

# Carbonate-hosted, Nonsulphide Zn (hypogene) Mineral Deposit Profile E18

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## IDENTIFICATION

### SYNONYMS

**Zinc-oxides, willemite-dominant deposits**

### COMMODITIES (BYPRODUCTS)

**Zn, Pb (Mn, Fe, Cu, V, Cd, Ag)**

### EXAMPLES

(British Columbia - Canada/International): *Structurally-controlled replacement deposits: Abenab West (Namibia), Berg Aukas (Namibia), Kabwe (Zambia), Star Zinc (Zambia), Vazante (Brazil), Ariense (Brazil), Beltana (Australia), Aroona (Australia), Reliance (Australia). Stratiform deposits: Abu Samar (Sudan), Desert View (US), Franklin/Sterling Hill (US).*

## GEOLOGICAL CHARACTERISTICS

### CAPSULE DESCRIPTION

Zinc oxide minerals, such as willemite, franklinite or zincite, occur as massive to disseminated zones hosted primarily by carbonate rocks. The two subtypes of hypogene carbonate-hosted nonsulphide Zn-Pb deposits are:

- 1) structurally-controlled replacement deposits in the form of podiform bodies, veins, and irregular pipes consisting mainly of willemite ( $\pm$ sphalerite,  $\pm$ hematite,  $\pm$ franklinite and  $\pm$ zincite) and spatially associated with fractures and fault zones; and
- 2) stratiform deposits forming lenses of franklinite-willemite-zincite ( $\pm$ gahnite) located in highly metamorphosed terrains.

### TECTONIC SETTING(S)

The structurally-controlled replacement deposits are located in intracratonic or continental margin

environments in fault-controlled sedimentary basins within orogenic belts.

The stratiform deposits are located in sedimentary or volcano-sedimentary basins within orogenic belts.

### DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING

Hostrocks to the structurally-controlled hypogene nonsulphide Zn-Pb deposits are carbonates deposited in platform successions. Shallowing-upward basins or proximity to major unconformities separating a reduced, carbonate-rich succession (below) from an oxidized sequence of terrestrial sedimentary rocks (above) are frequent settings (e.g., Beltana and Vazante deposits; Groves *et al.*, 2003; Monteiro *et al.*, 2006).

In case of stratiform deposits, metamorphic overprint obliterated all textural/structural indicators of depositional environment.

### AGE OF MINERALIZATION

Ages of hypogene nonsulphide Zn deposits are poorly constrained between the Proterozoic to Paleozoic time.

### HOST / ASSOCIATED ROCK TYPES

Structurally-controlled deposits are commonly hosted by dolostone, limestone, dolomitized limestone, argillaceous carbonate, marble and slate.

Stratiform deposits are typically hosted by metasedimentary rocks, such as calcitic and dolomitic marble, interlayered with metavolcanic and igneous intrusive rocks (Hague *et al.*, 1956; Hitzman *et al.*, 2003).

### DEPOSIT FORM

Structurally-controlled deposits are highly irregular, consisting of podiform bodies, veins within fault and shear zones, joint and fissure-fills, and open-space fills in breccia pipe-like karst structures. Individual podiform ore bodies range from a few tens to a few hundreds of metres in the two dimensions parallel with bedding. Perpendicular to bedding, dimensions are usually a few tens of metres.

Stratiform nonsulphide deposits consist of a series of stratabound discontinuous tabular lenses that considerably

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varied in thickness and length from few tens of metres to few hundreds of metres.

## TEXTURE / STRUCTURE

Mineralization in the structurally-controlled deposits is heterogeneous, resulting from various depositional mechanisms such as massive replacement of various hematitic and/or zincian dolomite wallrock facies, dissemination, internal sedimentation, fracture and vein fill, and brecciation. The massive ore is commonly granular and fine grained, and appears as finely porous to compact cryptocrystalline masses. The internal sediments consist of fine laminations of zinc oxide minerals in open cavities. Colloform or crustiform bands, rosettes and spherulites of willemite are deposited as vein and vug fill and in the matrix of breccias (Figures 1, 2).

Mineralization in the stratiform tabular lenses consists of massive to disseminated equigranular, subrounded aggregates of Zn-rich minerals (Figures 3, 4, 5). The ores may have gneissic or disseminated textures, and minerals are generally coarse grained (>2-3 mm) and euhedral to subhedral (Hitzman *et al.*, 2003).

## ORE MINERALOGY (Principal and subordinate)

Structurally-controlled replacement deposits: Willemite, *cerussite*, *coronadite*, *covellite*, *descloizite*, *franklinite*, *gahnite*, *galena*, *genthelvite*, *hedyphane*, *hemimorphite*, *hetaerolite*, *hydrozincite*, *mimetite*, *native silver*, *sauconite*, *scholzite*, *smithsonite*, *sphalerite*, *tarbuttite*, *vanadinite* and *zincite*.

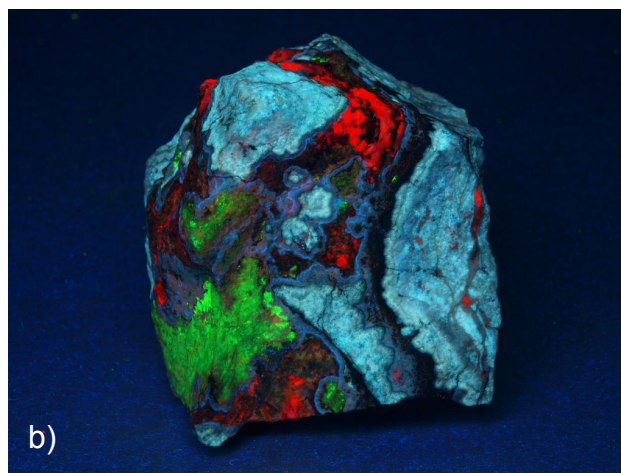
Stratiform deposits: Franklinite, willemite, zincite, *adamite*, *anglesite*, *arsenopyrite*, *aurichalcite*, *azurite*, *chalcophanite*, *chalcopyrite*, *cuprite*, *gahnite*, *galena*, *hemimorphite*, *hetaerolite*, *hydrozincite*, *magnetite*, *malachite*, *melangerite*, *sauconite*, *smithsonite*, *sphalerite*, *tephroite* and *zincian fayalite* (*roepperite*).

## GANGUE MINERALOGY (Principal and subordinate)

Structurally-controlled replacement deposits: Calcite,



**Figure 1.** Early dark red willemite covered by white willemite filling open spaces; Beltana mine, Australia. Pencil for scale. Photo used with permission of Data Metallogenica ([www.datametallogenica.com](http://www.datametallogenica.com)).



**Figure 2.** Zn-rich blocky ore from Beltana (Puttapa) consisting mostly of willemite. a) Under daylight conditions. b) Same photo under short wave ultraviolet light. Willemite fluoresces pale blue and shows green phosphorescence. Calcite fluoresces red. Specimen measures 9 by 8 by 8 cm. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

manganoc calcite, dolomite, ferroan dolomite, *apatite*, *barite*, *hematite*, *magnetite*, *quartz*, *siderite*, *Zn-rich chlorite*. Stratiform deposits: Calcite, manganoc calcite, dolomite, ferroan dolomite, *alleganyite*, *apatite*, *aragonite*, *barite*, *fluorite*, *garnet*, *goethite*, *graphite*, *hematite*, *leucophoenicite*, *jacobsite*, *löllingite*, *phlogopite*, *quartz*, *siderite*, *sonolite* and *rhodonite*.

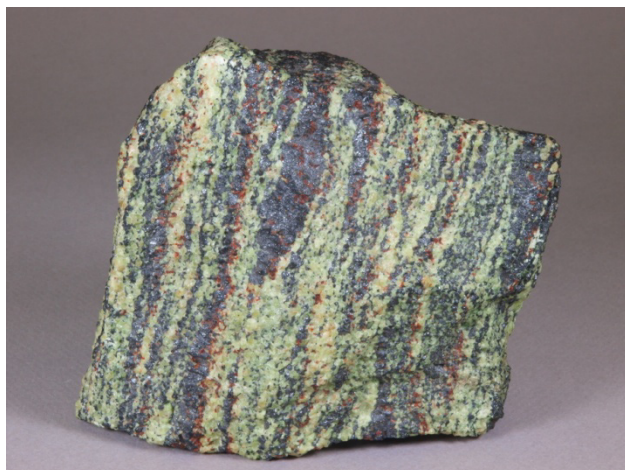
## ALTERATION MINERALOGY

The structurally-controlled replacement deposits display pre to syn-mineralization alteration of the host carbonate rocks that is largely fracture-controlled and extends for about 50 m to 20 km from the major structures. Alteration consists of silicification and formation of a broad halo of net-veined breccia filled by dolomite, ankerite, siderite, hematite, jasper, and chlorite. Post-mineralization alteration locally consists of hematite, Zn-chlorite, and dolomite assemblage, and/or calcite replacing earlier dolomite and zinc minerals. No alteration mineralogy is reported for stratiform deposits.





**Figure 3.** Typical granular willemite-franklinite-calcite ore from Sterling Hill (U.S.A.). Specimen measures 13 by 9.5 by 6.5 cm. Willemite is brownish red, franklinite and calcite are black and white, respectively. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

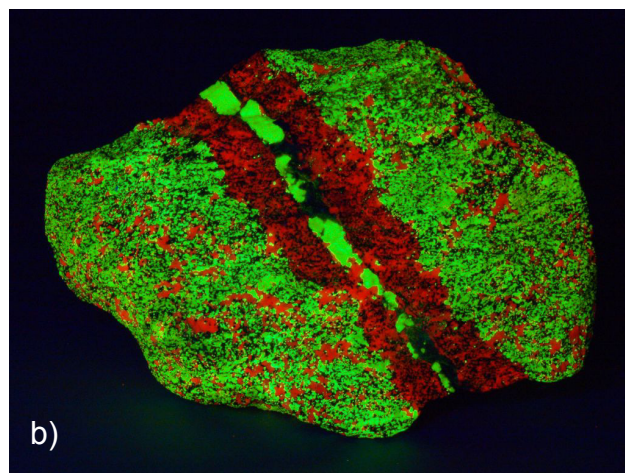


**Figure 4.** "Classic" granular ore from Franklin deposit (U.S.A.) showing pronounced gneissic foliation with green willemite, black franklinite, and minor red zincite. The colour of much willemite at Franklin is some shade of green; at Sterling Hill, it is usually brown, tan or brownish red. Specimen measures 10 by 10 by 7 cm. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

In the case of stratiform deposits, any original pre-metamorphic alteration mineralogy was probably destroyed by metamorphic overprint. The exception may be Desert View deposit (United States), which could have a preserved manganese halo (Leavens and Patton, 2008). Sphalerite present in some structurally-controlled replacement and stratiform deposits is replaced by willemite under hydrothermal conditions (*i.e.*, at temperatures higher than 100°C; Brugger *et al.*, 2003).

## WEATHERING

Nonsulphides in both deposit types can be altered by supergene processes to minerals observed in supergene nonsulphide zinc deposits. Supergene mineral assemblages form a near-surface direct-replacement cap



**Figure 5.** Sterling Hill franklinite-willemite-calcite ore. a) Daylight photograph of granular franklinite-willemite-calcite ore cut by a vein of willemite. The vein is enveloped by diffuse alteration zone. b) Same photograph under short wave ultraviolet light (colour-adjusted). Willemite fluoresces yellowish green and calcite fluoresces red. Specimen measures 17 cm in longest dimension. Photo used with permission of Dr. Earl R. Verbeek, Resident Geologist, Sterling Hill Mining Museum, Ogdensburg, New Jersey, U.S.A.

above many structurally-controlled replacement deposits. For example, an assemblage of hemimorphite, hydrozincite, and minrecordite form a cap above the willemite bodies of the Vazante deposit (Brazil). On the periphery of the Beltana deposit (Australia), hemimorphite and smithsonite formed by weathering of willemite. An assemblage of hemimorphite, cerussite, smithsonite, quartz, descloizite, pyromorphite, goethite, hematite, and iron-aluminum-manganese oxides replaces sulphides and willemite-bearing assemblages within the Kabwe (Zambia) and Berg Aukas (Namibia) deposits (Schneider *et al.*, 2008).

In the case of stratiform deposits, at least some goethite and hematite form by surface alteration of franklinite. Ferric oxide and hydroxide minerals are abundant within the Franklin and Sterling Hill deposits. Furthermore, under these conditions, hemimorphite, cerussite and hydrozincite commonly replace zincite.

## ORE CONTROLS

For structurally-controlled deposits, the main controls are favourable sedimentary successions with proper redox states and potential structural zones for fluid ore mixing, *i.e.*, regional basement structural features, such as growth faults, normal and reverse faults, and shear zones.

Favorable sedimentary hosts are important for the localization of stratiform zinc oxides deposits. Faults may also have played a role in the localization of stratiform deposits but metamorphism and deformation have obliterated all evidences.

## GENETIC MODEL

Structurally-controlled deposits formed where reduced, moderate to high temperature (100–330°C), Zn-rich, sulphur-poor fluid encountered a cooler, less saline, oxidized, sulphur-poor fluid of seawater, groundwater, or basinal origin (Hitzman *et al.*, 2003). The fundamental difference between the two deposit subtypes may be the site of fluid mixing (Hitzman *et al.*, 2003). The structurally-controlled deposits formed where fluids from a reduced sedimentary succession moved upwards along structures and encountered fluids that originated in oxidizing environment.

There is no consensus regarding the origin of the stratiform nonsulphide zinc deposits (*e.g.*, Franklin and Sterling Hill metamorphosed orebodies) because the nature of the primary mineralization is difficult to decipher. The stratiform deposits may have formed where Zn-rich hydrothermal fluids discharged into an oxidized, sulphur-poor body of water (*i.e.*, exhalative Zn carbonate-silicate oxide accumulations). Such mixing and accumulations of manganiferous sulphides and iron oxides may occur at the sediment/water interface or within sediments immediately beneath such body of water. There is also a possibility that the current ore assemblages may be the post-metamorphic equivalent of hemimorphite and hydrous Mn and Fe-oxides derived from the oxidation of preexisting sulphides. In general, high  $fO_2/fS_2$ , oxidizing and alkaline conditions at neutral to basic pH, and elevated temperatures favor stability of willemite relative to sphalerite (Brugger *et al.*, 2003).

## ASSOCIATED DEPOSIT TYPES

Carbonate-hosted, nonsulphide Zn-Pb (supergene, B09), Mississippi Valley-type (MVT, E12), and Irish-type (E13) are the most commonly associated deposits. Other potentially associated deposits are stratiform Zn sulphide and Fe (oxide or sulphide), Broken Hill-type (S01), magnetite (*i.e.*, iron oxide deposits), sedimentary manganese (F01), and carbonate-hosted  $Cu \pm Pb \pm Zn$  (E02) deposits.

## COMMENTS

These deposits are unusual in that they produce zinc, occasionally lead, and little else. The chemistry of the fluids responsible for the hypogene structurally-controlled

nonsulphide deposits is similar to solutions produced in many continental sedimentary basins. Therefore these deposits could be found in the same districts as MVT, Irish-type and potentially sedimentary exhalative (SEDEX) deposits. British Columbia has prospective strata for these deposits in the miogeoclinal carbonate platform rocks of the Ancestral North America continental margin and in the pericratonic rocks of the Kootenay terrane.

## EXPLORATION GUIDES

### GEOCHEMICAL SIGNATURE

Colorimetric field test for secondary zinc minerals (“Zinc Zap”) and hand-held x-ray fluorescence spectrometry are useful in exploration for nonsulphide Pb-Zn deposits in general (Paradis and Simandl, 2011; Simandl *et al.*, 2011). Positive Zn anomalies in residual soils and stream sediments and elevated concentrations of Pb, Mn, Fe, Cu, V, U, La, Cd, and As are also expected. Analysis of heavy mineral concentrates (identification of Zn-Pb nonsulphides) in stream and overburden may be effective in areas lacking deep weathering. Short wave ultraviolet light may help to detect an increase in the Mn content of calcite in proximity to deposit with these manganoan calcite fluorescing orange-red to red; however, calcite may also appear white, cream, yellow-orange, green or pink. If fluorescence of calcite is due to divalent Mn the colour of fluorescence will be orange-red to red. The other colours mentioned are due to different activators (quite diverse in calcite). Willemite may fluoresce green, yellow-orange or yellow under short wave ultraviolet light. Under long wave ultraviolet radiation, zincite may fluoresce yellow. Primary metamorphic zincite at Franklin and Sterling Hill does not fluoresce. Secondary zincite in veins or disseminated hydrothermal grains fluoresces in some specimens, but such zincite is uncommon and volumetrically insignificant. Willemite, ferroan dolomite, and supergene minerals such as hydrozincite and smithsonite, give distinct spectral responses in the short-wave near infrared portion of the spectrum (Hitzman *et al.*, 2003; McConachy *et al.*, 2009). Hyperspectral imaging holds promise as a useful tool for accurate mapping of structures, lithologies, and alteration.

### GEOPHYSICAL SIGNATURE

Deposits may produce a gravity signature. Electrical methods will not be successful due to the absence or small amounts of sulphides. Deposits that contain magnetite and franklinite can produce a magnetic response; a larger response should be observed with stratiform nonsulphide deposits.

## OTHER EXPLORATION GUIDES

Knowledge of the basin sedimentary succession with proper redox states and identification of potential zones for fluid mixing within major structures permits to focus

exploration efforts. Discovery of outcropping hypogene Zn-Pb nonsulphide deposits depends on recognition and knowledge of the physical properties of common nonsulphide zinc minerals. The selection of grassroots exploration areas should target sedimentary rock sequences that have known nonsulphide (supergene and hypogene) zinc prospects, stratiform manganese deposits, Mississippi Valley-type deposits or Broken Hill-type deposits.

## ECONOMIC FACTORS

### TYPICAL GRADE AND TONNAGE

Most of the known deposits (except Vazante with 28.5 Mt at 18.3% Zn, and Franklin with 21.8 Mt at 19.5% Zn) fall in the range of <1 to 10 Mt and grade 5 to 38% Zn and 0 to 11% Pb. They may contain low concentrations of Mn, Fe, Cu, V, Cd, Ag, and Ba.

### ECONOMIC LIMITATIONS

Some deposits (e.g., Beltana and Aroona) are amenable to open pit mining operations; however, most hypogene nonsulphide deposits are exploited by underground mining.

### IMPORTANCE

Nonsulphide deposits were the main source of zinc prior to the 1930s. Following the development of differential flotation and breakthroughs in smelting technology, the mining industry turned its attention almost entirely to sulphide ores. Today, most zinc is derived from sulphide ore. The nonsulphide deposits provided roughly 7% of the world's zinc production in 2009. Hypogene nonsulphide deposits are relatively rare compared to supergene nonsulphide deposits, and they currently represent less than 2% of the zinc production.

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## SELECTED BIBLIOGRAPHY

Boni, M., Terracciano, R., Balassone, G., Gleeson, S. and Matthews, A. (2011): The carbonate-hosted willemite prospects of the Zambezi metamorphic belt (Zambia); *Mineralium Deposita*, Volume 46, pages 707-729; <http://www.springerlink.com/content/c1817113765j7365/fulltext.pdf>.

Brugger, J., McPhail, D.C., Waters, J., Wallace, M. and Lees, T. (2003): Formation of willemite in hydrothermal environments; *Economic Geology*, Volume 98, pages 819-835.

Groves, I., Carman, C.E. and Dunlap, W.J. (2003): Geology of the Beltana willemite deposit, Flinders Ranges, South Australia; *Economic Geology*, Volume 98, pages 797-818.

Hague, J.M., Baum, J.L., Herrmann, L.A. and Pickering, R.J. (1956): Geology and structure of the Franklin-Sterling area, New Jersey; *Bulletin of the Geological Society of America*, Volume 67, pages 436-474.

Heyl, A.V. and Bozion, C.N. (1962): Oxidized zinc deposits of the United States, Part 1, General geology; *United States Geological Survey*, Bulletin 1135-A, 52 pages.

Hitzman, M.W., Reynolds, N.A., Sangster, D.F., Cameron, R.A. and Carman, C.E. (2003): Classification, genesis, and exploration guides for nonsulphide zinc deposits; *Economic Geology*, Volume 98, Number 4, pages 685-714.

Johnson, C.A. (2001): Geochemical constraints on the origin of the Sterling Hill and Franklin zinc deposits, and the Furnace magnetite bed, northwestern New Jersey; *Society of Economic Geologists Guidebook Series*, Volume 35, pages 89-97.

Johnson, C.A. and Skinner, B.J. (2003): Geochemistry of the Furnace magnetite bed, Franklin, New Jersey, and the relationship between stratiform iron oxide ores and stratiform zinc oxide-silicate ores in the New Jersey Highlands; *Economic Geology*, Volume 98, pages 837-854.

Leavens, P.B. and Patton, J.D. (2008): The Desert View Mine. San Bernardino Mountains, California: a possible intermediate between Långban, Sweden and Franklin, New Jersey; *Axis*, Volume 4, Number 1, pages 1-13.

McConachy, T.F., Yang, K., Boni, M. and Evans, N.J. (2009): Spectral reflectance: preliminary data on a new technique with potential for non-sulphide base metal exploration; *Geochemistry: Exploration, Environment, Analysis*, Volume 7, pages 139-151.

Monteiro, L.V.S., Bettencourt, J.S., Spiro, B., Graça, R. and Oliveira, T.F. (1999): The Vazante zinc mine, MG, Brazil: constraints on fluid evolution and willemite mineralization; *Exploration and Mining Geology*, Volume 8, pages 21-42.

Monteiro, L.V.S., Bettencourt, J.S., Juliani, C. and Oliveira, T.F. (2006): Geology, petrography, and mineral chemistry of the Vazante non-sulphide and Ambrosia and Fagundes sulphide-rich carbonate-hosted Zn-(Pb) deposits, Minas Gerais, Brazil; *Ore Geology Reviews*, Volume 28, pages 201-234.

Paradis, S. and Simandl, G.J. (2011): Carbonate-hosted, Nonsulphide Zn-Pb (supergene) Mineral Deposit Profile B09; in Geological Fieldwork 2010, *BC Ministry of Energy, Mines, and Petroleum Resources*, Paper 2011-1, pages 189-193; <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork>.

Peck, W.H., Volkert, R.A., Mansur, A.T. and Doverspike, B.A. (2009): Stable isotope and petrologic evidence for the origin of regional marble-hosted magnetite deposits and the zinc deposits at Franklin and Sterling Hill, New Jersey Highlands, United States; *Economic Geology*, Volume 104, pages 1037-1054.

- Sangster, D.F. (2003): A special issue devoted to nonsulfide zinc deposits: a new look; *Economic Geology*, Volume 98, Number 4, pages 683-684.
- Schneider, J., Boni, M., Laukamp, C., Bechstädt, T. and Petzel V. (2008): Willemite ( $\text{Zn}_2\text{SiO}_4$ ) as a possible Ribs geochronometer for dating nonsulfide Zn-Pb mineralization: Examples from the Otavi Mountainland (Namibia); *Ore Geology Reviews*, Volume 33, pages 152-167.
- Simandl, G.J., Paradis, S., Fajber, R., and Rogers, N. (2011): Hand-held, portable XRF in exploration for carbonate-hosted sulphide and nonsulphide Pb-Zn deposits; Geofile 2011-6, *BC Ministry of Energy, Mines, and Petroleum Resources*; <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/GeoFiles>.