**Tellurium**

Bibliography/Literature Search (**preliminary, *in-process***)

by

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Version Date: July 13th, 2010

This literature search is being conducted by Lindsey V. Maness, Jr., for personal use and roughly follows the standards of the geological profession. Items of special interest have been placed in **bold** lettering, often in **colored bold lettering** to emphasize certain categories of information. Items quoted from other languages have been *italicized*. Ellipses for certain types of information, some partially filled, have been inserted in the “(Notes: … Te, …)” section following each reference, with the ending portion set-aside for elements significant to that particular reference. This is an iterative document which **can**, and **will**, change with additional information. More references about Colorado’s Te are included, simply because I am more interested in Colorado’s Te. A similar abundance of references exist for many other Te-rich portions of the world. Clearly, many thousands of references about Te occurrences and geology exist: **this compilation represents only a very small portion of the totality**.

A preliminary search using GeoRef© has been completed and other readily available sources compiled (*e.g.*, the internet and certain USGS Library archival information, from friends and colleagues, *etc.*): this is what I refer to as a “First Order Search”. From that preliminary compilation, some of the more remarkable references (see **Important Note** following) have been acquired and references of interest extracted for further research: that is what I refer to as a “Second Order Search,” (the present status) being derived from a “First Order Search.” A “Third Order Search,” acquiring references, *etc.*, from “Second Order Search” materials is usually as far as it is necessary to go in a serious geological fact-finding effort. In general, I eschew using the expression “*et al.*,” preferring to list all known authors to facilitate more detailed (3rd Order) research about authors who wrote, or participated in writing, articles of particular interest. This “Literature Search” is only the first stage in a systematic effort to discover and document facts of interest to support a rigorous scientific effort, usually in support of geological exploration.

The second stage would be acquiring existing maps, enhanced satellite images (to be interpreted and analyzed), geological, geochemical, geophysical and other data, which are integrated into a composite whole to help sort from a mass of information the sites of greatest interest. Once these sites have been defined, field geology (first-hand observations) is conducted to further focus on the most promising targets. The next step is to gather additional geological, geochemical, geophysical and other data to fill-in the holes of existing data, to enable a further winnowing of prospects and compilation of documentation for a team effort, at all levels.

In a multi-phase exploration effort the final stages include acquiring the property(s), proving its/their actual value to industry standards (my strong preference is the **Canadian National Instrument 43-101**), raise capital and open the mine (or drill the oil well, etc.). This is a simplification of an immensely complex operation. It all starts with discovering what is already in the literature.

**About Elemental Correlations & Geological Exploration**

That both tellurium (Te) and indium (In) are chalcophilic, meaning positively correlated with chalcogenides (O, S, Se, Te) is readily apparent from the geochemical environments in which these elements are mined, even though both tend to concentrate in different minerals within the same deposit. This is directly analogous with gallium (Ga), which concentrates in galena, and with germanium (Ge), which concentrates in sphalerite, both within the same massive sulfide deposit. Note that in this situation, the more robust correlation is with the chalcogenidic environment and, in most cases, the lesser correlation with specific minerals.

In like manner, but in an extrapolation which may or may not be statistically robust (and, therefore, valuable for geological exploration), both In and Te positively correlate with chalcogenides, in a general sense, but perhaps not in a global sense, especially concerning tin-oxides (*i.e.*, the mineral cassiterite). Many of the best known In concentrations are recovered as by-products from the smelting of tin ore.

This could be expressed as follows:

In positively correlates with chalcogenides (O, S, Se, Te), in particular with the tin oxides and preferentially with certain sulfides, *etc*. The actual varying degrees of correlation with the other specific chalcogenides is unknown at this time. Correlations are expected to be deposit specific.

Te positively correlates with chalcogenides (O, S, Se, Te), in particular with compounds of that particular column on the periodic chart which corresponds with precious metals (Cu, Ag, Au), and with particular sulfides (*e.g.*, Cu). Correlations are expected to be deposit specific.

In addition, both In and Te positively correlate with the platinum group elements (Pt, Pd, …) with which both In and Te form very valuable chemical compounds. This type of occurrence is so rare that very little is known about the specific Pt, … mineralogy of this type of geological deposit. However, see: Heggie, G., 2005; Hudson, D.R., *et al.*, 1978; Johan, Z., *et al.*, 1989; Matkovic, P., *et al.*, 1978; McCallum, M.E., *et al.*, 1976; Miller, D.J., *et al.*, 1991; and Oberthur, T., 2002. Also see the Te minerals: michenerite and testibiopalladite, *etc*.

Both In and Te seem to correlate positively with Bi and Sb, which are strongly chalcophilic.

So, with all these positive correlations, is it reasonable to firmly conclude that Te will be found to positively correlate with In in tin-oxides? While this extrapolated correlation might be true, the untested reality is that such extended correlations might fall apart when closely examined: the extended correlation may be so tenuous as to be insignificant.

With this as the reality, in the following literature search, references to indium in tin-oxides have been included as **possible** sites for unrecognized Te mineralization, probably in other contained minerals (analogous to Ga in galena and Ge in sphalerite within a single deposit). Until further knowledge is gained, this extended correlation is questionable; however, if robust, it may lead to the discovery of substantial, previously unrecognized deposits of Te in tin-oxide deposits. An educated guess would be to look in the associated Fe (*i.e.*, pyrite, marcasite, …), As (*i.e.*, arsenopyrite, …), Cu, Bi, Sb and other (mostly gangue) accessory minerals. If formal access could be acquired to proprietary geochemical analyses performed by mining companies, this possibility could be quickly explored – something I have tried to accomplish without success. Proprietary data are usually closely-guarded secrets. In particular, I (as is normal among geologists) am constrained to not disclose others’ proprietary information.

***Arm-Waving Geology***

Geologists are fond of referring to theories or hypotheses with little supporting evidence, but with significant implications, with the expression “***Arm-Waving Geology***.” This is particularly true of large-scale phenomena, including at various times different aspects of the “*Plate Tectonics Theory*.” Sometimes, arm-waving geology is found to be correct, sometimes not.

While the previous section about “Elemental Correlations …” would clearly fit in this category to some geologists, in particular in combination with the following section about “Some Tellurium Minerals” as supporting facts, one more hypothesis is worthy of explication. In short, I believe, and it is solely my unsupported view, without convincing evidence (*i.e.*, ***Arm-Waving Geology***), that much or most of the gold, silver and, perhaps, even the platinum-group elements (Pt, Pd, …, *aka* PGE) that have been noted in pyrites occur in the form of tellurides. See Marchetto, C.M.L., 1990.

In general, geologists have ascribed the presence of gold, *etc.*, in pyrites as occurring in the form of native gold in the center of the pyrite crystals, assuming that somehow pyrite nucleated on and grew around a small mass of gold and/or that the pyrite grew around the gold, *etc*. It is not at all unusual to find small inclusions of native gold in pyrite (these could be alteration products). The assumption that all the gold in the pyrite occurs in the native form is just that – an assumption. Many gold mines acquire all or part of their gold from roasting/smelting pyritic {*aka* refractory} ores, ironic since pyrite’s common name is “***Fool’s Gold***.” Many such gold-rich deposits have been abandoned, when others spoke with derision of the claimant’s property being only *Fool’s Gold*, only to be reopened later by someone who knew that gold often occurs in pyrite. Also, regrettably, mining frauds continue to be propagated by those who falsely claim that: “***At the center of every pyrite crystal is a nugget of gold!***” Replace the words “every” and “nugget” with “some” and “speck,” respectively, and one might get a bit closer to the truth. See Cook, N.J., *et al.*, 1990.

My bit of *arm-waving geology* is that the gold, silver, mercury, palladium, platinum, *etc.*, which is sometimes found in iron and other pyrites probably occurs in large part in the form of tellurides. These tellurides probably occur not just as isolated inclusions, but probably more frequently as thin zones or zonations within the pyrite, much as indium minerals do in various sulfides (*e.g.*, Cu).

If my hypothesis is correct, such precious-metals telluride zonations might lend themselves to far more effective concentration mechanisms than previously considered. Indeed, this might even be a suitable topic for a Master’s or Doctoral thesis/dissertation, in particular for those who wish to use electron microprobe and similar technologies as a tool. See Stumpfl, E.F., 1970. Ample samples of gold-rich pyrites, *etc.*, exist as samples to be studied, analyzed and described.

**Some Tellurium Minerals**

//These Te minerals are presented to enable further research on particular telluride cations, *etc.*//

Aleksite Bi2PbTe2S2 (**?**)

Altaite PbTe

Bambollaite Cu(Se, Te)2

Benleonardite Ag8(Sb, As)Te2S3

Bezsmertnovite (Au, Ag)4Cu(Te,Pb)

Bilibinskite Au3Cu2PbTe2

Bogdanovite (Au, Te, Pb)3(Cu,Fe) or Au5(Cu, Fe)3(Te, Pb)2

Borovskite Pd3SbTe4

Buckhornite AuPb2BiTe2S3

Calaverite (Au, Ag)Te2 (Note: The calaverite end-member is AuTe2.)

Cameronite AgCu7Te10

Cervelleite Ag4TeS

Coloradoite HgTe

Emmonsite Fe2Te3O9·2(H2O)

Empressite AgTe

Frohbergite FeTe2

Goldfieldite Cu12(Sb, As)4(Te, S)13

Hedleyite Bi7Te3 (**?**)

Henryite Cu4Ag3Te4

Hessite Ag2Te

Hexastibiopanickelite Ni(Te, Sb)

Ingodite Bi(S, Te)

Joseite-alpha Bi4(S, Te)3

Joseite-beta Bi4(Te, S)3

Kawazulite Bi2SeTe2

Keithconnite Pd20Te7

Kitkaite NiTeSe

Kolarite PbTeCl2

Kostovite CuAuTe4

Kotulskite Pd(Te, Bi)

Krennerite (Au, Ag)2Te ***or*** (Au0.8Ag0.2)Te2

Maslovite PtBiTe

Mattagamite (Co, Fe)Te2

Melonite NiTe2

Merenskyite (Pd, Pt)(Te, Bi)2

Michenerite Pd(Bi, Sb)Te ***or*** (Pd, Pt)(Bi, Sb)Te (Note: The end-member is PdBiTe.

See testibiopalladite.)

Moncheite (Pt, Pd)(Te, Bi)2

Montbrayite (Au, Sb)2Te3

Museumite Pb5AuSbTe2S12

Muthmannite (Ag, Au)Te

Nagyagite Pb5Au(Sb, Bi)Te2S6 (Note: other proposed formulae exist.) (**?**)

Petzite Ag3AuTe2

Pilsenite Bi4Te3

Poubaite (Bi, Pb)3(Se, Te)4

Protojoseite Bi5(Te, S)4 (**?**)

Radhakrishnaite PbTe3(Cl, S)2

Rickardite Cu7Te5 ***or*** Cu3-xTe2 (x = 0 to 0.36)

Rucklidgeite (Bi, Pb)3Te4 (Note: The end-member is Bi3Te4.)

Skippenite Bi2(Se, Te)3 ***or*** Bi2Se2Te

Sonoraite FeTeO3(OH)·(H2O)

Sopcheite Ag4Pd3Te4

Stützite Ag7Te4

Sulphotsumoite Bi(Te, S)

Sylvanite (Au, Ag)2Te4 ***or*** AuAgTe4 (**?**)

Telargpalite (Pd, Ag)3Te

Tellurantimony Sb2Te3

Tellurite TeO2

Tellurium (native) Te

Tellurobismuthite Bi2Te3

Tellurohauchecornite Ni9BiTeS8

Telluropalladinite Pd9Te4

Temagamite Pd3HgTe3

Testibiopalladite Pd(Sb, Bi)Te (Note: The end-member is PdSbTe. See michenerite.)

Tetradymite Bi2STe2 (Note: One of the more common telluride minerals.)

Tsumoite BiTe

Vasilite (Pd, Cu)16(S, Te)7

Vincentite (Pd, Pt)3(As, Sb, Te)

Volynskite AgBiTe ***or*** AgBiTe2 (**?**)

Vulcanite CuTe

Watkinsonite Cu2PbBi4(Se, S, Te)8

Weissite Cu1.81Te

**Approximate % of Tellurides as Mineral Species**

//Total ≠ 100% because many tellurides include more than one other element.//

Element ~% of Te minerals containing indicated element

Ag 11.35

As 2.13

Au 8.51

Bi 17.73

Cl 1.42

Co 0.71

Cu 9.22

Fe 2.13

Hg 1.42

Ni 2.84

Pb 7.80

Pd 9.22

Pt 3.55

S 11.35

Sb 6.38

Se 4.26

{Note: The above **% Tellurides Table** provides a very rough estimate of compatibility of Te with certain other elements; however, a better, but still very approximate, estimate could be acquired by “*normalizing*” *versus* **Clarke Number**, to partly compensate for crustal abundance, and certain other, sometimes subtle (*e.g.*, number of valences), variables. **Even in the non-normalized form, it is obvious that Te has an unusually strong affinity for Pd and Pt, and a strong affinity for Au and Ag. Ditto for Bi and Sb!** The below table lists the approximate non-normalized compatibility of tellurides with the elements it is known to form minerals.}

**Approximate Compatibility of Tellurides with Elements**

Element ~ Compatibility, based upon non-normalized % of Te minerals

Bi 17.73

Ag 11.35

S 11.35

Pd 9.22

Cu 9.22

Au 8.51

Pb 7.80

Sb 6.38

Se 4.26

Pt 3.55

Ni 2.84

As 2.13

Fe 2.13

Hg 1.42

Cl 1.42

Co 0.71

Explanation: in the above chart, ~17.73% of known Te mineral species contain Bi. *Etc.*

Note: The word “mineral” denotes to most geologists that the described specimen has a definite chemical formula and a regular, defined, crystalline habit or structure. The first described occurrence usually becomes the “*definitive type specimen locale*,” from which all future comparisons of that mineral are made, and the discoverer usually has the privilege of naming the new mineral, within certain limits [*e.g.*, not more than one mineral can be named after a given individual]. That certain minerals are first described from alteration zones, are an intermediate in a solid-solution series, have a poorly-defined crystalline structure, are impure, *etc.*, can mean that the “mineral” fails the test and might be removed as an accepted mineral. Such challenges are frequently mounted: ensuing disputes can be very acrimonious, even “***ungentlemanly***.”

Note: Many of the tellurium-containing minerals are particularly controversial, with disputes about composition, crystal system, *etc.*, even about whether a given named mineral is, in fact, an unique mineral. Many long-accepted named minerals are probably in a solid-solution series between end-members. Those indicated with a (**?**) are particularly controversial. See Honea, R.M., 1964. In many cases, the reason for growing synthetic crystals of a mineral in a lab is to determine its crystalline habit. See Bayliss, P., 1991; and Pertlik, F., 1984.

Note: Many of the apparently intermediate crystal compositions which are ascribed to solid-solution series may actually be a consequence of structural disorder, *etc.*, which can lead to acrimonious academic disputes for others to engage in. Please be aware that in this document a mention of solid-solution may actually be another phenomenon, with the same apparent mineral composition. See Kissin, S.A., 1992.

Note: Michenerite and testibiopalladite are actually end members of a Pd solid-solution series in which Bi and Sb freely replace each other; however, it is also common for some Pt to occur, also in an apparent solid-solution series with Pd. A Pd mineral that is more Bi than Sb would be called michenerite, and one with more Sb than Bi would be called testibiopalladite. This type of solid-solution series is not at all unusual in nature. Other Pd-Te minerals exist in nature (*e.g.*, borovskite and keithconnite). In addition, Pt-Te minerals exist in nature (*e.g.*, maslovite). Some Pt-Pd solid-solution minerals (*e.g.*, merenskyite and vincentite) exist. The Pt and Pd tellurides are thought to tend to be found in close association with each other. See Lechler, P.J., *et al.*, 1989. Other similar Bi-S-Te solid-solution minerals include Joseite-alpha and Joseite-beta.

Note: TeO3 could be considered an analogue with SO3 (*e.g.*, emmonsite, sonoraite, …). *Etc*.

Note: Te, Se and S freely interchange with each other in many molecular structures. See Sindeeva, N.D., 1964. Therefore, it is quite common to find in a sulfide mineral a certain portion of Se and Te substituting for S. When such substitution occurs, the crystal habit usually deforms (*e.g.*, from straight faces/sides to curved faces/sides, and/or in color, *etc.*, according to the compositional deviation from each end-member). Usually, far more Se than Te substitutes, since there is far more Se than Te in the crust of the earth: S is far more common than either Se or Te, by orders of magnitude. See Foord, E.E., 1988. One of the reasons I label this table **Some Tellurium Minerals** is that, in theory, a solid-solution series could exist for all sulfides into selenides and tellurides, *etc*., with the consequence of thousands of “*new*” minerals. This phenomenon is the reason that smelters usually produce not just pure by-product S (or SO2), but also some associated Se and Te.

Note: Some of the minerals listed above are described in the form of synthetic crystals (*i.e.*, frohbergite, kotulskite, mattagamite, merenskyite, montbrayite, rickardite, stützite, tellurantimony, tellurium {native}, tellurobismuthite, temagamite and weissite). Obviously, creating clearly defined and cleanly-separated Pt- and Pd-telluride minerals would be of economic interest; however, the existence of synthetic merenskyite (and certain other Pd-Pt minerals) implies that this is not a trivial undertaking. Publications about each of these synthesized crystalline forms yields much information about the properties of Te, Pt, Pd, and of other elements combined with Te. See Markham, N.L., 1960.

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Other publications recommended by the U.S. Geological Survey for information about tellurium include:

American Metal Market, daily

Engineering and Mining Journal, monthly

Metal Bulletin, weekly and monthly

Mining Engineering, monthly

Mining Journal, weekly

Mining Record, weekly

Roskill’s Letter from Japan, monthly

Ryan’s Notes, weekly