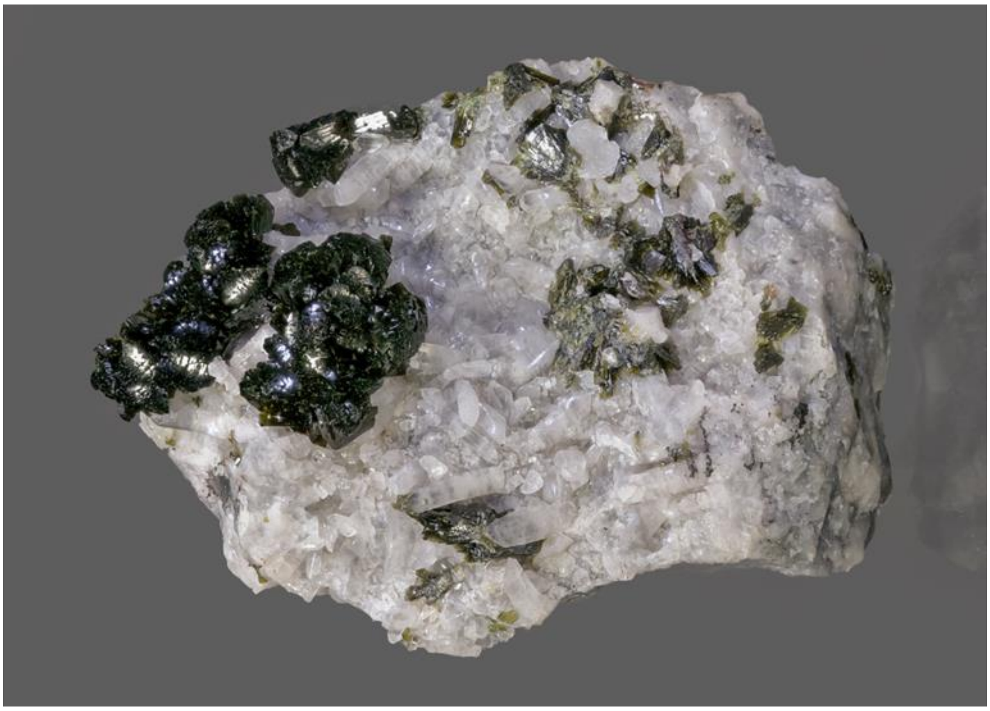

Figure 47. Curvilinear aggregates (to 10 mm) of blackish-green olivenite (mean MP_{Cu} = 87.97 %; range = 81.16 – 87.97 %), on quartz. 5 cm. Crystal Classics specimen; John Schneider photo.

Figure 48. Composite blades of blackish-green olivenite (mean MP_{Cu} = 92.90 %; range: 90.70 – 95.30 %), associated with a partial crust of malachite, over quartz. 3.5 cm. Malcolm Southwood specimen (# MS 1988.001) and photo.

Figure 49. Short prismatic crystals of blackish-green olivenite (mean MP_{Cu} = 96.84 %; range: 95.63 – 98.30 %), overgrown by isolated botryoidal aggregates of fibrous malachite (to 1 mm) in a vug in massive olivenite with relict sulfide. 5.5 cm. Malcolm Southwood specimen (# MS 1984.043) and photo.

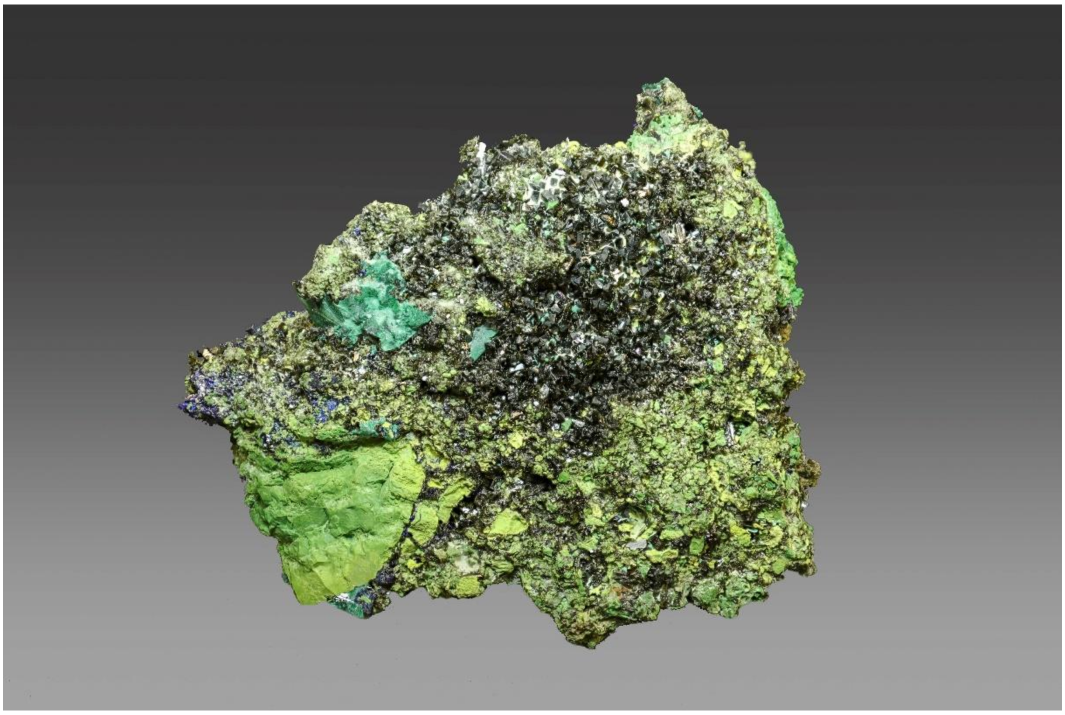

Figure 50. Elongated prismatic crystals of blackish-green olivenite (mean MP_{Cu} = 97.06 %; range: 94.78 – 97.82 %), intergrown in a shallow vug in a matrix of brecciated apple-green arsenates (undetermined) with malachite and minor azurite. 11 cm. Crystal Classics specimen and photo.

Figure 51. Blackish-green crystals (to 2 mm) of olivenite (mean MP_{Cu} = 98.03 %; range: 97.23 – 98.62 %) in a vug in massive olivenite, associated with minor malachite and arsentsumebite. 7 cm. Malcolm Southwood specimen (# MS 2017.023) and photo.

Figure 52. Stout prismatic crystals of bottle-green to blackish-green olivenite (mean MP_{Cu} = 98.39 %; range: 97.58 – 99.13 %), with minor azurite, malachite after azurite, and botryoidal malachite. The olivenite crystals are locally quite gemmy with yellowish-green translucency. 4.5 cm. Malcolm Southwood specimen (# MS 2017.053) and photo.