

Revisiting the Sterling Hill Orebody: Challenges in Understanding and Mining this Magnificent Deposit

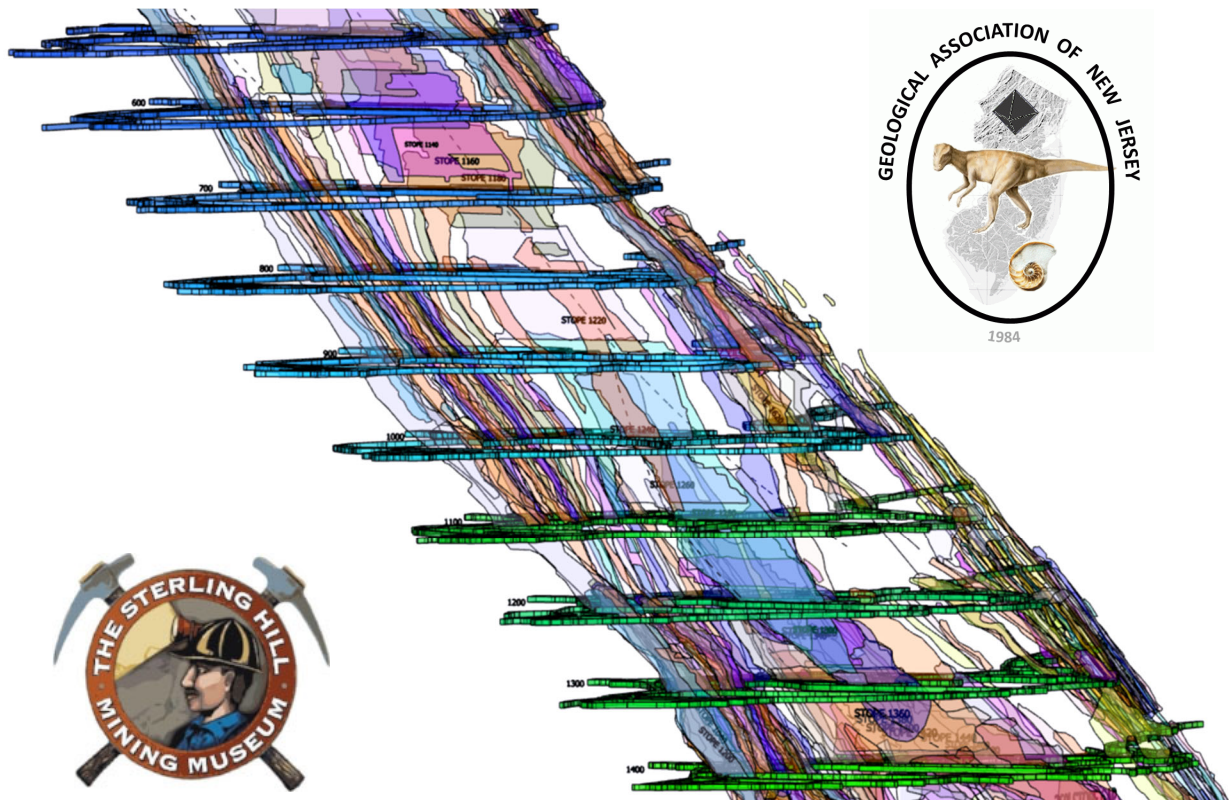
MEETING PROCEEDINGS AND FIELD GUIDE FOR THE
2025 CONFERENCE OF THE GEOLOGICAL ASSOCIATION OF NEW JERSEY

Edited by

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GEOLOGICAL ASSOCIATION OF NEW JERSEY ANNUAL CONFERENCE XLI (41)
AND FIELD TRIP OCTOBER 17-18, 2025,
THE STERLING HILL MINING MUSEUM, OGDENSBURG, NEW JERSEY

GEOLOGICAL ASSOCIATION OF NEW JERSEY ANNUAL CONFERENCES AND EDITORS

2025 XLI Revisiting the Sterling Hill Orebody: Challenges in Understanding and Mining this Magnificent Deposit, Michael Di Maio, Gregory Herman, and Earl Verbeek

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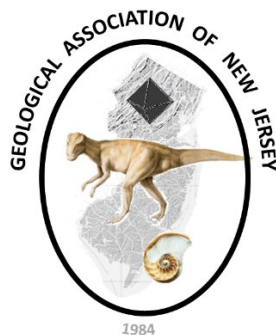
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- 1986 III Geology of the New Jersey Highlands and Radon in New Jersey, Jonathan Husch and Fred Goldstein
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PREFACE

It's an honor for us, as proceeding editors, to present the GANJ 41 volume that brings modern views upon a very old and unique mineral deposit in northern New Jersey. It's appropriate that this year's conference focuses on the geological feature that gives us the rare-mineral franklinite, New Jersey's state mineral, that's also featured in the logo of the Geological Association of New Jersey. But it's somewhat ironic that this mineral in its iconic, isometric, octahedral form was problematic with respect to resisting attempts at refinement during 19th century mining efforts. This gave rise to the 'franklinite problem' that helps explain why many franklinite-rich boulders are strewn about the surface pits at Sterling Hill. This is the first GANJ conference that focuses on the Sterling Hill and Franklin zinc deposits, 41 years after our conception. Why it took so long is a reflection of their ancient, complex mineralogical and structural nature. Each author and presenter shared the same sentiment about their exploration into the geology of this deposit, stating, in some form, that this project had turned out to be much more complex and involved than they anticipated. The work herein advances our geological viewpoints and legacy of these famous zinc mines, one of which bears the name of an American founding father.

This year's conference proceedings provide a modern basis for future work directed at better understanding the nature of one of the world's most famous zinc-ore deposits. It draws attention to the need for more geochemical research aimed toward solving the ore's genesis. The 3D computer-based architectural models of the mines will help place archived core into a precise perspective for testing new hypotheses and drawing well-informed and constrained conclusions regarding the ore evolution.

Chapter 1, by John Puffer, emeritus professor of Rutgers University, covers the fluid and geochemical origin of the zinc ore and places it into geological perspective with other invasive, metalliferous ore occurrences worldwide. John is a founding member of GANJ, presided over the first GANJ meeting, and now brings a career's bank of geologic deduction to bear on the mineral deposit over two scores of years later. His work is a critical review of the geochemical constraints necessary to establish probable cause for the occurrence of these precious ore deposits.

Chapter 2, by Gregory Herman, retiree of the New Jersey Geological Survey and now with Trap Rock Industries, LLC, presents new, three-dimensional (3D) architectural models of the Sterling Hill and Franklin (Mine Hill) zinc mines that emphasize their structural nature, and help place the ore body into a geological framework shaped by incremental, well-documented tectonic events that have periodically strained the region. This work is capped by the sharing of a spreadsheet-based solution for calculating geographic coordinates of mapped, notable features at Sterling Hill that relied upon the New Jersey Zinc Company's mining grid using North and West coordinate feet, and that's rotated 19° clockwise with respect to true north. The computer models

of the Sterling and Franklin mines are shared through the GANJ website in their native format (SketchUp Pro) and as object models for loading into Google Earth.

Chapter 3, by Earl Verbeek and Marilyn Grout, retirees of the U.S. Geological Survey in Denver, is an exposé on the mineralogical and structural nature of faulting and jointing at Sterling Hill. Earl is the curator at the Franklin Mineral Museum and retired to New Jersey after his USGS career to continue his prior work on the structure and mineralogy of the Sterling and Franklin zinc mines. This work details fault orientations, slip directions, and fault-lining minerals for over one thousand faults from the surface to -1200 feet below grade in the Sterling mine adits, drifts, and stopes as they were gradually filling with groundwater upon mine closure.

The field trip this year is in four parts, all within the grounds of the Sterling Hill Mining Museum (SHMM). One part will be an augmented version of the regular, daily mine tour that runs underground within the workings near the surface beneath Sterling Hill. The other part of the field trip is a tour of the surface pits and cuts immediately to the southwest. We expect to handle a full slate of 80 participants, with four groups of twenty taking concurrent tours on-site that include 1) the Passaic and Noble pits, 2) the SHMM underground mine tour, 3) some of the ore-processing facilities, and 4) Zobel Hall, the main exhibit hall of the SHMM. The mine tour has a 20-person limit, and we'll be running two groups of 40 through the open pits, one Saturday morning, and one later in the early afternoon. We've developed an itinerary to facilitate this process, so please pay attention to and abide by the group assignment you receive at the start of day 2.

DAILY ITINERARY FOR THE 41ST GEOLOGICAL ASSOCIATION OF NEW JERSEY ANNUAL MEETING

Day 1, Friday October 17, 2025 at the Sterling Hill Mining Museum

9:30 am: Registration and Coffee

10:00 -10:15 am Welcome and Opening Remarks: Mike Di Maio

10:15 – 11:00 am Keynote: John Puffer, PhD

11:05 – 11:30 am Platform Presentation 1 – Peter Matt, PhD

11:35 – 12:20 pm Platform Presentation 2 – Robert Martin, PhD

LUNCH AND POSTER SESSION 12:25 – 1:30 pm

1:30 – 2:10 pm Platform Presentation 4 – Gregory Herman, PhD

2:15 – 2:40 pm Platform Presentation 5 – Earl Verbeek, PhD

2:40 – 3:00 pm Coffee Break and Networking

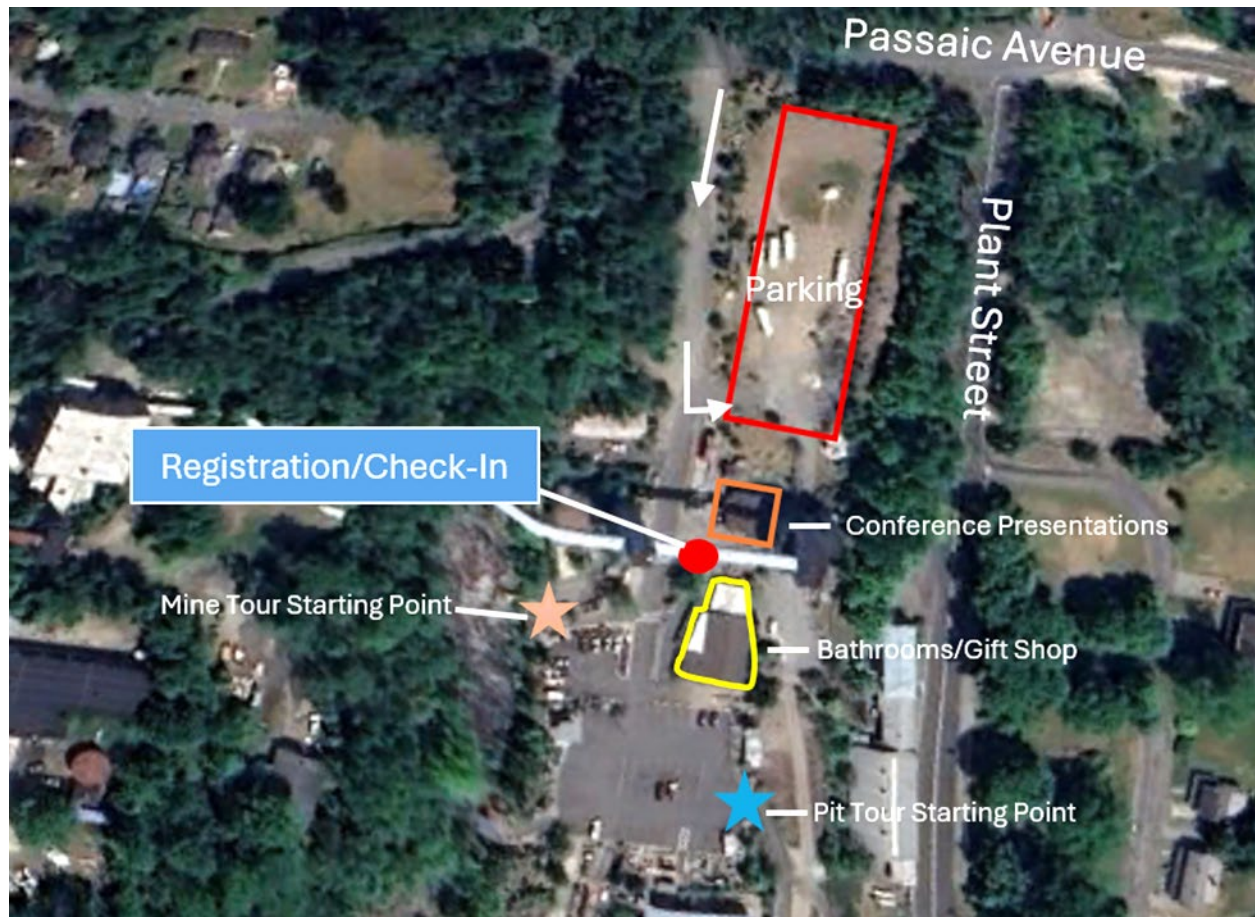
3:00 – 4:30 pm Business Meeting

DAY 2, Saturday October 18, 2025 at the Sterling Hill Mining Museum

8:30 am: Gathering with Coffee

	Group 1 (20)	Group 2 (20)	Group 3 (20)	Group 4 (20)
9 - 11 am	Pit Tour	Pit Tour	Mine Tour 1	Mine Tour 2
11 am - 12:30 pm	Zobel Hall & Rock Collecting	Zobel Hall & Rock Collecting	Warren Museum & Rock Collecting	Warren Museum & Rock Collecting
12:30 - 1:30 pm	Lunch & Platform Presentation			
1:30 – 3 pm	Mine Tour 1	Mine Tour 2	Pit Tour 2	Pit Tour 2

SITE MAP



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Abstracts

SPECIMENS AND RECORDS FROM THE STERLING HILL MINE IN THE NEW JERSEY STATE MUSEUM COLLECTIONS: A BRIEF HISTORY AND OVERVIEW

Rodrigo A. Pellegrini, New Jersey State Museum, Trenton, New Jersey

Robert (Bob) W. Metsger, manager and chief geologist of the New Jersey Zinc Company reached out to New Jersey State Museum curator David C. Parris after the Sterling Hill Zinc Mine closed in 1986 to arrange for the donation of specimens and artifacts before the town of Ogdensburg, New Jersey foreclosed on the property (1989). Bob had met with David at the Field Conference of Pennsylvania Geologists in the early 1980s, and had discussed the future of the mine and its artifacts, specimens and records. As a scientist he was concerned that materials would be destroyed when the mine closed, or at best perhaps used as a display that emphasized aesthetically pleasing mineral specimens rather than encourage scientific research. He also worked with the New Jersey Geological and Water Survey and Rutgers University to achieve two main goals: 1) safeguarding the specimens and artifacts against deterioration over time, and 2) guaranteeing access to the scientific community for future research. Following consultation with colleagues at the aforementioned institutions, Bob arranged for the distribution of most materials. In 1988, the glass mine model that he spent much time making was transferred to the State Museum along with eighty mineral specimens and six canisters of film. Also included was an additional, Plexiglas model of the mine in three sections, which was later loaned to the New Jersey Geological and Water Survey in 1995 (and in turn transferred on indefinite loan to the Sterling Hill Mining Museum on 26 May of 1995).

Subsequent gifts of additional mine materials followed in 2013 after Bob's passing in 2012. These included thin sections, thin section butts, drill hole and hand samples, a microscope, and more. All but the instruments were meticulously labeled, bearing reference to each hole or other locality within the mine. A final gift of records, reports, notes and maps was received by the State Museum in 2017. A general inventory of the items received from the Metsger estate is available on the GANJ website under the GANJ2025/data directory.

The NJSM collections catalog is not available for online searching by the general public, but we understand the importance of the Metsger materials and continually strive to make them available to anyone for geological research. Accessibility is controlled by the standing museum policy, which requires interested parties to contact the Bureau of Natural History to arrange a research visit. If necessary, requests for destructive analysis will be considered, but require an application that must be approved by the Bureau Curator and Museum Director.

ZINC ORE, FLUORESCENT, AND EPONYMOUS MINERALS, FRANKLIN AND STERLING HILL, NEW JERSEY

Pierre Lacombe, U.S. Geological Survey New Jersey Water Science Center (retired), Trenton, New Jersey

At least 370 minerals are identified in the mines at Franklin and Sterling Hill, New Jersey. Each has been assigned a name by the International Mineralogical Association (IMA). Minerals are generally named for people; places; type sections; derived from Greek, Latin, or words other languages; and for their chemistry. The purpose of this project is to highlight 36 eponymous minerals that honor local Native American words, scientists, mine workers, and place names.

Franklin-Sterling Hill area is America's first major zinc mining area. The area is touted as having more fluorescent minerals and the greatest variety of minerals than anywhere else on Earth. The names of the three principal zinc ore minerals from the area are franklinite, willemite, and zincite. The names of the four major fluorescent minerals are calcite, esperite, hardystonite, and willemite. The major minerals and fluorescent minerals are discussed as a foundation for the eponymous minerals.

Of the 370 minerals identified in the Franklin-Sterling Hill area, 131 minerals are named for a person, and 127 minerals get their name from some language, mostly Greek and Latin. 65 mineral names are for the region in which the mineral is located and 39 are named for the chemical compound. A few minerals are named for some other reason. 71 minerals are named for Europeans and 65 are named for Americans. The remaining 11 are named for people from other regions. About 98 minerals are fluorescent from brilliant to subtle displays.

The 'type locality' for 70 minerals is the Franklin-Sterling Hills area. Three mineral names honor local Native Americans: kittatinnyite, lennilenapeite, wawayandaite. I selected two mineral names that honor USGS employees, two mineral names that honor NJ State employees, and ten mineral names that honor employees of the zinc mining industry of New Jersey. Lastly, I selected four mineral names that honor communities or regions of the Franklin-Sterling Hill area.

In the investigation for this project, I freely used information from Franklin-Ogdensburg Mineralogical Society Inc. web page, the Franklin-Ogdensburg Mineralogical Society, and the Hudson Institute of Mineralogy Mindat.org - Mines, Minerals and More.

UNRAVELING THE MYSTERY OF HERKIMER 'DIAMONDS': A FRAMEWORK FOR FUTURE RESEARCH

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Herkimer “Diamonds,” the double-terminated quartz crystals hosted in the Late Cambrian Little Falls Dolostone of central New York, have long fascinated collectors and geologists around the world. Despite centuries of cultural significance, and decades of mining and investigation, fundamental questions regarding their origin remain unanswered. While descriptive accounts and syntheses exist, the system remains an underexplored natural laboratory for integrating sedimentology, diagenesis, isotope geochemistry, geochronology, and organic geochemistry

What we know. Within the Little Falls Dolostone, quartz crystals formed at estimated temperatures ranging from 50°C (Dunn and Fisher 1954) based on a single measurement, and 50-200°C based on more than 100 fluid inclusion measurements and bitumen reflectance values (O'Reilly and Parnell 1999). Burial history is a source of ongoing debate. Some models suggest up to 7 km of burial (Friedman 1987) or significantly less burial with additional heat being supplied by either the Acadian (Middle Devonian) or Alleghenian (Late Carboniferous-Permian) orogenies. These crystals occur in discrete pockets, associated with dolomite crystal linings and often encased in calcite crystals. Many crystals are included by black carbonaceous material which has been given the name “anthraxolite”. Fluid inclusion studies suggest the presence of saline brines migrating downwards from the overlying halite-bearing Silurian formations at the time of the quartz formation, with fluid inclusions being near saturation with NaCl (Roedder 1979). The exact timing of crystallization is unknown, but from basic subsidence models Muskatt and Tollerton (1992) suggest a Carboniferous age. Many questions remain insufficiently answered.

What we would like to understand better.

1. Depositional framework of the Little Falls Dolostone: Can mapping of dolostone facies combined with Sr isotope stratigraphy provide improved regional correlation of the quartz-bearing zones, and the constraints necessary for a depositional age model? Are there detrital zircons present in the LFD? Can we map the sedimentary facies in higher detail?
2. Burial history: To what depth was the Dolostone buried, what is the source of heat required for anthraxolite maturation?

3. Pocket formation: Were the crystal-bearing cavities linked to microbial mats, stromatolitic horizons, evaporites, karstification or diagenetic redox fronts?
4. Quartz paragenesis: What were the precise pressure-temperature-fluid conditions at the time of formation? How did these conditions vary across localities and crystal habits (classic, skeletal, and scepters)? Can we decipher fluid flow on a basinwide scale through geologic time?
5. Role of organic complexation: How do organics control silica mobility and crystal morphology? What evidence remains trapped within the crystals as anthraxolite?
6. Nature of anthraxolite: What is the source of the carbon, and how does it vary across different habits of quartz in the region? (inclusions within quartz, scepter stems, isolated grains, or in calcite) Stable isotope geochemistry ($\delta^{13}\text{C}$) and kerogen typing may provide insight into the source, and evolution of anthraxolite alongside the formation of quartz.
7. Timing of mineralization: Can $\text{Ar}_{40}/\text{Ar}_{39}$ dating of fluid inclusions, or U/Pb dating of calcite and dolomite phases constrain the timing of mineral formation?

REFERENCES

- Dunn, J.R., and Fisher, D.W., 1954, Occurrence, properties, and paragenesis of anthraxolite in the Mohawk Valley: *American Journal of Science*, vol. 252, p. 489–501.
- O'Reilly, C., and Parnell, J., 1999, Fluid flow and thermal histories for Cambrian-Ordovician platform deposits, New York: Evidence from fluid inclusion studies: *Geological Society of America Bulletin*, vol. 111, no. 12, p. 1884–1896.
- Friedman, G.M., 1987, Vertical movement of the crust: Case histories from the northern Appalachian Basin: *Geology*, vol. 15, p. 1130–1133.
- Roedder, E., 1979, Fluid inclusion evidence on the environments of sedimentary diagenesis, A review: *SEPM (Society for Sedimentary Geology) Special Publication*, no. 26, p. 89–107.
- Muskatt, H.S., and Tollerton, V.P., Jr., 1992, The Little Falls Dolostone (Late Cambrian) stratigraphy and mineralogy: *in* Guidebook to the 64th Annual Meeting of the New York State Geological Association, p. 200–215.

A CARBONATE MELT WAS LIKELY INVOLVED AT FRANKLIN AND STERLING HILL

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Dirk Schumann, Fibics Inc., Ottawa, Canada

One hundred years ago, Josiah Spurr and Volney Lewis wrote: “In both economic and scientific interest, the mines of the world offer few parallels to the great zinc deposits at Franklin Furnace, N.J.”. They concluded that the origin of the zinc ore ... “can be explained only as a rare and highly differentiated form of igneous magma”. Spurr and Lewis (1925) envisioned an injection of a zinc-rich sulfide melt at Franklin and Sterling Hill. The dikes of sulfide were later subjected to 1) a major rise of temperature and 2) a suffusion of water and other gases, which led to important plastic deformation and loss of sulfur through volatilization.

In our opinion, a melt was indeed involved at Franklin and Sterling Hill. We claim that the Franklin marble melted during the high-temperature late event recognized by Spurr and Lewis. The evidence that we will present is based on our interpretation of the mutual relationships (i.e., the texture) of the constituent minerals and their composition, determined by large-area light microscopy and SEM imaging with energy-dispersion (EDS) analyses. Ultimately, we believe that fluxed melting of the marble created a powerful solvent in which the sulfides could oxidize and dissolve. Sulfur and other volatile constituents were progressively lost by degassing. The event thus must have been rather ephemeral.

Our oral presentation is based on a detailed analysis of TWO polished thin sections. The first shows an assemblage of willemite, franklinite and zincite from Sterling Hill. Of the three minerals, the zincite grew last, interfering with calcite + rhodochrosite. Alleghanyite, a zinc-dominant humite-group mineral, is considered deuteritic. The evidence of a carbonate melt is more subtle in the second thin section, taken of the enclosing Franklin marble. During the brief interval in which the marble was molten, the assemblage changed drastically from reduced (graphite-bearing) to strongly oxidized. We will show evidence of two potentially new species. Incidentally, the temperatures documented in the literature on these deposits (for example by calcite-graphite geothermometry) are amply sufficient to account for the fluxed melting of a carbonate assemblage.

REFERENCE

Spurr, J.E., and Lewis, J.V., 1925, Ore deposition at Franklin Furnace, New Jersey: Engineering and Mining Journal-Press, vol. 119, p. 317–328.

GEOSPATIAL 3D VISUALIZATION OF THE VERBEEK AND GROUT (2025; CHAPTER 3) FAULTS USING AI AND CAD.

Gregory C. Herman, Trap Rock Industries, Kingston, New Jersey (N.J Geological Survey, retired)

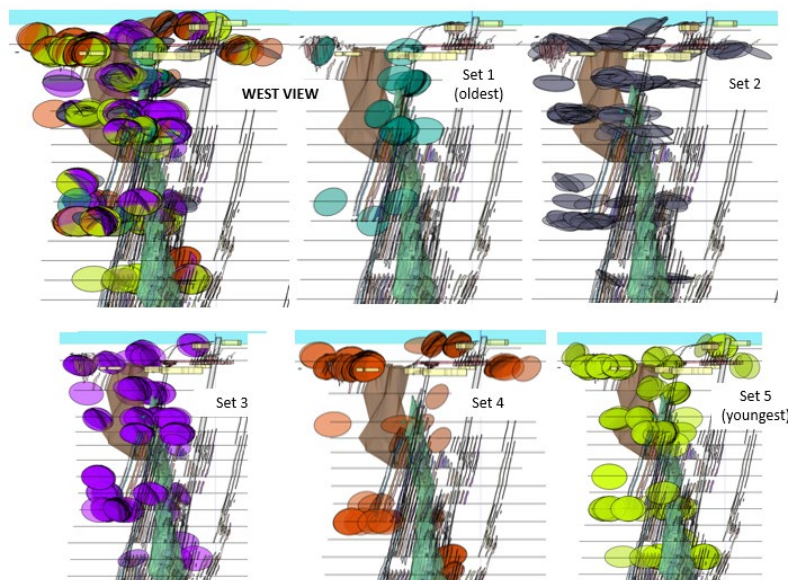
Earl R. Verbeek, Franklin Mineral Museum, Franklin, New Jersey (U.S. Geological Survey, retired)

The Google Gemini artificial-intelligence (AI) functionality was used to build a SketchUp Pro (SUP) extension that reads comma-separated-text (*.CSV) files containing fault location, orientation, and scaling parameters to automate plotting of scaled, titled fault planes at Sterling Hill based on the Verbeek and Groat (2025) fault database. Of their total 1158 mapped faults, 865 had the locational and type parameters required to spatially plot and discriminate between all five types of faults mapped from the surface to -1200 feet below using New Jersey Zinc Company mine coordinates. Because the mine grid is rotated 19° clockwise, rotated coordinates were computed to place the fault systems into relative positions with respect to true north.

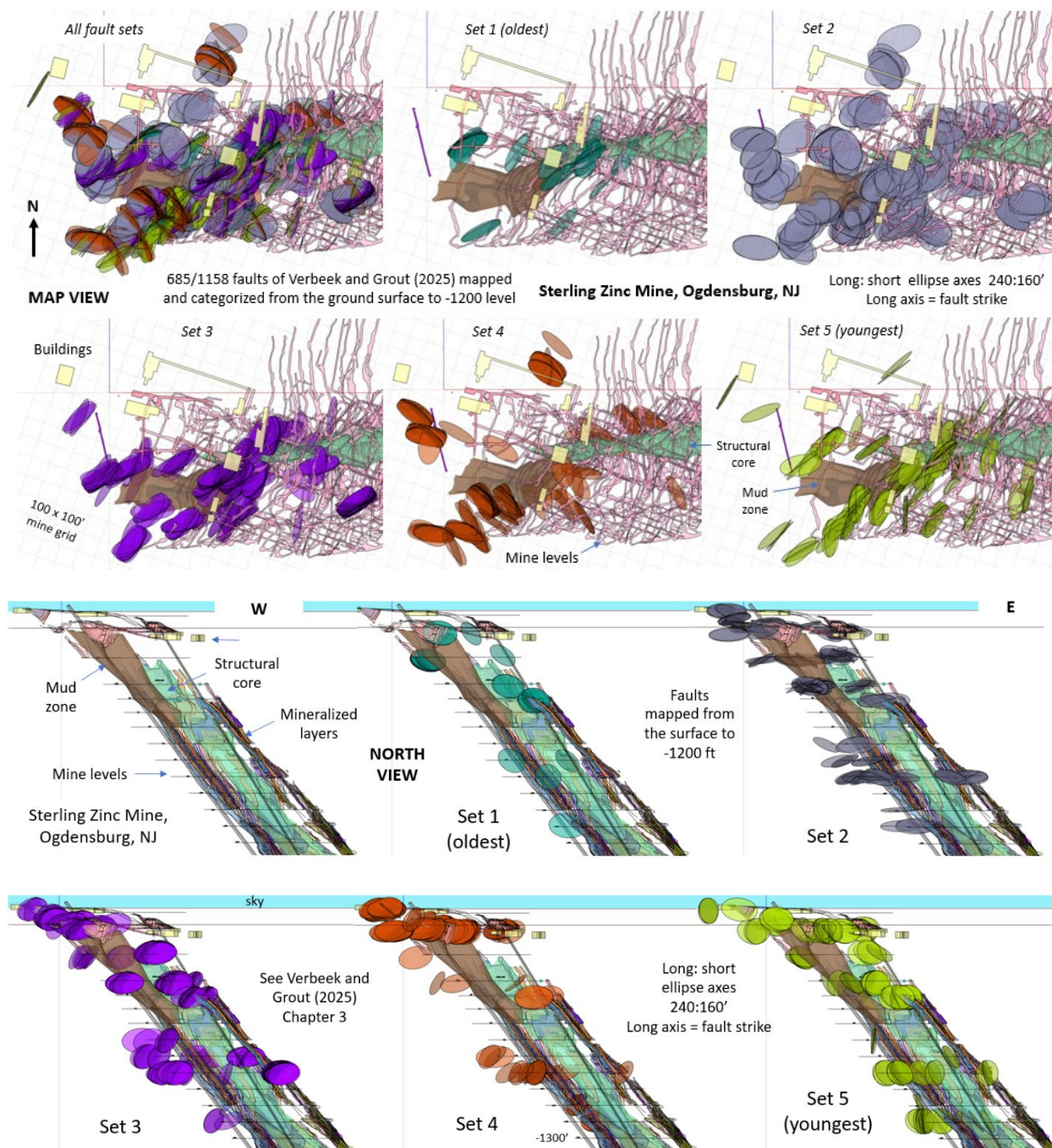
A Ruby script was written using Google Gemini that adapted code from the online GeoTools at www.impacttectonics.org/GeoTools/ that are used to generate oriented structural-geological symbols for display in Google Earth. The script was loaded into SketchUp Pro as an extension, and used to read CSV files compiled for each fault set to model them as tilted elliptical planes having a 3:2 axial ratio with the long axis oriented along structural strike. An example CSV file is shown to the left below. The collective set of faults was then added into the SUP model of the mine at Sterling Hill (see chapter 2 and images below). At this stage, all faults are scaled the same, but colored differently for each set. With continued refinement, a more realistic portrayal of the cross-cutting faults can be attained. The units of measure are feet. AZM = Plane dip azimuth. The mine and fault perspectives below show where and how old fault systems are repeatedly reactivated, and that their occurrence helps determine where good ore and bad ground occur.

EXAMPLE CSV data file

```
XCOORD,YCOORD,ALTITUDE,AZM,DIP,XSCALE,YSCALE
-909.34,1428.90,617,116,63,120,80
-1098.86,970.64,620,150,73,120,80
-1098.86,970.64,620,150,65,120,80
-1168.20,1475.73,452,153,60,120,80
-1168.20,1475.73,452,152,57,120,80
-1168.20,1475.73,452,151,58,120,80
-1168.20,1475.73,452,145,60,120,80
-1168.20,1475.73,452,145,47,120,80
-1168.20,1475.73,452,149,63,120,80
-1168.20,1475.73,452,126,63,120,80
-1168.20,1475.73,452,147,52,120,80
-1168.20,1475.73,452,122,52,120,80
-1200.28,1428.61,452,109,50,120,80
-720.08,1379.60,482,123,55,120,80
```



Email gcherman56@yahoo.com to request a copy of the Ruby script.



REFERENCE

Verbeek, E.R. and Grout, M.A., 2025, Chapter 3. Fault History of the Sterling Zinc Mine, Ogdensburg, Sussex County, New Jersey, with Appendices, *in* Di Maio, M.P., Herman, G.C., and Verbeek, E.R., editors, *Revisiting the Sterling Hill Orebody: Challenges in Understanding this Magnificent Deposit: 41st Annual proceedings and field guide of the Geological Association of New Jersey*, The Sterling Hill Mining Museum, Ogdensburg, NJ, p. 117-140.

THE CAMPTONITE DIKE IN THE FRANKLIN, NJ OREBODY, RECENT RESEARCH

David Vonderheide, National Weather Service (retired), Flagstaff, Arizona

A lamprophyric dike cut through the orebody at Franklin, NJ during the late Ordovician. It played a prominent role in shaping the course of early mining operations. In the late 19th century, the dike rock was identified by names such as mica diabase and kugel-minette, reflecting changes in petrologic nomenclature during that period. In 1889 the name camptonite was applied by F. Nason to the dike in Franklin, using nomenclature established by H. Rosenbusch two years earlier. Several geochemical analyses were published in those early years, but no additional work was done in the succeeding century. Publications mentioning the camptonite would refer back to the earlier articles for geochemical data. In 2020 this author, aware that geochemical methods had advanced greatly, and that knowledge of the geological structure of the New Jersey Highlands had become more detailed, realized that the dike needed an updated study. Discussions with geologists familiar with the dike established research requirements. Samples were collected and documented, thin sections were made, and chemical analyses were done by fusion/acid digestion, ICP-MS and nondestructive-INAA. Mineral content was determined using the XRD-Rietveld method. XRF (portable) and Raman equipment were available locally and made available for use. Microprobe work is yet to be done.

The dike is alkalic, hydrous and rich in CO₂. Silica in the Franklin dike ranges between 35 and 41 wt.% (very undersaturated). Anomalously high amounts of Ti, Ba, Sr, V and Zn may indicate metasomatism occurring within a mantle previously subjected to fluids derived from oceanic crust (subduction-sourced). Another possibility is that crustal contamination/assimilation occurred during crustal intrusion. Primary minerals in the Franklin dike are augitic clinopyroxene, biotite, and labradoritic plagioclase. Alteration during cooling has resulted in analcimitization, epidotization, and to a lesser degree, chloritization of the primary phases. Two generations of biotite exist, an earlier set of large euhedral crystals (phenocrysts), and a groundmass set that appears to have developed later during the intrusion process. Some of the smaller biotites are kinked, raising the question of whether these are xenocrysts of crustal origin. There are also two generations of augite, similarly showing an earlier set of large euhedral crystals displaying growth zonation, and a later set of small, elongated prisms within the groundmass. As the crystal mush moved upward into the crust, cooling accelerated, hence the trend from larger phenocrysts to smaller groundmass crystals. Plagioclase (23 to 46 wt.% of total rock, from XRD) displays deformational albite twinning that may have been caused by stress placed on the dike during the late stage of cooling. Titanite is ubiquitous. The lack of zircons combined with the high Zr content in whole-rock analyses implies that Zr is in the most likely host, titanite. Ocelli within the outer portion of the dike are exclusively albite, analcime and calcite. Ti is present in titanite and in opaque Fe-Ti oxide (ilmenite or Ti-magnetite). Cr, Ni, and Co are low. REE plots all show higher LREEs sloping down to lower HREEs. There is no Eu anomaly ($\text{Eu}/\text{Eu}^* = 1.01$), indicating that this

element was neither depleting nor enriching from plagioclase while crystals grew in the magma. Acicular apatite implies that the dike was intruded rapidly. There is a lack of deep crustal xenoliths throughout the dike. The only xenoliths within the dike are from the adjacent zinc orebody, occurring as elongated slabs and slivers that appear to be due to spalling of ore into the magma. Xenoliths of zinc ore within the dike commonly have a rind of brown ceramic-like material that is high in SiO₂, Zn and Mn, yet the only Raman-active phase is pyrophanite. Dike contact with the Franklin Marble shows metasomatism only on the microscopic scale (in thin sections), indicating that the magma chilled rapidly enough at the contact to prevent much exchange of metasomatic fluid.

Nelson Eby (UMass/Lowell) has calculated a melting temperature of about 1700°C (at 5 to 7 GPa) and a crustal intrusion temperature of 1000° to 1100°C. Radiometric dating of the biotite using the Ar₄₀/Ar₃₉ method, in biotite, determined an intrusion age of 446.36 ± 0.81 Ma (plateau age). This date places the intrusion within the Taconic Orogeny, not with Triassic and Proterozoic diabase dikes occurring in the NJ Highlands. Isotope analysis (Nd TDM age = 1329 Ma ±2.4) indicates a depleted subcontinental lithosphere source.

ZINC ISOTOPE CONSTRAINTS ON THE FORMATION OF SEDIMENTARY EXHALATIVE (SEDEX) ORE DEPOSITS: NEW EVIDENCE FROM THE FRANKLIN, NJ MINING DISTRICT

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William H. Peck, Department of Geology, Colgate University, Hamilton, NY

Ryan Mathur, Department of Geology, Juniata College, Huntingdon, PA

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We report $\delta^{66}\text{Zn}$ for the high temperature metamorphic zinc oxide and silicate minerals franklinite (Fr) ($\text{Zn}^{2+}\text{Fe}^{3+}_2\text{O}_4$), zincite (Zc) (ZnO) and willemite (Wlm) (Zn_2SiO_4) from the Franklin, NJ, historic mining district. With reference to the JMC-Lyon standard, $\delta^{66}\text{Zn}$ franklinite ranges from -0.10 to 0.48‰ with an average of $0.20 \pm 0.17\text{‰}$ ($n=22$). $\delta^{66}\text{Zn}$ willemite ranges from 0.23 to 0.48‰ with an average of $0.37 \pm 0.09\text{‰}$ ($n=7$). $\delta^{66}\text{Zn}$ zincite ranges from 0.29 to .060‰ with an average of $0.47 \pm 0.12\text{‰}$ ($n=9$). These data suggest that the analyzed phases fractionate heavy zinc in the order $\text{Fr} < \text{Wlm} < \text{Zc}$. Taken as a group, these minerals have an average $\delta^{66}\text{Zn}$ of $0.30 \pm 0.19\text{‰}$. This is 0.16‰ heavier than an estimated global mean $\delta^{66}\text{Zn}$ for sphalerite (ZnS) of $0.14 \pm 0.16\text{‰}$ for seafloor zinc deposits. Our results are consistent with fractionation factors that predict that Zn oxides and silicates (protoliths of these ores) should be isotopically heavier than sphalerite when precipitated from fluids of the same temperature with similar zinc isotope compositions. Our samples from Sterling Hill are taken from two short transects across the orebody. Calcite (Cal) (CaCO_3) from the same samples has $\delta^{13}\text{C}$ from -0.54 to 1.46 with an average of $0.79 \pm 0.51\text{‰}$ (VPDB), while $\delta^{18}\text{O}$ ranges from 9.72 to 15.12 with an average of $12.42 \pm 1.35\text{‰}$ (VSMOW; $n=30$). Results for these two isotope systems are consistent with earlier studies. $\delta^{13}\text{C}$ decreases smoothly with distance towards the west along both transects; $\delta^{18}\text{O}$ in contrast stays very close to its mean on the longer, southern transect but increases with distance to the west along the shorter, northern transect. There is no apparent covariation between $\delta^{66}\text{Zn}$ and either of the other isotopic ratios measured.

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Chapter 1. The Sterling and Franklin Zinc Mines: The Case for Partial Melting, and the Legacy of Robert Metsger.

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ABSTRACT

The Sterling and Franklin zinc mines are located in the Proterozoic terrain of the New Jersey Highlands. On the basis of published whole-rock chemical and oxygen isotope data, the most likely marine protolith of carbonate, clay, and oxyhydroxide minerals for the zinc ore equilibrated at a temperature of 150 +/- 50°C. This temperature is consistent with a sulfur-poor zinc assemblage precipitated directly from a metal-transporting fluid, presumably through hydrothermal vents. The protolith carbonate sediments have been metamorphosed at granulite facies temperatures and pressures into a franklinite - and willemite - enriched marble during the Ottawan phase of the Grenville Orogeny. Research published by Robert Metsger has proposed that the zinc ore has undergone partial melting. His evidence includes the occurrence of exposures of the contact between graphitic white Franklin marble and the zinc - enriched marble ore body that closely resemble sharp igneous contacts. Fusion of the calcite component of high-grade franklinite-willemite layers of ore appears to have disaggregated the ore where it collapsed into adjacent bands of carbonate melt forming very common (0.5 to 2 cm) clusters of medium- grained (1 to 3 mm) franklinite and willemite frozen into coarse-grained (1 to 3 cm) calcite marble.

Within some of the high-grade ore the relationship between the ore and gangue resembles rounded (0.5 to 5 m) enclaves of ore cumulate dropped into a calcite melt. The geologic cause of the proposed melting of the ore is ambiguous and may have been the result of anatexis during granulite facies metamorphism. However, if the graphite-free marble ore is post-orogenic as some textural evidence suggests, it may have been melted due to its proximity to the intrusion of the Mount Eve Granite. The published levels of measured $\delta^{13}\text{C}$ and $\delta^{13}\text{O}$ isotopic data pertaining to the Franklin Marble and related zinc ore are almost unchanged from levels consistent with initial deposition in a marine environment near hydrothermal vents. Any melting might be expected to be accompanied by a shift of these isotopic levels due to decarbonation. However, the heated hydrothermal fluids emanating from the Mount Eve Granite may have been buffered by reactions with marble from a distal source before intermingling with any melt. Therefore, the principal role of the Mount Eve Granite was as a heat source that triggered local melting of marble fluxed with high levels of fluorine that were mixed with the zinc ore as observed by Metsger.

INTRODUCTION

The Sterling and Franklin zinc mines (fig. 1) were both operated by the New Jersey Zinc Company and are located in the Proterozoic terrain of the New Jersey Highlands. The Sterling Mine is located in the Borough of Ogdensburg, New Jersey and the Franklin Mine is located 4 km to the north in the town of Franklin. In 1986 the Sterling Mine ceased operation; the Franklin Mine stopped production in 1954. The Precambrian rocks of figure 1 are part of a fold that has become a horst in fault contact with members of the Kittatinny Supergroup of lower Ordovician and Cambrian age (Drake and others, 1996). The Precambrian formations of figure 1 from oldest to youngest are the Franklin Marble, the Cork Hill Gneiss, the Wildcat Marble and the Hornblende Granite (also known as the Byram Granite portion of the Vernon Intrusive Suite, figure 2).

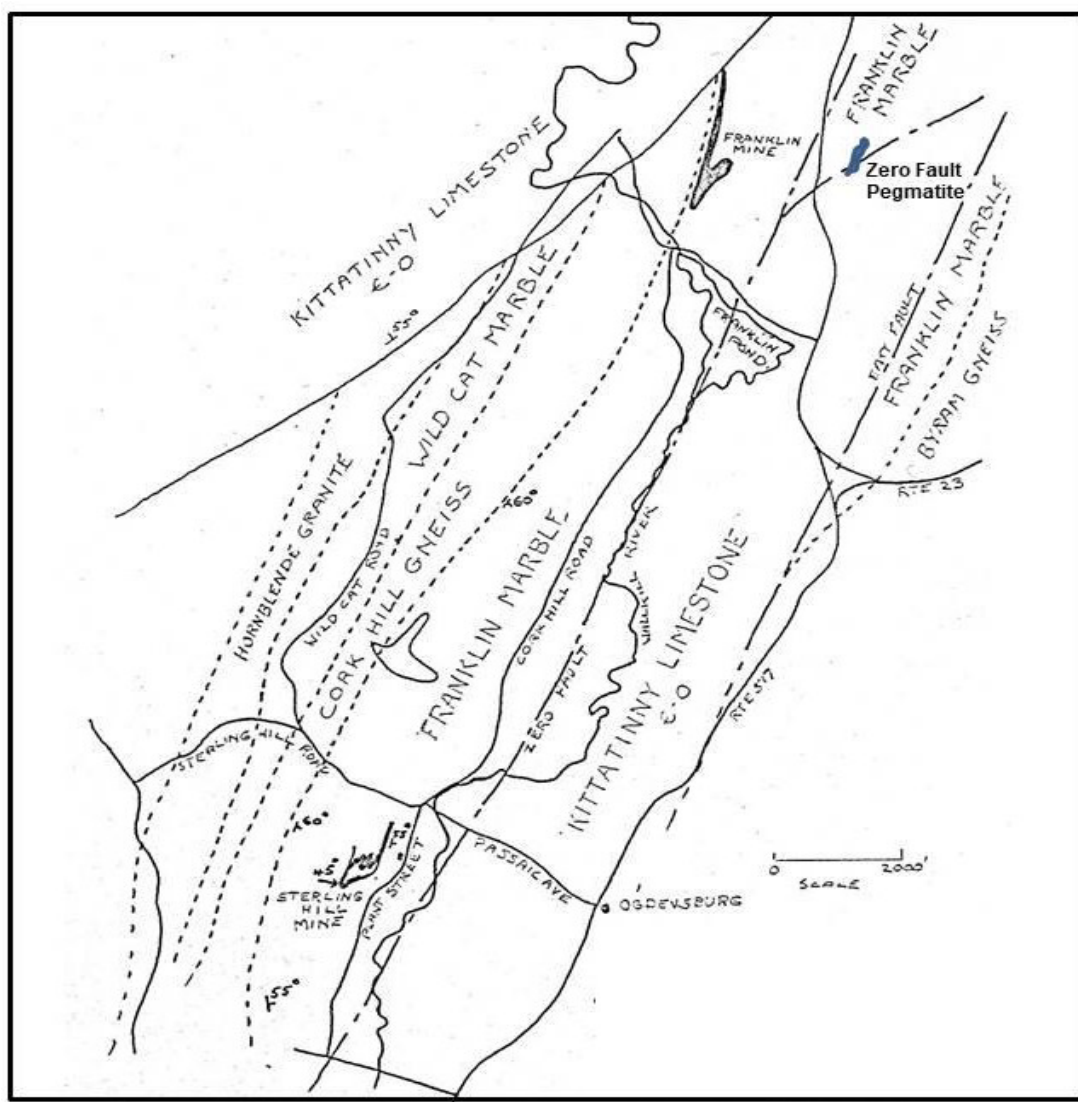


Figure 1. Sketch map of the Franklin and Sterling zinc mines after Baker and Buddington (1970) as modified by Metsger (1981).

The Franklin Marble, the Cork Hill Gneiss, and the Wildcat Band of the Franklin Marble are part of a sequence of metasedimentary and metavolcanic rocks deposited unconformably on the calc-alkaline, arc related metavolcanoclastic, dacitic, tonalitic and trondhjemitic rocks of the Losee Suite (Puffer and Volkert (1991) about 1299 until 1240 Ma (fig. 2). These rocks were then intruded by the Byram Granite (Hornblende granite of fig. 1) and the Lake Hopatcong Granite of the Vernon Intrusive Suite dated at 1188 to 1182 Ma just before the peak of the granulite facies metamorphism of the Grenville Orogeny (fig. 2). Finally, post-orogenic pegmatites and related Mount Eve Granite intruded the Franklin Marble and other rocks of the New Jersey Highlands about 1019 Ma (fig. 2).

DEPOSITION OF THE ZINC-ORE PROTOLITH

There is good evidence that the Franklin / Sterling Hill ore was originally deposited as a manganese-and zinc-enriched argillaceous marine carbonate sediment. Johnson and Skinner (2003) proposed a model in which the sediments of the Franklin and Sterling Hill zinc deposits formed along the western edge of a Middle Proterozoic marine basin where zinc was transported by sulfate-stable brines.

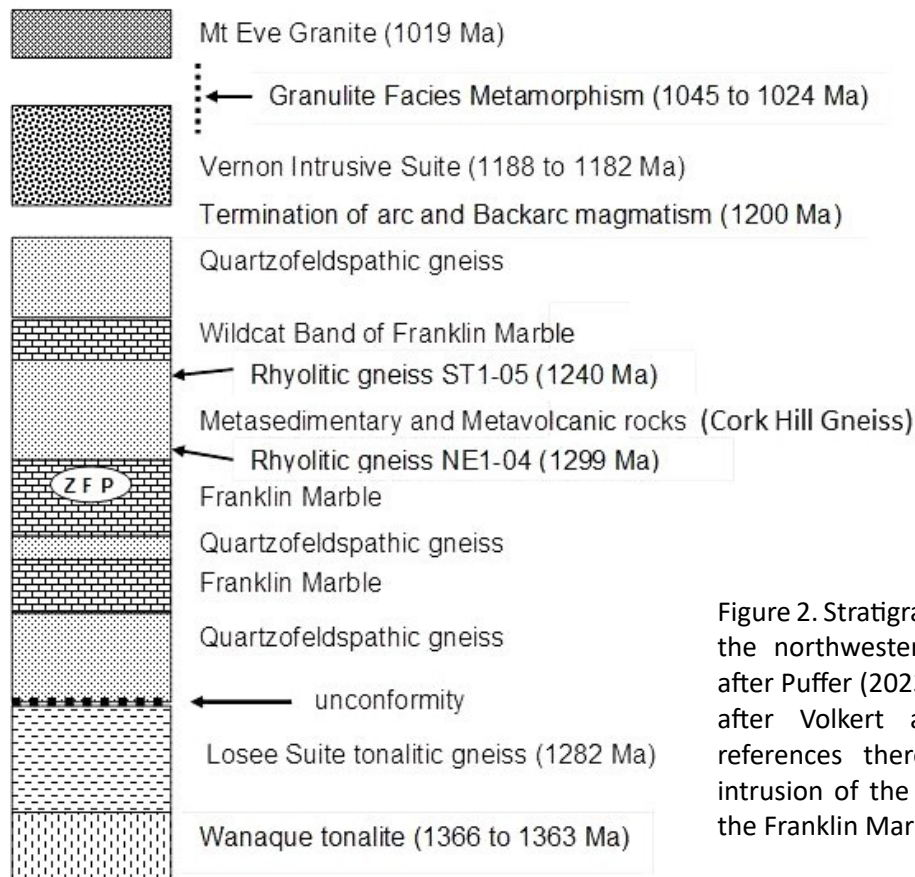


Figure 2. Stratigraphy of Proterozoic units of the northwestern New Jersey Highlands after Puffer (2023). Age determinations are after Volkert and others (2010) and references therein. ZFP symbolizes the intrusion of the Zero Fault Pegmatite into the Franklin Marble (Puffer, 2023).

Johnson (2001) has shown that the Franklin zinc ores formed under conditions more oxidizing and less sulfurizing than conditions typical of marine limestones. This would result in the local oxidation of any organic material and might explain the absence of graphite in the ores and its presence in marble outside the ore zone. It might also explain the lack of sulfur in the zinc ore due to oxidization of any reduced sulfur to soluble sulfate ions. The mineralogy of the ores at the Sterling and Franklin zinc mines is listed in table 1. There is considerable variation among ore types ranging from black franklinite-enriched, brown willemite-enriched, and white calcite-enriched types. The type represented by figure 3 is a common pepper-and-salt type composed of clusters of franklinite + willemite + zincite disseminated in calcite. The mineralogy of the Franklin Mine is about the same (table 1), although the willemite is typically green.

Johnson (2001) explains the high oxidation state / low sulfidation state of the zinc ores by proposing that the protolith formed on the seafloor in shallow, well irrigated sediments where

Table 1. Composition of ore (wt. %) from Sterling Hill in 1935 and Franklin in 1930-1934, after Frondel and Baum (1974) and Bostwick (2016).

	Franklin	Sterling Hill
Franklinite	41	31.8
Willemite	23.8	18.5
Zincite	0.07	2.8
Tephroite	0.6	1.6
Rhodonite	1.6	0.8
Garnet	2.5	0.01
Hendricksite	0.2	0.05
Pyroxene	0.2	0.7
Hardystonite	0.3	<0.3
Gahnite	<0.1	0.1
Friedelite	<0.03	0.03
Calcite	20.7	39.4
Fluorite*	>tr	>tr
Sulfides (mostly sphalerite)	<1.5	1.5
Feldspar and miscellaneous	7.5	2.7

* Fluorite contents of Franklin and Sterling Hill ores are described by Bostwick (2016) as "relatively common if not abundant" and by Frondel and Baum (1974) as an occurrence of the primary ores and veins.

the redox conditions were controlled by oxygenated seawater. Johnson (2001) points out that the characteristics of the Sterling zinc ore are shared by most large global sediment-hosted submarine exhalative (sed-ex) Pb-Zn deposits described by Large (1980). However, the Franklin and Sterling Hill ores are unique among this class of deposits because of the extremely high Zn/Pb ratio, the near absence of sphalerite and pyrite, and the high degree of regional metamorphism.

Johnson (1997) and Johnson and others (1990) showed that, on the basis of whole-rock chemical and oxygen isotope data, the carbonate, clay, and oxyhydroxide minerals of the ore protolith precipitated at a temperature of 150 +/- 50° C. This temperature is higher than expected for seawater weathering of a pre-existing massive sulfide body but is consistent with a sulfur-poor zinc

assemblage precipitated directly from a metal-transporting fluid, presumably a hydrothermal vent. The low silicon content of the zinc ore suggests that the fluid was also low in silica and that the ore was precipitated as carbonate (smithsonite, ZnCO_3) and/or hydrozincite $\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$. Alwan and Williams (1979) have shown that hydrozincite is very stable in seawater environments and is the probable dominant zinc phase of the protolith. Isotopic and chemical data (Johnson and others, 1990) indicate that the ore-forming fluid at Sterling Hill had a $\delta^{18}\text{O}$ value of 2 +/- 4 per mil consistent with a seawater origin and possible $\delta^{18}\text{O}$ enrichment by exchange with rocks along a hydrothermal path.

The interpretations of Johnson and others (1990) are consistent with more recent analyses by Peck and others (2009), who conclude that the Franklin Marble protolith reflects "water-rock interaction between the marble protolith and a mixture of igneous fluids and seawater". They also suggest that the heat source that drove the hydrothermal system was the underplating of the back-arc tectonic setting by mafic magma. However, Aleinikoff and Volkert (2007) maintain that the data of Johnson and others (1990) do not reflect significant changes due to subsequent metamorphism that will be discussed later.

Johnson and Skinner (2003) proposed that the protolith of the zinc ore of Franklin and Sterling Hill resembles the current sediments precipitated near the hydrothermal vents of the Red Sea. The zinc contained in the sediments beneath the Atlantis 11 Deep is estimated at 1.8 million tons (Nawab, 1984) which is similar to the production of 2.2 million tons of zinc recovered at Sterling Hill (Metsger, 2001).

Callahan (1966) was the first to propose that the Sterling Hill and Franklin ores were deposited in brine pools similar to those at the bottom of the Red Sea rift basin such as those

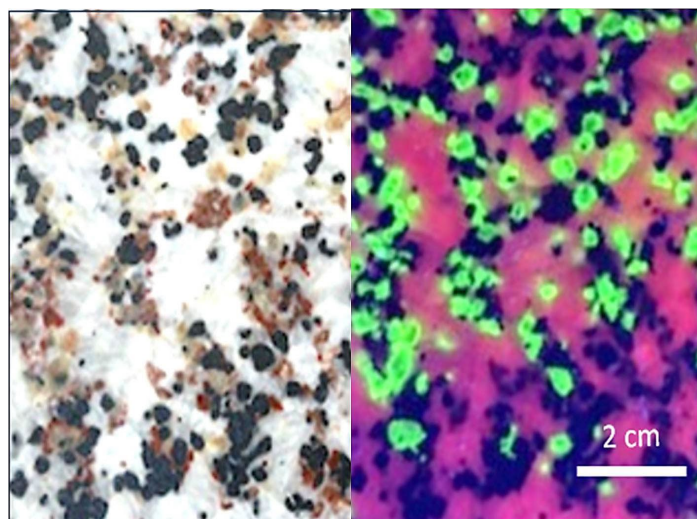


Figure 3. Slab of zinc ore from the Passaic Pit of the Sterling Mine. (Left) Under white light, calcite is white and light gray; willemite is very pale tan, reddish tan, and yellow; franklinite is black; zincite is dark red. Note that the willemite and franklinite are not evenly distributed but are concentrated in small 1 to 2 cm clusters interpreted as xenoliths. (Right) Under ultraviolet light, calcite is violet, red and orange; willemite is green; zincite and franklinite are black.

later described by Pautot and others (1984). X-ray diffraction data indicates that the benthic Red Sea oozes consist of calcite + dolomite + quartz + kaolinite + plagioclase + illite + pyrite and some amorphous material. The zinc content measures 0.3 to 0.6 % as is common in mineralized deeps.

The sediment collected by Pautot and others (1984) was located directly over volcanic basement extruded out of active rifts. Hamed and others (2007) found that the Red Sea sediment zinc fraction consists of carbonates, oxides, organic bound compounds and an amorphous residual form. The MnO content of the Red Sea sediment was measured at only 0.04 to 0.05% but must have been considerably higher in the basin containing the Franklin and Sterling Hill protolith. Glasby (1972) studied the manganese mineralogy from several marine environments and found that manganite, $\text{MnO}(\text{OH})$, is clearly the most widespread and dominant of the manganese phases, particularly in shallow-water, continental-margin environments. We are, therefore, left with calcite and several hydrous phases of varying high-temperature stability as the sedimentary protolith for the subsequent metamorphic development of the zinc ore (table 2).

METAMORPHISM OF THE SEDIMENTARY ZINC-ORE PROTOLITH

Johnson and others (1990) have shown that the zinc carbonate phases of the protolith broke down during Grenville metamorphism to develop the willemite +/- franklinite +/- zincite assemblages that are observed today (table 2). Except for the metamorphic recrystallization of the calcite, each of the metamorphic reactions was a dehydration reaction that released considerable water, an important flux involved in subsequent proposed melting. The metamorphic rocks of the Cork Hill Gneiss and other gneisses and schists that underlie the Franklin Marble are highly foliated and layered upper almandine-amphibolite facies rocks that transition into granulite facies rocks and represent deep katazone continental crustal rocks (Baker and Buddington, 1970; Sims, 1953). The highest of the four subfacies of almandine-amphibolite

Table 2. The principal mineral content of the sedimentary protolith (Begin) compared with the mineralogy of the ore deposit (Final).

<u>Begin</u>		<u>Intermediate</u>		<u>Final</u>
Hydrothermal	→ High T/P Metamorphism	Metamorphic	→ Partial Melt	Igneous
Calcite - CaCO_3		Calcite	→ melt	Calcite
Manganite - $\text{MnO}(\text{OH})$		Willemite - Zn_2SiO_4	→	Willemite
Limonite - $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$		Franklinite - ZnFe_2O_4	→ melt(?)	Franklinite
Hydrozincite - $\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$		Zincite - ZnO	→ melt	Zincite
Smithsonite - ZnCO_2		+ CO_2 + H_2O		
Quartz and clays				

regional metamorphic facies is the sillimanite-almandine-orthoclase subfacies. Turner and Verhoogen (1960) conclude that metamorphism in the almandine-amphibolite facies covers a temperature range of 550 to 750° C and pressures between 4 and 8 kb. Somewhere near the upper end of this range probably best represents the gneisses of the New Jersey Highlands. Volkert and others (2010) have calculated a peak metamorphic temperature of 720 +/-40°C for the New Jersey Highlands which involved considerable anatectic partial melting resulting in the widespread pre-orogenic pegmatites and the granites of the Vernon Intrusive Suite (fig. 2).

Metamorphic reactions that occurred in this deep lower-crustal environment include:

1. Muscovite + quartz --> sillimanite + orthoclase + water
2. Hornblende --> pyroxene + water
3. Biotite --> almandine + orthoclase + hypersthene + water.
4. Biotite --> magnetite + orthoclase + water.

Each of these reactions is a dehydration reaction that releases water. Metamorphism of the protolith of the zinc ores (table 2) would have also released considerable water. For examples:

Limonite + zincite --> franklinite + water

Hydrozincite + quartz --> willemite + water + CO₂

The Franklin Marble is a dolomite marble, locally a calcite marble. It commonly contains enough graphite, phlogopite, or other silicates to display foliation. However, the marble of the zinc ore is a calcite marble that is not foliated and may have undergone partial melting.

MELTING OF THE ZINC ORE

There are three lines of evidence supporting the hypothesis that most of the high-grade ore of the Franklin and Sterling Hill mines underwent fusion. The first line is based on textural and structural observations made by Metsger (1962, 1979, 1980, 1981, 1997, 2001), Metsger and others (1958, 1969, 2001), and Metsger (personal communication). The second line is based on recent advancements in our understanding of the metamorphic history of the deposit and experimental geochemistry pertaining to the melting of calcite. The third line of evidence has not yet (July 2025) been applied to the ore bodies but is a potentially important set of ideas recently developed by Dr. Robert Martin and his colleagues based on microtextural observations.

1. Textural and structural evidence

The contact between the ore-zone marble and the typical Franklin Marble -- Metsger (1981) has carefully observed that the shape of the Franklin and Sterling Hill ore bodies strongly suggests a "huge flow fold in the marble" (fig. 4). Metsger (1980, 1981, 2001) has noted that the marble of

the ore zones differs in several ways from non-ore Franklin marble. Calcite associated with the ore is uniformly mangiferous, typically containing about 2.5% Mn. The manganese content causes a characteristic brown color that develops on exposed surfaces, that darkens to black after a few years. This allows observation of a sharp contact with non-ore marble (fig. 5).

The ore grade marble is also free of disseminated graphite that is a characteristic of the non-ore marble. Exposures of the contact between graphitic white marble and the marble ore body closely resemble sharp igneous contacts that are in this case are typically discordant to the banding of the host rock. In addition, the marble outside the ore zone is characterized by distinctive conformable graphite-phlogopite-chondrodite-pyrrhotite banding in contrast to the largely massive coarse-grained marble of the ore. The marble outside the ore zone contains only 0.15 wt. percent FeO_t, 0.01 wt. percent MnO (sample FM1, Puffer, 2023) and 11 ppm Zn (sample FM1, unpublished) in contrast to the zinc ore averaging 25 wt. percent FeO_t, 10 wt. percent MnO and 31 wt. percent ZnO (Palache, 1937). Another major difference that will be discussed in a later section is the fact that the oxygen and carbon isotopic composition of the ore zone is distinctively different than the marble from outside the ore zone. We, therefore have two distinct rocks: an ore zone that may have melted and an exterior marble that probably didn't.

Xenoliths" of amphibolite and gneiss?

- Lithic fragments resembling xenoliths are commonly found in marbles that may or may not have undergone fusion. Such structures are also commonly found in the typical foliated graphite-bearing Franklin Marble, but their origin is ambiguous, including those found in the graphitic marble that constitutes the core of the ore body around which the ore is

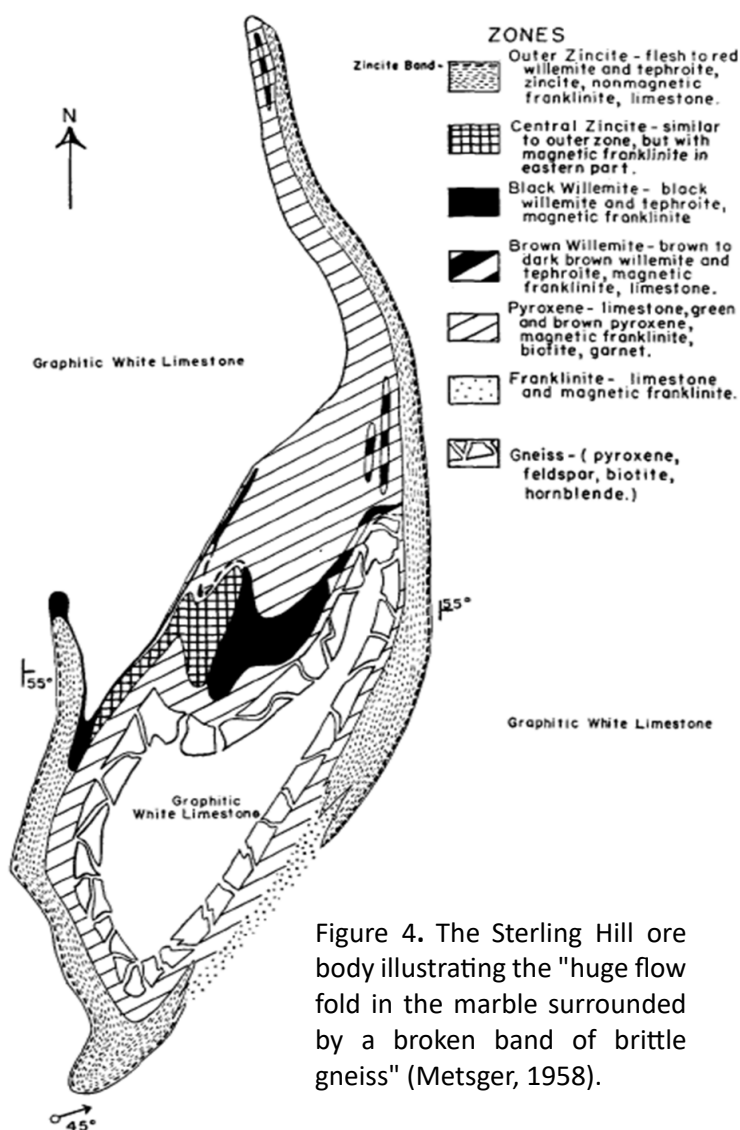


Figure 4. The Sterling Hill ore body illustrating the "huge flow fold in the marble surrounded by a broken band of brittle gneiss" (Metsger, 1958).

wrapped (figs. 4 and 5). However, Metsger (1981, 2001) has observed structures that he has interpreted as xenoliths within the marble of the ore zone that appear much more convincing. The graphitic marble core is lined with a "band, as much as six meters thick, of biotite, pyroxene, gahnite, garnet, and magnetic franklinite disseminated in graphite-free fluorescent marble" consisting of "a broken band of brittle gneiss fragments" engulfed in marble (figs. 6 and 7). In addition, there are broken blocks of brittle gneiss at the Sterling mine that are engulfed in willemite-enriched marble (fig. 8). The willemite occurs as disseminated grains that appear to have been carried by molten calcite. The density of the willemite is relatively high (3.9 to 4.1) and

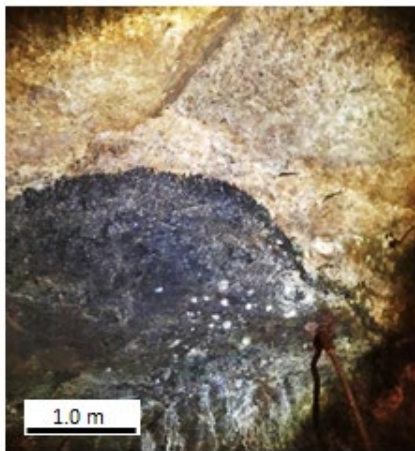


Figure 5. Dark gray manganiferous Sterling Hill zinc ore in contact with white Franklin marble. Note the coarse-grained calcite reaction rim lining the zinc ore. Photograph taken underground within about 30 m from the eastern entrance to the Sterling Hill Mine.



Figure 6. The southern surface exposure of the Sterling Hill Passaic pit illustrating the ore zones of figure 4 beginning with the "white limestone" at the center surrounded by the "brecciated gneiss"; "pyroxene limestone"; and "brown and black willemite" zones.

would quickly sink into a low-viscosity carbonate melt. A pure calciocarbonatitic melt such as the one proposed here has a very low viscosity (Martin et al., 2024). Figure 8 provides strong evidence for melting. Another example of a gneissic "xenolith" is illustrated by figure 9 that compares closely to figure 7.

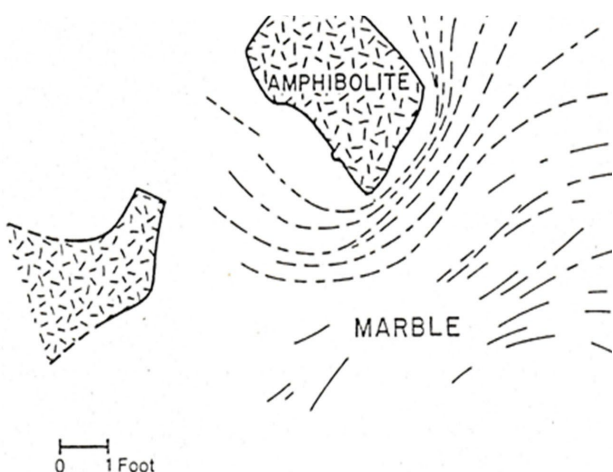


Figure 7. "Xenoliths" of amphibolite contained within the white marble at Sterling Hill, after Metsger (1980, 1981).

Marble dikes - Structures described as "marble dikes" were observed by Metsger (1980, 1981, 2001), that appear to be intruding into xenoliths (fig. 10).

Galena Vein - A vein of galena and calcite was observed "intruding" (Metsger, 1981) into a fracture in a marble dike (fig. 11). The galena was dated at 1100×10^6 years (Metsger, 1980; 1981) although details of the presumably radiometric dating have not been published.

Disaggregation of xenoliths of willemite-franklinite ore – Metsger (1980) has identified several local bands or layers of various ore types across the Franklin and Sterling Hill

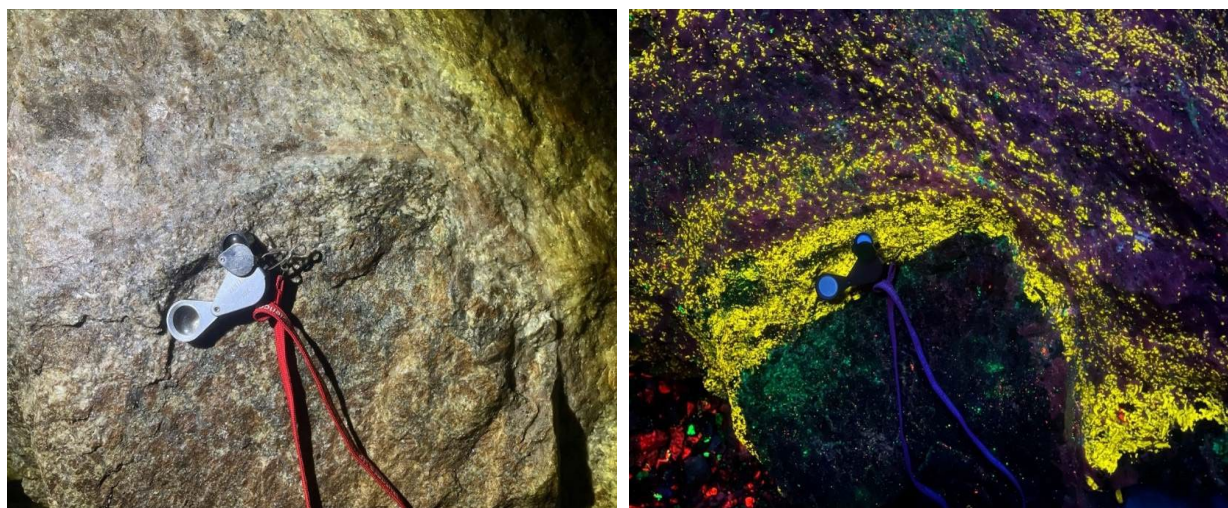


Figure 8. Block "xenolith" of granitic gneiss below hand-lens. The same block photographed in ultraviolet light exposing "igneous" flow structure around the block consisting of willemite (yellow grains) interpreted as carried by molten calcite (dark blue). The orientation of the xenolith during the proposed melting event is unknown but apparently the relatively dense willemite grains carried by flowing calcite melt sunk by gravity and accumulated on top of the block and at the base but not much on the sides. Photographs were taken by Michel Di Maio at the Sterling zinc mine.

mineralization that are consistent with the stratiform interpretations of Johnson (1990, 1997). In particular, steeply dipping layers of willemite-franklinite ore in contact with coarse-grained graphite-free marble have been mapped as in figure 6. Friable masses of willemite-franklinite ore have been disaggregated by what Metsger (1980, 1981, and 2001) has interpreted as "extremely plastic or, in part, even fluid carbonate" (fig. 12). This would explain the transition from the massive black willemite-franklinite ore to the disseminated "pepper and salt" willemite, franklinite and calcite ore of the Sterling Hill mine (figs. 3, 12 and 13).



Figure 9. A black rectangular amphibolite "xenolith" surrounded by marble, some of which appears to have flowed into the space between the xenolith and a black mass of franklinite at the lower right corner. The orientation of the "xenolith" is unknown. The diameter of the flashlight-illuminated circle is about one meter. Compare the photograph to Figures 7 and 8. The photograph was taken by Mike Di Maio on the ceiling of the Landmesser Tunnel at the Sterling Zinc mine.

The disaggregation depicted in figures 12 and 13 is not consistent with any sedimentary, metamorphic, or hydrothermal process but is consistent with igneous activity. There is no evidence of penetrating metamorphic shearing, or retrograde or secondary hydrothermal mineralization along fault or joint planes seen in the zinc ore of figure 3. Instead, it appears that the carbonate content of the willemite-franklinite ore underwent fusion and loss of cohesion as it became engulfed by a molten surrounding carbonate melt (figs. 8, 9, 12 and 13). Calcite is at least a minor component of each of the ore types (Metsger 2001) and acts as a cement that holds the rock together. If the calcite melted, most of the ore would fall apart and disaggregate into a low viscosity carbonate melt with clusters of various sizes consisting of relatively refractory franklinite, willemite, and zincite.

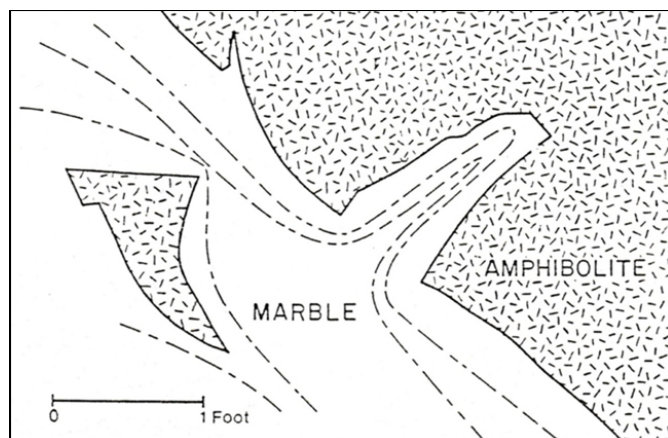


Figure 10. Marble dike formed when "mobile carbonates flowed into fissures" (Metsger, 1980, 1981, 2002)

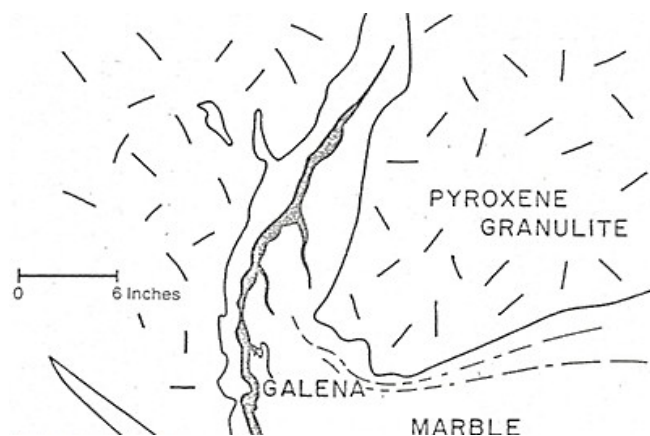


Figure 11. A vein of galena occupying a fracture in a dike of marble that "flowed into fissures" in the granulite (Metsger 1980, 1981).

These clusters, or xenoliths, are very commonly found throughout both zinc mines. Some of the larger fragments, or xenoliths, measure over a meter across while the smaller clusters are typically about 1 cm across with equally common xenocrysts of franklinite and willemite typically 1 to 3 mm across that are embedded in a coarse-grained (1 to 3 cm) marble host (figs. 3, 12, 13, and 14).

A sketch near the base of the Franklin mine with a focus at the 900 to 1000' level (fig. 15) was made by Frondel and Baum (1974). There is an absence of any structures resembling bedding, metamorphic folding, or layering. Instead, the relationships among the ore types and gangue resembles rounded enclaves of cumulates or autoliths dropped into a fluid composed of calcite. Metsger and others (1969) and Metsger (2001) suggested that the relatively dense orebody was folded during pressure-temperature conditions high enough to "plasticize or perhaps, even melt the enclosing carbonate through which it sank." The franklinite appears to have accumulated at the base

of an inverted diapir as a cumulate resembling the chromite cumulates at the Great Dike of intrusion of East Greenland. (Turner and Verhoogen, 1960).

Igneous textures - Additional evidence of melting is provided by Metsger (2001) where he observed that the manganiferous marble of the ore deposit is extremely coarse grained compared to the typical Franklin marble. Where the marble of the ore deposit is low-grade, with sparse franklinite and intergranular mica, very large, rounded, oval-shaped calcite crystals 20 to 50 cm in diameter are mixed with the fine-grained ore. The resulting texture resembles rounded phenocrysts of feldspar in fine-grained felsite porphyry but at a larger scale. Where the ore-to-calcite ratio is higher, the calcite is much finer grained, about 2.5 cm in diameter, and the calcite

occupies intergranular spaces between otherwise massive ore minerals. Metsger (2001) specifically asked "Can this be evidence that some of the marble crystallized from a melt?"

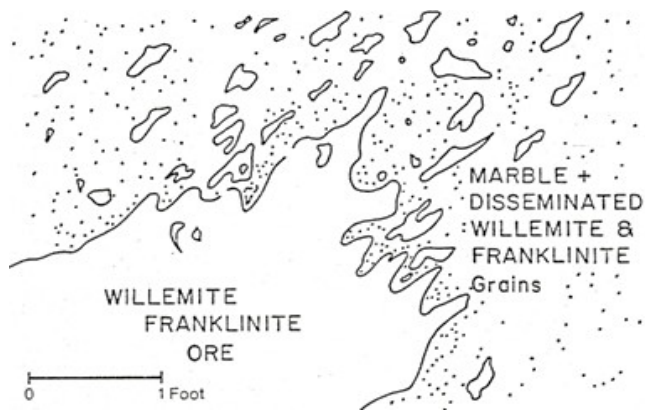


Figure 12. Willemite franklinite ore disaggregated within "extremely plastic or fluid carbonate" after Metsger (1980, 1981, and 2001). The black dots represent xenocrysts of franklinite and willemite. The small blebs represent clusters of franklinite and willemite grains.

Compelling evidence of the melting of Sterling Hill zinc ore is also provided by a photograph of an intergrowth of willemite (green) and calcite (red) under shortwave UV light (fig. 16). The quenching of a melt where the passive phase, in this case calcite, specimen is about 10 cm in

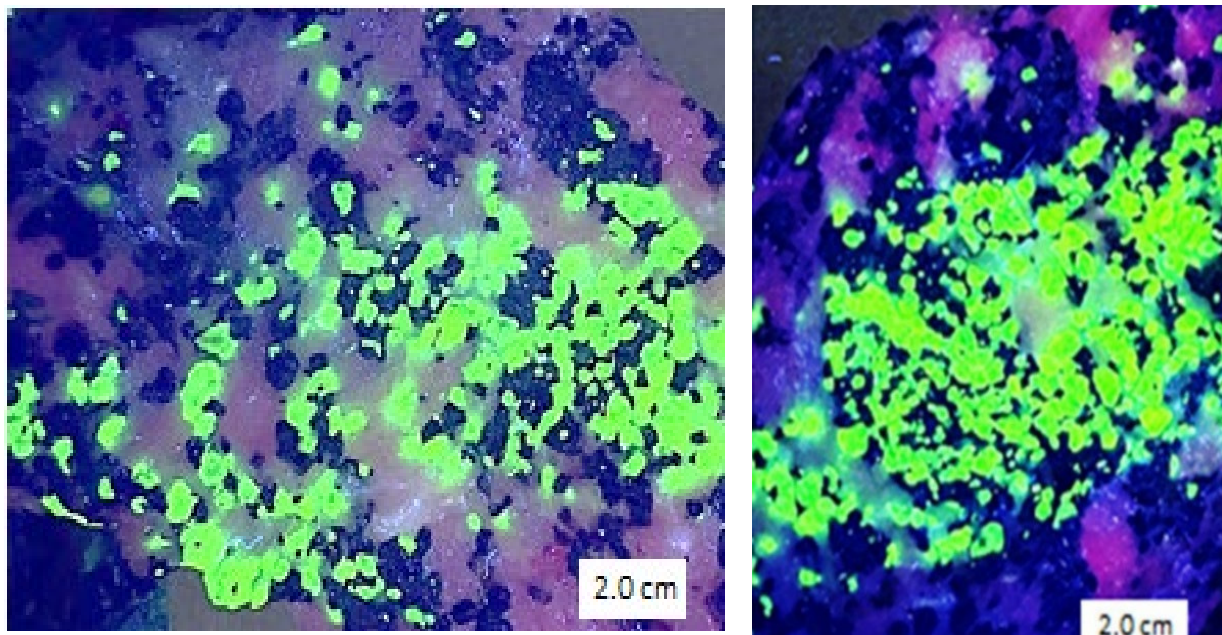


Figure 13. Close-up photographs of willemite and franklinite ore (bright green - black) disaggregating into coarse-grained (2 cm) marble host (dark blue and violet). Figure 3 represents a more advanced stage.

length and was photographed by Earl Verbeek. The straight edge of the willemite crystal (fig. 16) is interpreted by Robert Martin (personal communication, 2025) as part of a skeletal crystal and evidence that the two minerals were growing together from a melt and mutually interfering with



Figure 14. Steeply dipping layers (2.5 m thick) of coarse-grained, graphite-free marble (red) and willemite – franklinite ore (green) on the right have been converted into shapeless blobs of willemite – franklinite ore in a matrix of fused carbonate on the left. Photo is modified after Barberia (2016).

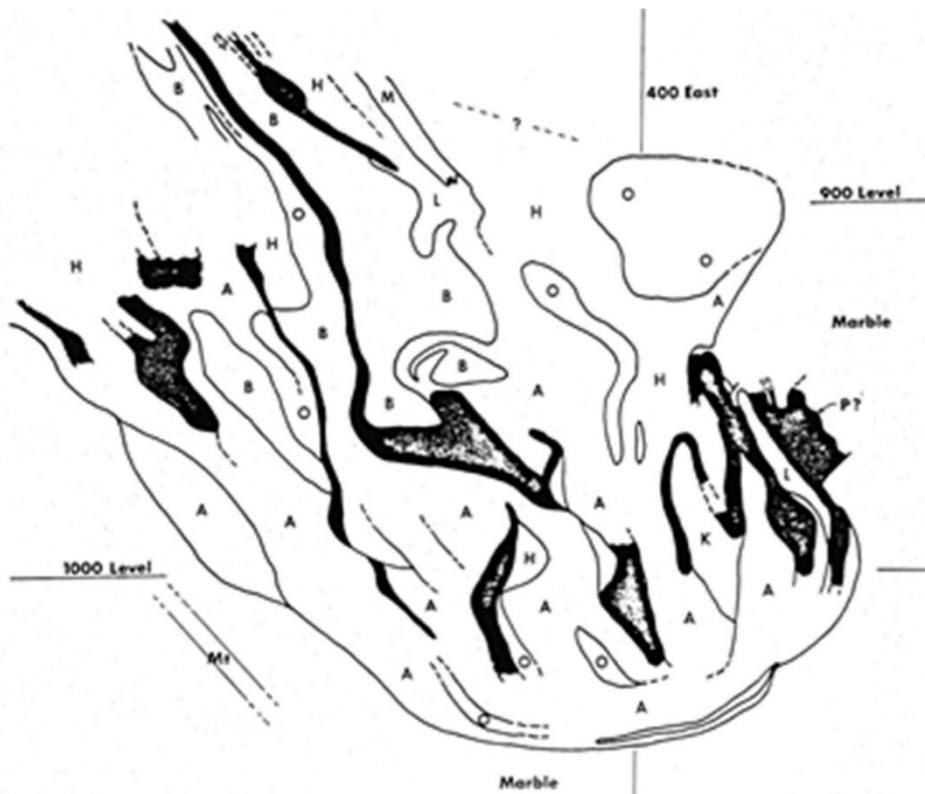


Figure 15. Cross section near the keel area of the Franklin ore deposit showing "crumpled structure" after Frondel and Baum (1974). A = franklinite, willemite, calcite; B = franklinite, willemite, zincite; H = calcite franklinite, willemite; K = franklinite with sparse calcite; L = massive calcite; M = calcite; O = massive franklinite and willemite. This deep level contains the highest-grade ore. Note the paucity of calcite gangue (L and M) trapped in spaces between high grade ore.

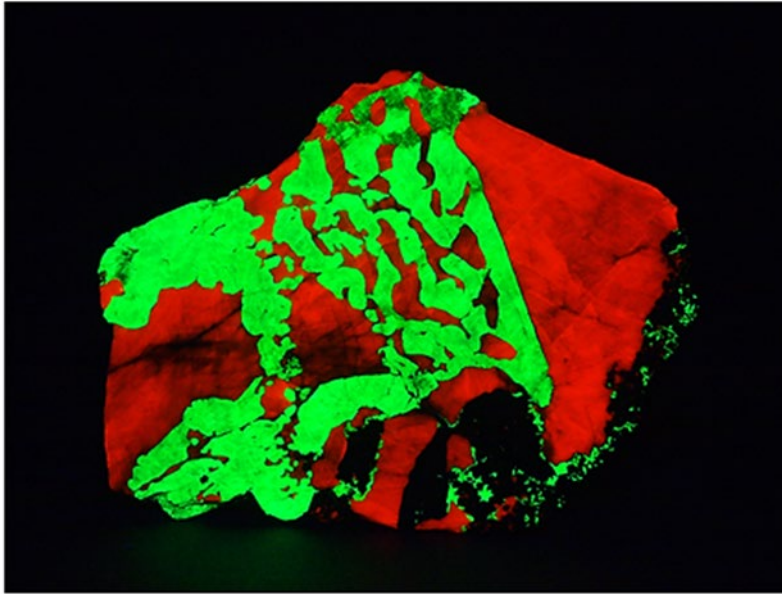


Figure 16. Intergrowth of willemite (green) and calcite (red) under shortwave UV light. The specimen is Sterling Hill ore about 10 cm in length, Earl Verbeek photo.

each other. The graphic texture of quartz and potassium feldspar intergrowths commonly found in pegmatites (Puffer 2023) is another example of rapid simultaneous crystallization of two minerals occupying the same space. Skeletal texture is a reliable characteristic of very rapid crystallization, or quenching of a melt where the passive phase, in this case calcite, does not have enough time to completely drain from the structurally dominant phase (willemite) and is trapped in the crystal lattice.

Metsger (1981) concluded that "the marble became extremely plastic or, perhaps, fluid" and that the complex configuration of the ore body "was produced by its movement downward through a viscous marble at the peak of sillimanite grade metamorphism". Although Metsger did not explicitly suggest anatectic melting, the inference is clear enough to consider.

2. Metamorphic considerations: Did Anatectic Melting Occur during Granulite Facies Metamorphism?

An important dehydration reaction involving the metamorphic breakdown of biotite to form magnetite and orthoclase feldspar was simulated experimentally by Wones and Eugster (1965) over a wide range of temperatures and oxygen pressures:



This geothermometer and water geobarometer was used by Puffer (1970, 1975, 1980, 2001) and Puffer and Gorrington (2005) to explain the common occurrence of magnetite in pegmatites associated with prograde Grenville metamorphism, such as the Edison magnetite mines located east of the Sterling mine in Ogdensburg.

There is no need for additional water to flux the reaction; it is simply driven by prograde, increasing metamorphic temperatures and pressures. There is no need for hydrous input transmitted through fault or shear systems, as commonly proposed. Faulting would most likely follow peak metamorphic pressures and temperatures in retrograde environments. Faulting is associated with pressure drops and can only destroy pegmatite development or diminish the conditions necessary for their development. In addition, retrograde reactions occurring along shear zones tend to absorb iron and precipitate secondary ferruginous minerals such as limonite, chlorite, and epidote.

The magnetite-bearing pegmatites common throughout the New Jersey Highlands were studied by Baker and Buddington (1970) and sampled and analyzed by Puffer (1970, 1975, 1997); Lindburg and Puffer (2004); and Puffer and others (1993). Magnetite-bearing pegmatites typically associated with biotite, microcline and/or amphiboles were found to be an integral part of several of the magnetite ore deposits throughout the New Jersey Highlands. Co-existing ilmenite or ilmeno-hematite is typically found in small quantities accompanying magnetite in most igneous rocks, making it possible for chemical analyses of these mineral pairs to be applied to the Buddington and Lindsley (1964) magnetite/ilmenite geothermometer. Puffer (1970, 1975, and 1997) chemically analyzed several samples from New Jersey Iron mines, particularly the Edison mine and determined the following data (table 3).

The temperature range of 706 to 748° C for the metamorphic equilibration of the magnetite ore is within the range of the 720° C +/- 40° C estimate made by Volkert and others (2010) for the peak metamorphism for the Ottawan phase of the Grenville Orogeny on the basis of a variety of temperature estimates. In particular, the minimum peak temperature of 760° C attained during regional metamorphism at the Sterling mine based on experimentally determined zinc oxide phase diagrams (Carvalho and Sclar, 1988) and the average temperature of 769° C of metamorphism associated with the Ottawan phase of the Grenville Orogeny in the New Jersey Highlands based on fractionations between calcite and graphite for analyzed Franklin Marble samples (Peck and others, 2006) are at the high end of the Volkert and others (2010) temperature range but are completely consistent with local anatexis melting. Peck and others (2006) also report calcite-graphite temperatures of 818° and 789° C for two samples of Franklin marble from the Trotter dump at Franklin and a 779° C average for two samples from the Buckwheat open cut at the Franklin deposit. Two samples of Franklin marble collected about 300 m away from the Sterling Hill deposit average 789° C. These are temperatures consistent with a deep katazonal crustal granulite facies environments and the "ubiquitous presence of migmatites" particularly in the quartzofeldspathic lithologies (Peck and others, 2006) including the Cork Hill Gneiss adjacent to the Franklin marble. In addition, a similar temperature range and metamorphic conditions were experienced by the Balmat zinc orebodies of the Northwest Adirondacks, New York that resulted in "localized anatexis" producing "polymetallic sulfide melts" (Matt and others, 2019).

Table 3. Co-existing oxide pairs from the Edison mine area. Temperature and oxygen fugacities are based on the Buddington and Lindsley (1964) magnetite-ilmenite geothermometer. Magnetite ore samples analyses are from Baker and Buddington (1970); microcline gneiss and pegmatite analyses from Puffer (1975).

Ore sample 145			Ore sample 149			Ore sample 154		
	ilmeno-mag	ilmeno-hem	ilmeno-mag	ilmeno-hem		ilmeno-mag	ilmeno-hem	
Fe ₂ O ₃	70.23	56.61	68.49	46.59		63.26	29.1	
FeO	21.77	2.83	25.27	16.32		26.45	12.79	
TiO ₂	1.01	16.16	0.88	23.67		1.39	30.63	
Temp C°	748		717			706		
log fO ₂	-11.46		-12.13			-13.33		

Microcline gneiss			Pegmatite		
	ilmeno-mag	hemo-ilmenite	ilmeno-mag	ilmeno-hem	
Fe ₂ O ₃	53.72	6.44	70.31	60.43	
FeO	31.06	41.45	26.57	14.25	
TiO ₂	2.8	40.44	0.7	20.29	
Temp C°	732		707		
log fO ₂	-13.67		-12.11		

In addition to the implied local anatexic melting of the Franklin Marble ore (Metsger, 1981), there are several other examples of crustal anatexic melting of marble. Su and others (2024) have described "pegmatitic" carbonate rocks composed of very coarse-grained (1 to 15 cm) calcite plus phlogopite, apatite, clinopyroxene, and olivine intruded into Proterozoic high-temperature granulites and marbles in Sri Lanka. The pegmatitic carbonates do not show any indication of metamorphic textures but instead display igneous textures and contain silicate xenoliths similar to those described by Metsger (1981). Su and others (2024) interpret the pegmatitic carbonate structures as anatexic carbonate pegmatites and suggest that they originated from the anatexic melting of the silicate and marble host rocks at deep crustal levels during high-temperature granulite-facies metamorphism.

Su and others (2024) list seventeen additional occurrences of crustal-derived "carbonatites". Each of the occurrences of marble fusion are found in orogenic belts and most commonly are found in high-grade metamorphic gneiss and marble terrains and show carbon and oxygen isotopic signatures typical of crustal sources. Su and others (2024) list four genetic mechanisms for these occurrences:

1. Metasedimentary carbonate rock intruded by felsic granites that can produce carbonate melts in conjunction with skarn assemblages;

2. Intrusion of high-temperature magmas (mafic magmas or A-type granites) that can supply sufficient heat to melt carbonate rock and generate buoyant carbonate melts;
3. Partial melting of carbonate rock due to intense regional metamorphism (anatexis) as also proposed by Liu and others (2006) and Wang and others (2024); and
4. Partial melting of marble triggered by crustal thickening (orogenesis); upwelling asthenosphere into thinned lithosphere; basaltic underplating; and rapid ductile shearing. They apply the third mechanism above (anatexis) to the carbonate melting at Sri Lanka. Anatexis is also consistent with the granulite-facies metamorphism that was going on during the Grenville Orogeny and may apply to the Franklin zinc ores for the reasons described above.

However, the Sterling Hill zinc ore does not seem to have been deformed due to metamorphism (figs. 8, 15, and 16), and unlike the foliated Vernon Magmatic Suite it appears to have formed in a post-orogenic environment at temperatures even higher than granulite-facies temperatures. The foliation of Franklin marble on the basis of the oriented graphite and phlogopite is not observed in the ore zone. Instead, the banding of the marble in the ore zone may be interpreted as igneous flow banding. It therefore may be prudent to consider alternatives to anatexis that were identified by Su and others (2024), particularly mechanisms 1) skarn development and 2) melting due to high temperature A-type granite intrusion. Before considering these alternative melting mechanisms, there are some interesting isotopic data to consider.

Carbon and Oxygen Isotopic Considerations

Johnson (1990) used an oxygen isotopic and chemical mass balance model applied to the Sterling Hill zinc ore to derive a temperature of deposition of 150 +/- 50°C. To avoid confusion, it should be noted that isotopic ratios of limestones are locked in at initial depositional conditions and are not necessarily changed by subsequent metamorphism or even melting. The initial ratio of heavy vs light isotopes is controlled by environmental conditions sensitive to minor variations in isotopic weight. However, isotopic ratios initially set by sedimentary depositional conditions can be modified by prograde metasomatism, contact metasomatism, late-stage low temperature retrograde metasomatism, hydrothermal alteration, or weathering. Hydrothermal alteration has the potential to change initial values depending on the source of the fluids and the temperature of alteration.

Altered carbonate rocks, particularly those affected by igneous activity, isotopically display a trend toward lighter $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values compared to limestones. There are two ways to interpret the downward shift in the $\delta^{18}\text{C}$ values and the decrease in $\delta^{18}\text{O}$ experienced by skarn carbonates (fig. 17). Typically, skarn carbonates with measured stable isotopic values that are

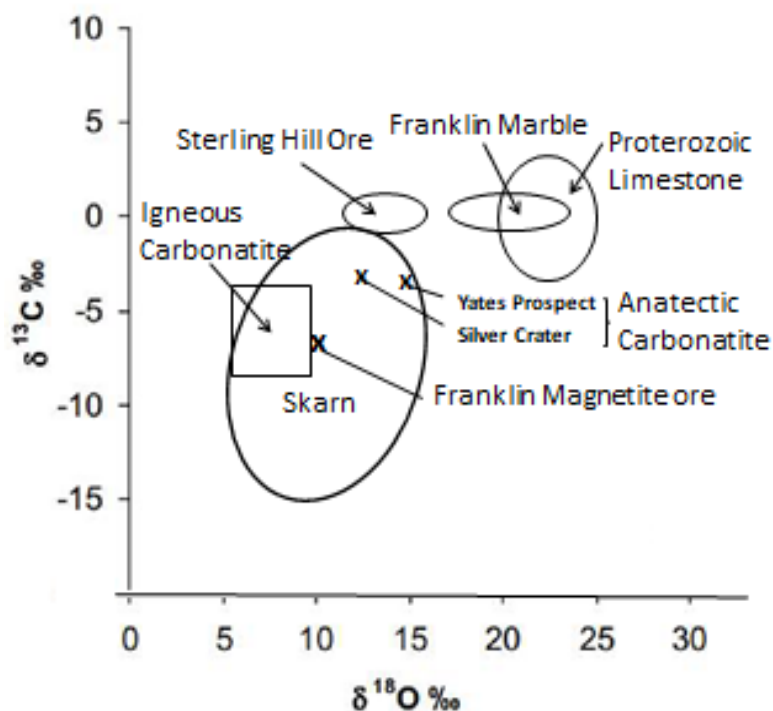


Figure 17. Plot of $\delta^{13}\text{C}$ PDB (Vienna Pee Dee Belemnite) and $\delta^{18}\text{O}$ VSMO (Vienna Standard Mean Ocean Water). The field representing the range for Proterozoic Limestone at 1.25 Ga is after Marais and others (1992) carbon data; and Jaffres and others (2007) oxygen data converted from PDB data. The isotopic ranges of The Furnace Bed (Franklin magnetite Ore) are after Johnson (1997) and the range of the Franklin Marble is after Johnson (1997) and Peck and others, (2006); the field of Sterling Hill Ore is after Matt and others (2022); the field of typical Skarn is after Bowman and others (1985); Shimazaki and others (1986); Du and others (2017) and Edraki and others (2025); the field of igneous carbonatites is after Valley (1986); the Yates prospect is after Schumann and others. (2019); the Silver Crater mine is after Emproto and others (2020).

considerably reduced from sedimentary levels are interpreted (Meinert and others, 2005; Edraki and others, 2025; Valley, 1986; Zaw and Singoyi, 2000) as having been replaced or metasomatized by fluids derived from a mantle-derived magmatic source or a granite source to a degree depending on the type of granite (I, S, or A). An alternative interpretation (Lentz, 1999; Lui and others, 2006; Wang and others, 2024; Xu and others, 2023; Floess and others, 2015) is where limestones or metasedimentary marbles that have undergone partial melting are recognized as having experienced decarbonation reactions that preferentially remove heavy isotopes through the loss of CO_2 . A third mechanism, high pressure metamorphism, can also remove heavy isotopes due to any loss of CO_2 , although the maximum decrease in $\delta^{18}\text{O}$ due

to regional metamorphism is typically limited to only 2% (Taylor, 1987).

Matt and others (2022) measured $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic values of calcite in zinc ore from the Sterling Mine from samples taken along two short transects across the orebody. Their results indicate $\delta^{13}\text{C}$ in a range from -0.19 to 1.46 with an average of $0.79 \pm 0.51\%$ ($n=30$), while $\delta^{18}\text{O}$ ranges from 11.61 to 15.12 with an average of $12.42 \pm 1.35\%$ ($n=30$) (fig. 17).

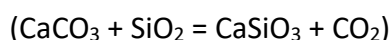
Johnson (1997) found that the Franklin Marble host rock at Sterling Hill has uniform $\delta^{18}\text{O}$ values in a tight range of 18 to 22 and a $\delta^{13}\text{C}$ range of 0.0 to 1.0 (fig. 17). These data indicate that

the Sterling Hill zinc ore plots within a range that transitions into the upper limit of the skarn field of figure 17 after Bowman and others (1985); Shimazaki and others (1986), Du and others (2017), and Edraki and others (2025).

Was the Franklin Marble Zinc Ore Subjected to Skarn Melting?

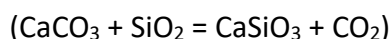
Skarn deposits are typically interpreted as hydrothermal or "pneumatolytic" (Meinert and others, 2005). Most low-temperature (<700°C), water-saturated calcite melting experiments yield fluids that span the transition between hydrothermal and igneous processes. Pegmatites are typically interpreted as the product of igneous melts but are also the product of very low-viscosity fluids that in certain cases could be interpreted as hydrothermal. A recent paper by Xu and others (2023) addresses this ambiguity and points out that during hydrothermal skarn formation an aqueous fluid from igneous intrusions supplies the silica to the carbonate wall rock to generate calc-silicate skarn minerals as:

1) Limestone (marble) + aqueous silica = skarn + aqueous CO₂



In contrast, igneous petrologists may interpret assimilation of a carbonate by an igneous intrusion which undergoes depletion of SiO₂ through a process such as:

2) Limestone (marble) + silicate melt = reaction rim + CO₂ vapor



However, the hydrothermal interpretation (reaction 1) must comply with severe quantitative restrictions. For example, the amount of aqueous fluid released by an igneous intrusion is limited by the solubility of water in the magma (about 8 wt. % in granitic magma) and the solubility of silica in the aqueous fluid (about 1 wt. %), (Philpotts and Ague, 2009). Therefore, only about 0.1% of the total SiO₂ of the intrusion is accessible for the reaction and the 1:1 exchange of aqueous SiO₂ for CO₂. The CO₂ could only be dissolved gradually as a dilute solute in the aqueous fluid. Instead, the chief constraints on reaction 2 are the melting point of the limestone and heat content of the intrusion. If melting occurs, the reaction can proceed efficiently because silicate melts typically contain about 50 to 70 % SiO₂.

Recently, some skarns are being reinterpreted as "magmatic skarn"; evidence of melting is being found; and the importance of volatile fluxes (particularly chloride, fluoride, and phosphate) is emphasized (Lentz, 1999; Floess and others, 2015; Durand and others, 2015; Martin and others. 2023; Martin and others. 2024). Floess and others (2015) have shown that enough experimental data has been published and applied to Schreinemaker analyses to predict formation of calcite-rich melts between 650-880° C. These temperatures are in agreement with their observations of partial melting of carbonates intruded by the Western Adamello Tonalite

(Northern Italy). Durand and others (2015) re-investigated the system $\text{CaCO}_3\text{-H}_2\text{O}$ to explore whether calcite-rich melts can be produced under shallow crustal conditions. Their experiments confirm the presence of melt at temperatures close to 650°C despite very low degrees of partial melting. This temperature is about 60°C lower than that reported by Wyllie and Tuttle (1960). The difference is due in part to technical improvements allowing a better rapid quench and a new method for sample observations. Durand and others (2015) also observed that many skarn mineral assemblages are enriched in fluorides and phosphates which are consistent with the important role that such fluxes play.

Lentz (1999) has shown that the formation of a carbonate melt from a skarn system would produce a whole spectrum of heavy to light isotopic signatures similar to that found in the carbonate vein systems commonly associated with skarns (Shimazaki and others, 1986). Variables include the extent of decarbonization reactions and fluid exchange. In carbonatites, variables include Rayleigh crystal fractionation and mixing with low-temperature hydrothermal and/or meteoric water (Deines, 1989; Lentz, 1999). However, in contrast to most skarn systems, the Sterling Hill and Franklin ore deposits formed under a much higher confining pressure that may have greatly restricted the release of CO_2 , resulting in minimal decarbonization. In addition, there is no evidence of systematic alteration of the Sterling Hill or Franklin ore due to low-temperature hydrothermal alteration or weathering, with only localized exceptions.

Potential Melting Trigger

As summarized above by Su and others (2024), two of the mechanisms responsible for occurrences of marble fusion are 1) Metasedimentary carbonate rock intruded by felsic granites that can produce carbonate melts in conjunction with skarn assemblages; and 2) Intrusion of high-temperature magmas (mafic magmas or A-type granites) that can supply sufficient heat to melt carbonate rock.

Post-orogenic decompressional melting of A-type granite (Mount Eve granite) was occurring at 1019 Ma during the end stages of the granulite-facies metamorphism associated with the Ottawan stage of the Grenville Orogeny (fig. 2). Intrusion of Mount Eve granite was mapped by Drake and others (1996) about 15 km northeast of the Franklin zinc mine. Some of the Mount Eve Granite has intruded into the Franklin Marble and at a few locations has quenched into pegmatites characterized by graphic granite. One such pegmatite from a Mount Eve Granite source intruded the Franklin Marble about 1 km northeast of the Franklin zinc mine and was quickly quenched into a large pegmatite composed exclusively of graphic granite (Puffer, 2023). This pegmatite was displaced by the Zero Fault and is exposed as a large (35 x 120 m), lens-shaped pegmatite, commonly referred to as the “Zero Fault Pegmatite” (fig. 1). Puffer (2023) provides considerable geochemical evidence indicating that the pegmatite was derived from the intrusion of Mount Eve Granite into the Franklin Marble. In addition to the Zero Fault Pegmatite, several

lenses of graphic granite of probably similar origin occur at the Braen Stone of Franklin quarry and at the Braen Stone of Sparta quarry, formerly known as the Lime Crest quarry (Puffer, 2023). One of the graphic granite pegmatites at the Braen Stone of Sparta quarry, described by King (1987), is 70 m long, ~7 m wide, and is well exposed along the southwest wall of the quarry. Therefore, although there is no Mount Eve Granite exposed within the boundaries of the Franklin or Sterling zinc mines, there is good evidence that it has intruded the Franklin Marble near the mines.

The remote (15 km) involvement of the Mount Eve Granite is consistent with zinc-skarn ore deposits in general. Meinert and others (2005) summarized the characteristics of more than 1700 skarn deposits in 35 countries. They subdivided the skarns into several groups including the various metal ores including Fe, Au, Cu, Zn, W, Mo, and Sn. One characteristic of zinc-skarn ore deposits is that they are not closely associated with their igneous counterparts and a magmatic source cannot be identified for some deposits. Zinc skarns are also characteristically enriched in Mn and Fe mineralogy. Both of these characteristics of zinc skarns apply to the zinc ore deposits of the Franklin Marble. This author is not suggesting that the Franklin/Sterling Hill zinc deposits are skarns; however, these examples demonstrate that remote associations with magmatic sources can profoundly influence and perhaps even locally melt distal reactive rocks.

The intrusion of the Mount Eve Granite and associated pegmatites may have served as a heat source for the partial melting of the Franklin zinc ore and simultaneously may have provided a water source to help flux the melting. The failure of $\delta^{13}\text{C}$ to shift to lower values (fig. 17) may be due to the buffering effect of the surrounding marble. This explanation was proposed by Nabelek and Morgan (2012) when they measured unshifted $\delta^{13}\text{C}$ values in calcite marbles near the contact of an intrusion at Eureka Valley, California.

In addition to water, there is evidence that fluorine was available as a flux. Fluorine is a particularly potent flux and has been proposed by London (1996) as the principal fluxing agent responsible for the development of most of Earth's largest zoned gem-bearing pegmatites. It is well documented that the presence of fluorine lowers the solidus of the system (Gittins and Tuttle, 1964). Martin and Schumann (2022) have presented compelling microtextural evidence for melting of a fluoro- calciocarbonatite at the Dwyer Mine, Wilberforce, Ontario, Canada. Fluorite is described by Bostwick (2016) as "relatively common, if not abundant in both orebodies" (the Franklin and Sterling Hill mines) and as grains and masses in multiple assemblages. Fluorite is also described by Verbeek and Grout (2018) as "common" in the lining of a swarm of faults within the graphitic marble of the Sterling Mine. Probably the best evidence that melting occurred at the Sterling zinc mine is the band of fluorite mapped by Metsger (1981) at the outer contact between the ore and the non-ore marble.

Lentz (1999) has shown that the volatile fluxing required for the melting of skarn systems, (HF, HCL, H₃PO₄) if present in any intrusion exsolving these volatiles into carbonates at appropriate pressures should produce some carbonate melt. Fluorite has not been observed in the Mount Eve Granite. Instead, the source of fluorine was probably the marine sediments near the hydrothermal vents of the initial depositional environment. The experimental results of Seyfried and Ding (1995) indicate that in seawater at temperatures greater than about 150°C, but less than or equal to 250°C, fluorine precipitates with magnesite and magnesium-hydroxide-sulfate-hydrate. At temperatures greater than 250°C, F-rich minerals dissolve. In addition, any phosphorus in the seawater will precipitate as fluorapatite (Kendrick, 2018) which is also present at Franklin and Sterling Hill. The 150 to 250°C temperature range of Seyfried and Ding (1995) is within the 150 ± 50°C temperature range proposed by Johnson and others (1990) for the precipitation of the zinc-enriched sediments of the zinc ore protolith and is consistent with the abundant fluorite mineralization found there.

3. Microtextural Evidence

The third line of evidence pertains to microtextural observations. This line of evidence has not yet been applied to the Sterling Hill ore as of today (July 2025), although there are hopeful indications that Robert Martin of McGill University and some of his colleagues may develop a project related to the Sterling Hill ore. Martin and others. (2023) pointed out that any proposal that marble has melted must generally rely on a confluence of subtle textural indicators. For example, Martin and others. (2019) have studied the Otter Lake, Quebec apatite mine, that all serious mineral collectors are aware of, and found good evidence for a magmatic origin for the apatite-bearing carbonate body. His evidence includes the occurrence of millimetric globules of orange calcite seen in polished sections of apatite that are similar to the matrix calcite. They interpret the globules to have been inclusions trapped in the apatite phenocrysts during growth. Degassing then occurred and the melt froze quickly. This interpretation is a departure from the previous skarn interpretation.

Unlike Otter Lake, most of the minerals contained within the Sterling Hill ore marble are here interpreted as xenocrysts, or solid, metamorphic-derived phases (principally franklinite and willemite) that were incorporated into a carbonate melt. Therefore, it is conceivable that calcite may be the only igneous phase at the Sterling and Franklin mines, but it is more likely that a search for igneous phenocrysts or quench phases will be successful if the marble is actually igneous.

Although it is unlikely that franklinite and willemite crystallized during the cooling of the marble (carbonate) melt, some textural evidence indicates that some of the franklinite grains may have melted. It was pointed out by Dr. James Brown (personal communication) that about one third of the 1-4 mm grains of franklinite in samples of the pepper-and-salt type of ore (fig. 3) appear as spherical blebs (fig. 18). This is in contrast to most franklinite grains that are either

euohedral (fig. 18) or have retained some of their flat crystalline surfaces. If any grains melted, it is likely that they would become rounded immiscible blebs as depicted in figure 17, although this interpretation is pure speculation and the melting-point of franklinite in a high- pressure fluorine enriched carbonate flux has not been determined. Willemite grains surrounded by calcite do not display similar common rounding although a few large spherical grains have been observed on the figure 3 slab. Interestingly, most zincite grains appear to have been pushed into interstices between calcite grain boundaries and appear as triangular shapes at triple junctions similar to the appearance of quartz grains in granite.

Most published mineral exsolution studies of the Sterling / Franklin ore do not pertain directly to evidence of melting but do include studies of exsolution textures that imply cooling from elevated, possibly igneous temperatures, and an absence of any tectonic deformation following the development of these very delicate textures. Palanche and others. (1944) proposed a continuous solid-solution series between franklinite and magnetite that was later confirmed by Ramdohr (1980), Valentino and Sclar (1982), Valentino and others. (1990) and Sclar and Leonard (1992). However, Sclar and Leonard determined experimentally that the consolute temperature (top) of the miscibility gap between the two end members was only 500°C or less. Carvalho and Sclar (1988) studied franklinite-gahnite exsolution textures from Sterling Hill samples and experimentally determined the consolute temperature of a miscibility gap at 957°C. Their integration of the Sterling Hill samples with their experimentally determined miscibility gap indicated a minimum peak temperature at Sterling Hill of 760°C, but evidence of melting was not provided. Valentino, and others. (1990) studied franklinite-magnetite-pyrophanite intergrowths in samples from the Sterling Hill zinc deposit and found pyrophanite lamellae they interpreted as analogous to the oxidation exsolution lamellae of ilmenite in titanomagnetite but at temperatures less than 500°C.



Figure 18. Franklinite grains from the slab of Sterling Hill ore depicted in figure 3. The spherical grain (left) appears to be a 2.3 mm droplet or globule of franklinite dripping off of a larger grain of franklinite. In contrast, most grains of franklinite are euohedral (right). Photos were taken with an I-Phone 16 camera using a magnification application that facilitates optical scanning of large unpolished surfaces.

Another microtextural approach is quite high-tech. Martin and others. (2023) and Martin and Schumann (2025) have examined several carbonatites from Quebec interpreted as anatectic utilizing high-resolution ZEISS Atlas 5 large-area imaging equipment in combination with detailed energy-dispersive spectroscopic analyses to assemble digital map-like online datasets of entire samples to display their textures and characteristics. They have described in detail the texture and mineralogy of several marble specimens on the basis of their large-area imaging results. If this new level of research is applied to the Sterling and Franklin deposits it may lead to exciting advancements in our understanding of franklinite/willemite ore genesis.

CONCLUSIONS

The first line of evidence supporting the hypothesis that the Franklin/Sterling Hill zinc ore underwent partial melting is based largely on observations made by Metsger (1962, 1980, 1981, 2001), Metsger and others (1969) and Metsger (personal communication):

Exposures of the contact between graphitic white marble and the marble ore body closely resemble sharp igneous contacts. The marble outside the ore zone is characterized by distinctive, conformable, graphite-phlogopite-chondrodite banding in contrast to the largely massive, graphite-free, manganese-enriched, coarse-grained marble of the ore.

1. The marine, stratiform, zinc-enriched carbonate protolith of the Franklin and Sterling Hill zinc mines has experienced granulite-facies metamorphism and recrystallization into layers or bands of ore composed of varying amounts of franklinite, willemite, and calcite. Even the highest-grade bands of franklinite and willemite contain at least minor amounts of calcite. Where the temperature of the ore bands locally exceeded the melting point of the calcite, fusion of the calcite appears to have disaggregated the ore where it collapsed into adjacent bands of low-viscosity carbonate melt.
2. The resulting assemblage of ore types includes black or brown layers, breccia, slabs or blocks composed of franklinite and willemite grains cemented with calcite that are veined with calcite. The larger blocks appear to display relic bedding and metamorphic foliation. Locally, these black and brown blocks have partially or completely disaggregated into underlying or adjacent molten carbonate, resulting in calcite-enriched ore containing clusters composed of willemite and franklinite plus disseminated grains of willemite and franklinite. The franklinite and willemite clusters are interpreted as xenoliths and range in size from about 0.5 to 2 cm (fig. 3). The individual grains are interpreted as xenocrysts and retain the same 2 to 5 mm diameter where they comprise the layers of massive franklinite and willemite ore.

The second line of evidence that the zinc ore underwent partial melting is based on metamorphic considerations and related experimental geochemistry and stable isotopic data:

1. Recently published experimental research confirms the presence of carbonate melts at temperatures close to 650°C in crustal environments despite low degrees of partial melting.
2. Previously published $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic values of calcite in zinc ore from the Sterling Mine are within a range close to the original values proposed for the deposition of the Franklin Marble protolith in a marine environment adjacent to hydrothermal venting but approach the range consistent with skarns and associated partial fusion.
3. The reason for the lack of expected additional shifting closer to the range of fusion may be due to the high confining pressures of the Franklin zinc ore, thus restricting the loss of CO_2 , together with the buffering effect of Franklin Marble during transport of fluids from a remote source. This author proposes that intrusions of Mount Eve granite were close enough to the zinc ore deposits to have acted as a heat source that could have partially melted any reactive rocks.
4. The zinc ore was particularly reactive because of its abundant fluorite content. The layer of fluorite observed by Metsger (1980) surrounding the zinc ore deposit at the Sterling Mine would have helped flux the fusion of zinc ore.

The third line of evidence supporting the melting hypothesis is based largely on microtextural methods that have not yet (July, 2025) been applied to the Franklin – Sterling ore deposits. Future research focused on these methods will, hopefully, elucidate some of the remaining questions.

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I first met Robert Metsger in 1966 while I was visiting New Jersey in search of a thesis project as a graduate student at Stanford. My thesis committee consisted of Richard Jahns (pegmatites), Charles Park (iron ore) and Frank Tuttle (granites), so I developed some ideas involving magnetite-bearing pegmatites. I sampled several magnetite-bearing pegmatite sites in California, New Jersey, New York, and Canada before settling on a project in Colorado. While sampling the Edison magnetite mine near Ogdensburg, I drove past the Sterling Mine and out of

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curiosity stopped in at Metsger's office just before his routine visit to the mine. He took me with him underground and generously let me sample the ore. Four years later I began teaching an Ore Deposits course at Rutgers-Newark and asked him if my students and I could visit the mine. Almost each year until the mine closed in 1987, Robert (Bob) would take my class underground to experience the excitement of deep-rock mining. Bob showed me several places in the mine that he interpreted as evidence of melting. The evidence was compelling and I became convinced. We became friends and would see each other at GSA conventions that we would always attend. He was very highly respected as an astute observer among the hard-rock geologists that we would see at GSA.



Robert Metsger was born in 1920, enlisted in the U.S. Navy in 1940, became a lieutenant commander, and remained in active service until 1945. He received a bachelor of arts from Columbia College in 1948 with a major in geology. He began his career with the New Jersey Zinc Company in 1949, where he shared his time between the Sterling Mine at Ogdensburg and the zinc mine at Friedensville, Pennsylvania until his retirement in 1988, and then as a consultant until 2008.

Robert Metsger was a senior fellow of the Geological Society of America until his death in 2012 and a member of several other geologic organizations, including the Geological Association of New Jersey (president, 1993-94). Robert is survived by his three children, Mary, Deborah, and Robert.

REFERENCES

- Aleinikoff, J.N., and Volkert, R.A., 2007, SHRIMP U-Pb geochronology of zircon and monazite from ca. 1.3 Ga. arc-related rocks. New Jersey Highlands: Geological Society of America Abstracts with Programs, vol. 39, no. 1, p. 37.
- Alwan, A.K., and Williams, P.A., 1979, Mineral formation from aqueous solution. Part I. The deposition of hydrozincite, $\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$, from natural waters. Transition Metal Chemistry, vol. 4, no. 2, p. 128-132.
- American Geological Institute, 1962, Dictionary of Geological Terms, Dolphin Books, Garden City, New York, 545 p.
- Baker, D.R., and Buddington, A.F., 1970, Geology and magnetite deposits of the Franklin quadrangle and part of the Hamburg quadrangle, New Jersey: a study of the rocks, structure,

- and magnetite deposits of an area in northern New Jersey, v. 638. US Government Printing Office.
- Barberia, J., 2016, A visit to The Sterling Hill Mining Museum & The Franklin Mineral Museum, URL: newjerseyisntboring.com/sterling-hill-mining-museum.
- Bostwick, R.C., 2016, Fluorescent Minerals of Franklin and Sterling Hill, N.J., Part 1. The Picking Table vol. 57, p. 10-21.
- Bowman, J. R., O'Neil, J. R., and Essene, E. J., 1985, Contact skarn formation at Elkhorn, Montana; II, Origin and evolution of COH skarn fluids. *American Journal of Science*, vol. 285, no. 7, 621-660.
- Buddington, A.F., and Lindsley, D. H., 1964, Iron-titanium oxide minerals and synthetic equivalents. *Journal of petrology*, vol. 5, no. 2, p. 310-357.
- Callahan, W.H., 1966, Genesis of the Franklin-Sterling, New Jersey, orebodies. *Economic Geology*, vol. 61, no. 6, p. 1140-1141.
- Carvalho, A.V. and Sclar, C.B., 1988. Experimental determination of the ZnFe_2O_4 - ZnAl_2O_4 miscibility gap with application to franklinite-gahnite exsolution intergrowths from the Sterling Hill zinc deposit, New Jersey. *Economic Geology*, vol. 83, no. 7, p. 1447-1452.
- Deines P., 1989, Stable isotope variations in carbonatites. *In* Carbonatites-Genesis and Evolution Bell, K., ed., p. 301-359. Cambridge University Press.
- Drake, A.A., JR., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1996, Bedrock geologic map of New Jersey. U.S. Geological Survey Miscellaneous Investigations Series Map I-2540-A, 2 sheets, scale 1:100,000.
- Du, L.J., Li, B., Huang, Z.L., Zhou, J.X., Zou, G.F. and Yan, Z.F., 2017. Carbon-oxygen isotopic geochemistry of the Yangla Cu skarn deposit, SW China: Implications for the source and evolution of hydrothermal fluids. *Ore Geology Reviews*, vol. 88, p. 809-821.
- Durand, C., Baumgartner, L.P., and Marquer, D., 2015, Low melting temperature for calcite at 1000 bars on the join CaCO_3 - H_2O —some geological implications. *Terra Nova*, vol. 27, no. 5, p. 364-369.
- Edraki, M., Somarin, A.K., and Ashley, P.M., 2025, A genetic model for the Biggenden Gold-Bearing Fe Skarn Deposit, Queensland, Australia: Geology, Mineralogy, Isotope Geochemistry and Fluid Inclusion Studies. *Minerals*, vol. 15.

Chapter 1. The Sterling and Franklin Zinc Mines: The Case for Partial Melting,
and the Legacy of Robert Metsger.

- Emproto, C., Alvarez, A., Anderkin, C., and Rakovan, J. (2020). The crystallinity of apatite in contact with metamict pyrochlore from the Silver Crater mine, ON, Canada. *Minerals*, vol. 10, no. 3, p. 244.
- Floess, D., Baumgartner, L.P., and Vonlanthen, P., 2015, An observational and thermodynamic investigation of carbonate partial melting. *Earth and Planetary Science Letters*, vol. 409, p. 147-156.
- Fronzel and Baum, 1974, Structure and mineralogy of the Franklin zinc-iron-manganese deposit, New Jersey: *Economic Geology*, vol. 69, p. 157-180.
- Glasby, G.P., 1972, The mineralogy of manganese nodules from a range of marine environments. *Marine Geology*, vol. 13, no. 1, p. 57-72.
- Gittins, J., and Tuttle, O.F. 1964, The system $\text{CaF}_2\text{-Ca(OH)}_2\text{-CaCO}_3$. *American Journal of Science*, vol. 262, no. 1, p. 66-75.
- Hamed, M.A., Lotfy, H.R. and Kandawa-Schulz, M., 2007. Chemical forms of copper, zinc, lead and cadmium in sediments of the northern part of the Red Sea, Egypt. *Pakistan Journal of Marine Science*, vol. 16, no. 2, p. 69-78.
- Jaffrés, J. B., Shields, G. A., and Wallmann, K., 2007, The oxygen isotope evolution of seawater: A critical review of a long-standing controversy and an improved geological water cycle model for the past 3.4 billion years. *Earth-Science Reviews*, vol. 83(, nos. 1-2), p. 83-122.
- Johnson, C. A., 1990, Petrology and stable isotopic studies of the metamorphosed zinc-iron-manganese deposit at Sterling Hill, New Jersey, Doctoral dissertation, Yale University.
- Johnson, C. A., 1997, Genesis of the marble-hosted zinc deposits and iron deposits at Sterling Hill and Franklin, NJ and comparisons with gneiss-hosted iron deposits at Cornwall, NY *In* Benimoff, A.I., and Puffer, J. H., editors, *The economic geology of northern New Jersey: Field Guide and Proceedings of the fourteenth annual meeting of the Geological Association of New Jersey*, p. 47- 59.
- 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, *in* Slack J.F., editor, Part 1. Proterozoic Iron and Zinc Deposits of the Adirondack Mountains of New York and the New Jersey Highlands. Society of Economic Geologists, Inc. Guidebook Series vol. 35, p. 89-97.
- Johnson, C. A., Rye, D. M., and Skinner, B. J., 1990, Petrology and stable isotope geochemistry of the metamorphosed zinc-iron-manganese deposit at Sterling Hill, New Jersey. *Economic Geology*, vol. 85, no. 6, p. 1133-1161.

- 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*, vol. 98, no. 4, p.837-854
- Kendrick, M. A., 2018, Halogens in seawater, marine sediments and the altered oceanic lithosphere,. *in* Harlov and Aranovich, editors, *The role of halogens in Terrestrial and extraterrestrial geochemical processes*, Springer Geochemistry, p. 591-648.
- King, J. J., 1987, A Field Investigation of a Select Group of New Jersey Highland Pegmatites. Master's Thesis. Rutgers University, Newark, New Jersey.
- Large, D. E., 1980, Geological parameters associated with sediment-hosted, submarine exhalative Pb-Zn deposits: An empirical model for mineral exploration: *Geologisches Jahrbuch*, vol. 40, p. 59-129.
- Lentz, D. R., 1999, Carbonatite genesis: a reexamination of the role of intrusion-related pneumatolytic skarn processes in limestone melting. *Geology*, vol. 27, no. 4, p. 335-338.
- Liu, Y., Berner, Z., Massonne, H. J., and Zhong, D., 2006, Carbonatite-like dykes from the eastern Himalayan syntaxis: geochemical, isotopic, and petrogenetic evidence for melting of metasedimentary carbonate rocks within the orogenic crust. *Journal of Asian Earth Sciences*, vol. 26, no. 1, p. 105-120.
- Lindburg, S. R. and Puffer, J. H., 2004, The Sterling Hill Zinc Mine, Ogdensburg New Jersey: in Gates, A. E., editor, 2004 NAGT-ES Conference Field Trip Guide, National Association of Geoscience Teachers, Rutgers University, Newark, NJ, p. 103-114.
- London, D., 1996, Granitic pegmatites. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, vol. 87, nos. 1-2, p. 305-319.
- Marais, D. J. D., Strauss, H., Summons, R. E., and Hayes, J. M., 1992, Carbon isotope evidence for the stepwise oxidation of the Proterozoic environment. *Nature*, vol. 359, no. 6396, p. 605-609.
- Martin, R. F. and Schumann, D., 2022, Fluorite mineralization at the Dwyer Mine, Wilberforce Area, Ontario, Canada. Microtextural indications of a fluor-calciocarbonatite. *The Canadian Mineralogist* vol. 60, 385–403.
- Martin, R. F., Schumann, D., De Fourestier, J., & Fuchs, S. 2023. Varicolored Marble in the Central Metasedimentary Belt, Grenville Supergroup. I. Circumstantial Evidence of Melting. *The Canadian Journal of Mineralogy and Petrology*, vol. 61(4), 675-731.
- Martin, R.F., Schumann, D., Kumarapeli, S., and Abdel-Rahman, A. M., 2024, The Eppawala anatectic carbonatite, Sri Lanka: a mineralogical, petrological and geochronological contribution. *Journal of the Geological Society of Sri Lanka* vol. 24-2, 13-30.

Chapter 1. The Sterling and Franklin Zinc Mines: The Case for Partial Melting,
and the Legacy of Robert Metsger.

- Martin, R. F., & Schumann, D. 2025, Varicolored Marble in the Central Metasedimentary Belt, Grenville Supergroup. II. Petrogenetic Insight from Apatite. *The Canadian Journal of Mineralogy and Petrology*, vol. 63(3), 223-247.
- Matt, P., Powell, W., deLorraine, W.F. and Chiarenzelli, J., 2019. Sulfide and silicate anatexis in the Balmat zinc deposit (New York, USA) and its implications for ore remobilization. *Ore Geology Reviews*, 107, pp.392-401.
- Matt, P., Peck, W. H., Mathur, R., Hurtgen, M. R., and Godfrey, L., 2022, Zinc isotope constraints on the formation of sedimentary exhalative (SEDEX) ore deposits: New evidence from the Franklin, NJ mining district. *Ore Geology Reviews*, 147, 104970.
- Metsger, R. W., 1962, Notes on the Sterling Hill orebody, Ogdensburg, NJ: Washington, D.C., International Mineralogical Association, 3rd General Congress, Northern Field Excursion Guidebook, p. 12-18.
- Metsger, R. W., 1979, Mining problems in a karst valley – technical and social: *Bulletin of the Association of Engineering Geologists*, vol. 16, p. 427-447.
- Metsger, R. W., 1997, The Geology and Mining of the Sterling Hill Zinc Deposit Ogdensburg, Sussex County, New Jersey, *in* Benimoff A. I., and Puffer, J. H., editors, *The Economic Geology of Northern New Jersey: Field Guide and Proceedings of the fourteenth annual meeting of the Geological Association of New Jersey*, p. 33-46.
- Metsger, R.W. 1980, The geologic setting of the Sterling Hill zinc-iron-manganese deposit. *in* Manspeizer, W. (ed.). *Field Studies of New Jersey Geology and Guide to Field Trips*, 52nd Annual Meeting of the New York State Geological Association (pp. 210-215). Newark, NJ: Rutgers Univ.
- Metsger, R.W., 1981, The Sterling Hill Zinc Deposit and the Franklin-Sterling Mineral District, The New Jersey Zinc Company. 16 pp.
- Metsger, R.W., 2001, Evolution of the Sterling Hill zinc deposit, Ogdensburg, Sussex County, New Jersey, *in* Slack, J. F., editor, Part 1. Proterozoic iron and zinc deposits of the Adirondack Mountains of New York and the New Jersey Highlands. *Society of Economic Geologists Guidebook Series*, vol. 35, p. 75-87.
- Metsger, R.W., Tennant, C.B., and Rodda, J.I., 1958, Geochemistry of the Sterling Hill and deposit, Sussex County, New Jersey: *Geological Society of America Bulletin*, vol. 69, p. 776-788.
- Metsger, R.W., Skinner, B.J., and Barton, P.B., 1969, Structural interpretation of the Sterling Hill ore body: Ogdensburg, New Jersey: *Geological Society of America Abstracts with Program*, vol. 7,

p. 150.

Metsger, R. W., Volkert, R. A., and Johnson, C. A., 2001, Field Trip Day Four: Road Log for the Sterling Hill and Franklin Zinc Mines, New Jersey. in Slack, J.F. (ed.), Part 1. Proterozoic iron and zinc deposits of the Adirondack Mountains of New York and the New Jersey Highlands. Society of Economic Geologists Guidebook Series, vol. 35, p. 75-87.

Meinert, L. D., Dipple, G. M., and Nicolescu, S., 2005, World skarn deposits. *Economic Geology*, 100th Anniversary Volume, p. 299–336.

Nabelek, P.I. and Morgan, S.S., 2012. Metamorphism and fluid flow in the contact aureole of the Eureka Valley–Joshua Flat–Beer Creek pluton, California. *Geological Society of America Bulletin* v. 124(1-2), pp.228-239.

Nawab, Z. A., 1984, Red Sea mining: a new era. *Deep Sea Research Part A. Oceanographic Research Papers*, 31(6-8), 813-822.

Palache, C., Berman, H., and Frondel, C., 1944. *Dana's system of mineralogy*, 7th ed., New York, John Wiley, 834 p.

Pautot, G., Guennoc, P., Coutelle, A., and Lyberis, N., 1984, Discovery of a large brine deep in the northern Red Sea. *Nature*, vol. 310, no. 5973, p. 133-136.

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*, vol. 104, p. 1037-1054.

Peck, W. H., Volkert, R.A., Meredith, M.T., and Rader, E.L., 2006, Calcite graphite thermometry of the Franklin Marble, New Jersey Highlands. *Journal of Geology*, vol. 114, p. 485-499.

Philpotts, A. R., and Ague, J. J., 2009, *Principles of igneous and metamorphic petrology*. Cambridge University Press.

Puffer, J. H., 1970, Exsolution in magnetite and ilmenite from granite and pegmatite: *International Metallographic Society Proceedings*, vol. 3, p. 141-150.

Puffer, J. H., 1975, Some North American iron-titanium oxide bearing pegmatites: *American Journal of Science*, vol. 275, p. 708-730.

Puffer, J. H., 1980, Iron ore deposits of the New Jersey Highlands. *Field studies of New Jersey geology and guide to field trips: New York State Geological Association Annual Meeting 52*, Rutgers University, Newark, New Jersey, p. 202-209.

Chapter 1. The Sterling and Franklin Zinc Mines: The Case for Partial Melting,
and the Legacy of Robert Metsger.

- Puffer, J. H., 1997, Genesis of the New Jersey Highlands magnetite deposits on the basis of geochemical and structural evidence, *in* Benimoff, A.I. and Puffer, J. H., editors, The Economic Geology of Northern New Jersey, Field Guide and Proceedings, Fourteenth Annual Meeting, Geological Association of New Jersey, p. 71-96.
- Puffer, J. H., 2001, Origin of five types of magnetite deposits in the New Jersey Highlands. In Proterozoic Iron and Zinc Mines of the Adirondack Mountains and New Jersey Highlands, Slack, J. F., editor, Society of Economic Geologists, Field Trip Guidebook Series 35, p. 103–110.
- Puffer, J. H., 2023, The Zero Fault Pegmatite is Associated with Marble at Franklin, New Jersey, USA. The Canadian Journal of Mineralogy and Petrology. vol. 61, p. 1-18 , DOI: 10.3749/2200030.
- Puffer, J. H. and Gorrington, M. L., 2005, The Edison magnetite deposits in the context of pre-, syn-, and post-orogenic metallogenesis in the Grenville Highlands of New Jersey, Canadian Journal of Earth Sciences, vol. 42, p. 1735-1748.
- Puffer, J. H., Pangnamamula, R. V., and Davin, M. T., 1993, Proterozoic iron deposits of the New Jersey Highlands: *in* Puffer, J. H., editor, Geologic Traverse across the Precambrian Highlands of New Jersey: Geological Association of New Jersey, Ledgewood, New Jersey, p. 56-96.
- Ramdohr, P., 1980, The ore minerals and their intergrowths, 2nd ed. Oxford Pergamon Press, v. 2, 1205 p.
- Schumann, D., Martin, R. F., Fuchs, S., & De Fourestier, J. (2019). Silicocarbonatitic melt inclusions in fluorapatite from the Yates prospect, Otter Lake, Québec: Evidence of marble anatexis in the central metasedimentary belt of the Grenville Province. The Canadian Mineralogist, vol. 57(5), 583-604.
- Sclar, C.B. and Leonard, B.F., 1992. Quantitative chemical relationships in a franklinite-magnetite exsolution intergrowth from Franklin, Sussex County, New Jersey. Economic Geology, 87(4), pp.1180-1183.
- Seyfried Jr, W. E., & Ding, K., 1995, The hydrothermal chemistry of fluoride in seawater. Geochimica et Cosmochimica Acta, vol. 59, no. 6, p. 1063-1071.
- Shimazaki, H., Shimizu, M., and Nakano, T., 1986, Carbon and oxygen isotopes of calcites from Japanese skarn deposits. Geochemical Journal, vol. 20, no. 6, p. 297-310.
- Sims, P. K., 1953, Geology of the Dover magnetite district, Morris County, New Jersey: U.S. Geological Survey Bulletin 982-G, 305 p.

- Su, B. X., Wang, S. Y., Dharmapriya, P. L., Wang, J., Malaviarachchi, S. P., Yang, K. F., and Fan, H. R., 2024, Crustal anatectic origin of the pegmatitic carbonate rocks in the Proterozoic Highland Complex, Sri Lanka. *Contributions to Mineralogy and Petrology*, vol. 179, no. 11, p. 96.
- Taylor, B. E., 1987, Stable isotope geochemistry of ore-forming fluids. Mineral. in Kyser T.K. ed. *Stable isotope geochemistry of low temperature fluids*. Assoc. Canada, Short Course Handbook, vol. 13, p. 337-445.
- Turner, F. J. and Verhoogen, J. 1960, *Igneous and Metamorphic Petrology*, Second Edition. New York: McGraw-Hill, 694 pp.
- Valentino, A. J., and Sclar, C. B., 1982. Experimental study of the magnetite (FeFe_2O_4)-franklinite (ZnFe_2O_4) solid-solution series [abs.]. *American Geophysical Union Transactions*, vol. 63, p. 470.
- Valentino, A.J., Carvalho, A.V. and Sclar, C.B., 1990. Franklinite-magnetite-pyrophanite intergrowths in the Sterling Hill zinc deposit, New Jersey. *Economic Geology*, 85(8), pp.1941-1946.
- Valley, J. W., 1986, Stable isotope geochemistry of metamorphic rocks. *Reviews in mineralogy and geochemistry*, vol. 16, no. 1, p. 445-489.
- Verbeek, E. R. and Grout, M. A., 2018, Hydrothermal mineral deposition in a rock-dominated fluid system at Sterling Hill, New Jersey. *The Picking Table*, vol. 59, no. 2, p. 15-22.
- Volkert, R. A., Aleinikoff, J. N., and Fanning, C. M., 2010, Tectonic, magmatic, and metamorphic history of the New Jersey Highlands – New insights from SHRIMP U-Pb geochronology, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, *From Rodinia to Pangea – the Lithotectonic Record of the Appalachian Region*. Geological Society of America Memoir 206, p. 307-346.
- Wang, J., Foley, S., Wang, X., Wang, C., and Liu, Y., 2024, Melting behavior of impure limestone under H₂O-poor conditions: Implications for the contribution of carbonate-rich sediments to arc magmatic carbon output. *Chemical Geology*, vol. 654, 122066.
- Wones D.R. and Eugster, H.P., 1965, Stability of Biotite: experiment, theory, and applications. *American Mineralogist* vol. 50, p. 1228-1272.
- Wyllie, P. J., and Tuttle, O. F., 1960, The system CaO-CO₂-H₂O and the origin of carbonatites. *Journal of Petrology*, vol. 1, no. 1, page 1-1.
- Xu, X., Xu, X., Szmihelsky, M., Yan, J., Xie, Q., and Steele-MacInnis, M., 2023, Melt inclusion evidence for limestone assimilation, calc-silicate melts, and “magmatic skarn”: *Geology*, vol. 51, no. 5, p. 491-495.

Chapter 1. The Sterling and Franklin Zinc Mines: The Case for Partial Melting,
and the Legacy of Robert Metsger.

Zaw, K., and Singoyi, B., 2000, Formation of magnetite-scheelite skarn mineralization at Kara, Northwestern Tasmania: evidence from mineral chemistry and stable isotopes. *Economic Geology*, vol. 95, no. 6, p. 1215-12



An old photograph of Sterling Hill circa 1875 looking West including notation of the 1) office, 2) blacksmith shop, 3) hoisting engine. The mine entrance is to the right of the blacksmith shop. The owner is wearing a top hat, third from the left in the group of four sitting in front of the office building. Photo brought to our attention by Dave Kaminski from Albanese, John, 1961, Notes on the Minerals of Franklin and Sterling Hill, vol. 1, no. 8, 195 p.

Chapter 2. Structural, Tectonic, and Geospatial Aspects of the Sterling and Franklin Zinc Mines, Sussex County, New Jersey

Gregory C. Herman, Trap Rock Industries, Kingston, New Jersey (N.J. Geological Survey, retired)

ABSTRACT

Computerized, architectural models of the New Jersey Zinc Company (NJZC) mines at Sterling Hill and Franklin, Sussex County were built for the 2025 GANJ conference and are being shared on the Internet. These mines hold rare and unique mineral species with respect to their fluorescent-mineral assemblages. Mine models were built using Trimble, Inc.'s SketchUp Pro (SUP) architectural software (ver. 2024), with some model features also exported as object models for display and manipulation in Google Earth Pro (GE). The models were built using plan maps and cross sections of the mine adits, drifts, cross-cut tunnels, and stopes that are held by the Sterling Hill Mining Museum, Inc. in Ogdensburg, and include geological aspects of other maps and documents kept by the New Jersey State Museum in Trenton. The models are used to interpret the structural and tectonic nature of these ore deposits in an effort to understand the where, when, and how they formed. The Sterling computer model is the most complete of the two, with the Franklin model including only a small portion of the information that is available.

“Where” the ore bodies occur was determined by registering the computer models in geographic space (WGS84) using SUP and GE and sets of reference buildings and roads on historical aerial imagery. The mines are located with estimated accuracies of ± 10 feet. “When” they formed is constrained by radiometric ages to the Middle Proterozoic (~1100 Ma), although multiple generations of mineralization have occurred. “How” they formed is the least understood, but this work supports a metasomatic replacement origin through fault-mediated ascent of the mineralizing fluids. Ferrous fluids were fed into a limestone and clastic sedimentary protolith by old faults that cut older gneiss intruded by hot, felsic plutons that were being sheared, folded, squeezed, and deeply buried. The Sterling Hill deposit includes a dike-like core structure striking ~N80E across the strike of metamorphic layering (~N20E) exhibits localized plasticity along its margins with adjacent, mineralized layers. This cross structure has also branched “cross members” leading from the core to mineralized zones lying above and below it. The zinc ore at the mines average ~20% bulk and locally exceeds 30% where layers are enriched in zincite.

This work also includes a digital method for determining geographical coordinates for mined features using north and west coordinate feet and the NJZC reference grid. The mine grid is rotated 19° clockwise from true north with respect to its origin point at zero ft north and zero ft west. This Microsoft Excel spreadsheet was programmed using trigonometric functions to convert mine coordinates into geographic latitude and longitude (WGS84). Please visit <https://ganj.org/2025-auxiliary-data/> to access online data archived for this year's conference.

INTRODUCTION

This chapter covers structural, tectonic, and geospatial aspects of the zinc-ore bodies in Ogdensburg and Franklin boroughs in Sussex County as portrayed in historical mine maps, cross sections, and reports of the New Jersey Zinc Company (NJZC), supplemented by a week of field work. Virtual, three-dimensional (3D) computer models covering the NJZC Sterling and Franklin mines were built in 2024-2025 and are being shared for the 2025 Geological Association of New Jersey annual meeting. These models together cover about 300 surface acres, portray mine workings extending nearly one-half mile below ground, and are illustrated and explained below in detail following a brief overview of the historical and regional setting, and mineralogy (figs. 1 to 4). The Franklin mine was formerly called “Mine Hill” until 1897 and is located in Franklin, NJ (Dunn, 2002).

I met Michael (Mike) Di Maio, this year’s Geological Association of New Jersey (GANJ) president, for the first time at the 2024 GANJ conference and learned about the 2025 focus on the Sterling mine at Sterling Hill in Sussex County, New Jersey. Upon also learning that Mike is a mine guide for the Sterling Hill Mining Museum (SHMM) in Ogdensburg, I expressed enthusiasm for this Highlands theme as I’d previously been in the mine before it closed in 1986, had descended to the -1850-foot level in one of the elevator cars on its inclined west shaft, and had helped move and store many boxes of rock core collected by NJZC during mining operations just prior to the closure. Some of the boxes were trucked to the Rutgers University warehouse for rock core while others were kept by the New Jersey Geological Survey (NJGS), my employer at the time. The NJGS lot was eventually transferred to Rutgers where they also now reside. Robert (Bob) Metsger, the mine manager and chief geologist of the NJZC had arranged the site visit and core-transfer work that took a couple of days with the crew of six field mappers and Richard Dalton, the bureau chief of geology and topography. It was the first operational mine that I had been in, and I remember thinking how warm, stark and dark it was at depth. To think that these were the everyday conditions for men working twelve-hour shifts impressed me with a sense of awe and respect, for what they did was naturally perilous.

Now, almost forty years later, with my continuing interest in the structure and tectonics of the New Jersey region, I asked Mike Di Maio if it were possible to get access to the cache of mining maps generated by the NJZC and now held by the SHMM to build a detailed model of the ore body to advance our understanding of the structure and tectonics of a famous zinc deposit, now known worldwide for its rare, fluorescent minerals. With Mike’s help the museum agreed to my request, and immediately shared the set of twenty-six level maps (-180 ft to -2550 ft) of the Sterling Mine by the end of October 2024. Mike, Jim Peterson, and I soon after spent half a day inspecting the open cuts at Sterling Hill for the first time, including the Passaic and Noble pits (fig. 3). I had yet to see the large saw cuts made shortly before closure of the Sterling Mine in 2017 by contractors hired by the SHMM on behalf of the American Museum of Natural History in New

York City to extract thin slabs of the zinc ore for display using ultraviolet light. These cut across a southeast-dipping ore pillar and provide visual insights into the ore petrology and genesis (fig. 4).

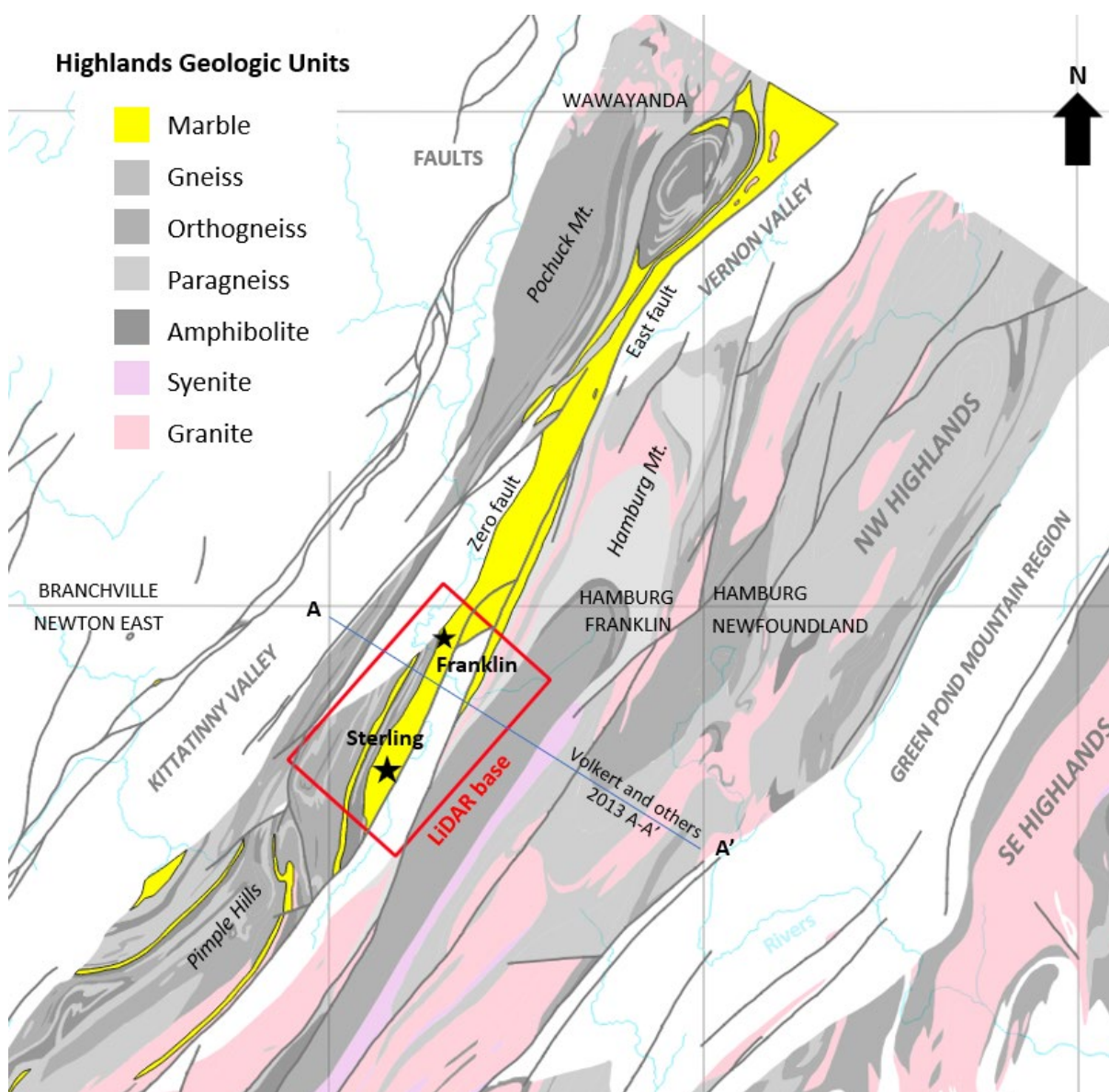


Figure 1. Generalized bedrock geology of the northeast part of the New Jersey Highlands with Mesoproterozoic marble highlighted yellow and the locations of the Franklin-Sterling Hill ore bodies noted. The map trace of a bedrock cross section is shown along with prominent physiographic and structural features. Field notes in Mesoproterozoic bedrock were collected near cross section A-A' in 1985 during my first year of employment and the NJ Geological Survey shortly before the Sterling Mine closed.

After assembling preliminary versions of the Sterling mine model using Trimble Inc. SketchUp Pro (SUP) software, the study was then expanded to include the adjacent Franklin Mine in order to portray both ore bodies and place them into a uniform, digital, geospatial and structural context for the first time (figs. 2 and 5 to 7). Because the Franklin Mine was added later, and because it is a uniformly dipping layered sequence that is truncated and segmented by faulting, only part of that model was developed with certain components that were selected to adequately portray its extent and represent the structural nature of the ore body. For this report I depart from primarily using metric distances as the mine workings are based on the standard foot measure which is also followed herein, with only limited use of metric units.

Following is an explanation of the methods used to convert and integrate the analog mine maps and stope sections into 3D models generated by computer processing. The 3D digital model

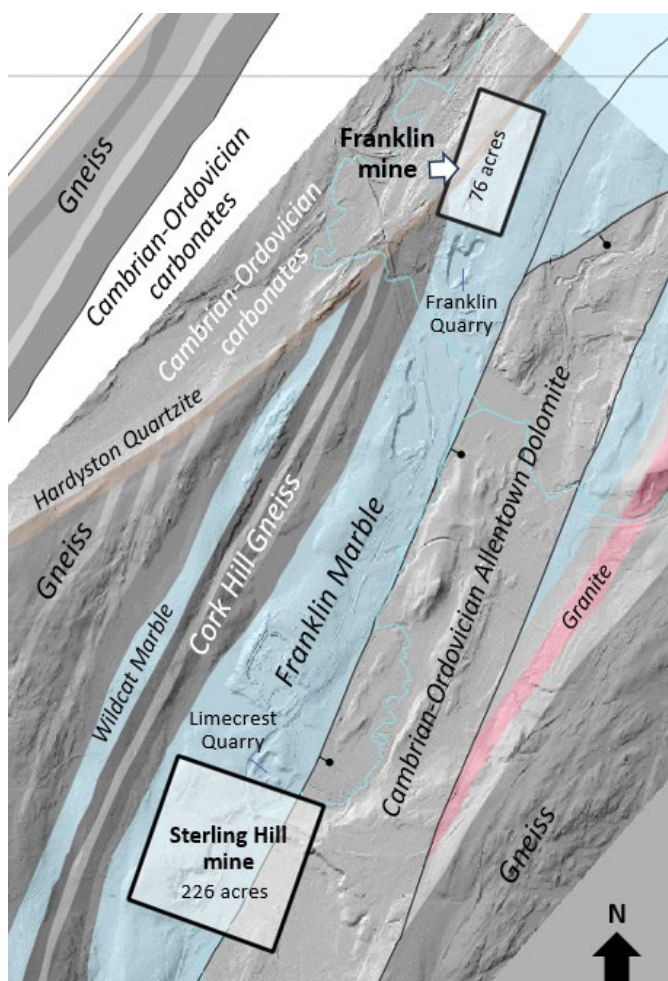


Figure 2. Bedrock map of the study area covering the Sterling Hill and Franklin mines. Balls and sticks placed on downthrown fault blocks.

of Sterling Mine includes over 35 miles of tunnels following the ore bodies to a depth of 2,675 feet. The subsurface modelling was complemented by six, half-days of field mapping around Sterling Hill and Franklin with colleagues to see the remaining visible mine infrastructures and outcrops showing geological structures. This effort therefore uses precise underground records and surface outcrops to help decipher complex structural elements within the repeatedly tectonized Precambrian Highlands of northern New Jersey (fig. 8).

After one year of planning, discussions, field mapping, seeking resources in institutions, and building digital models, I am herein reporting the results and sharing the models online.

GEOLOGICAL REVIEW

The ore bodies at Franklin and Sterling Hill are unique and among the most concentrated zinc deposits in the world. According to the US Geological Survey (USGS) National Minerals Information Center, zinc is the 23rd most abundant

element in the earth's crust (~ 70 ppm average) with similar concentrations for copper (~ 60 ppm), and nickel (~ 84 ppm). By comparison titanium (5650 ppm or 0.56%) and iron (~ 5.6%) are far more abundant. Three principal ore minerals occurring at Sterling Hill and Franklin are the oxide minerals zincite (ZnO) and franklinite (ZnFe_2O_4), and the nesosilicate willemite (Zn_2SiO_4). Recognition of this unusual ore as a profitable commodity in the late 18th century led to litigation over mineral rights in the 19th century that forced a more thorough scientific understanding and definition of ore and the methods to produce it (Dunn, 2002). The consolidation of mining rights and interests with the founding of the NJZC in 1897 enabled successful production afterwards until closure in 1986.



Figure 3. A Google Earth Pro historical image (2002) showing the Sterling Mine site and some notable features. Reference buildings outlined in red were used to aid in georeferencing imagery and other geospatial themes.

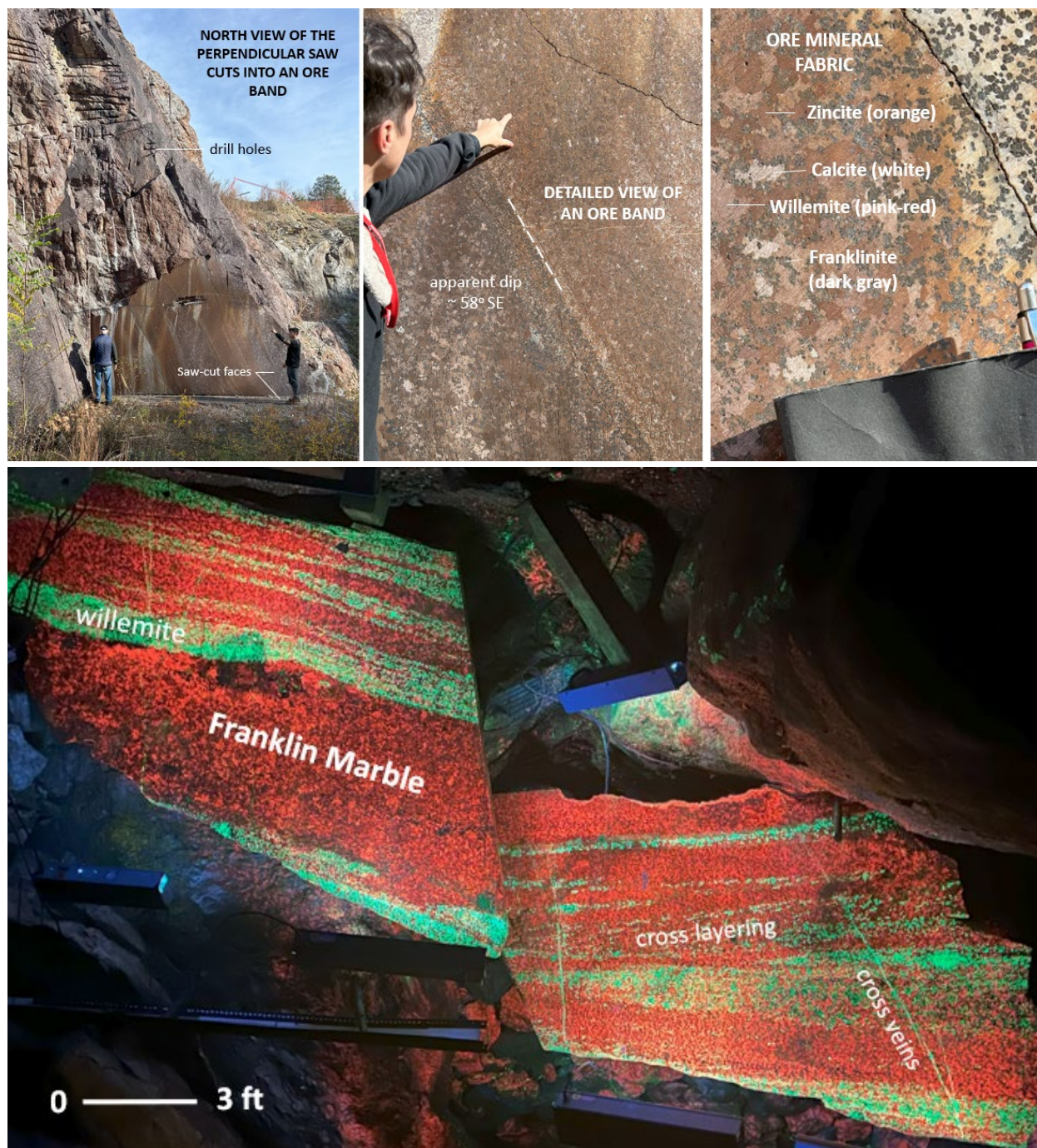


Figure 4. Rock slabs from the Passaic Pit outcrop are now housed at American Museum of Natural History in NYC and at the Sterling Mining Museum in their "slab room," viewable under ultraviolet light as part of their underground mine tour. Those pictured are not geologically orientated. They were cut from the first upper layers striking about N60E and dipping ~60° SE (fig. 10). Willemite fluoresces light green and highlights siliceous seams within the marble (calcite fluoresces red-orange) in the form of metamorphic cross layering. Also note a different generation of willemite filling secondary fractures cutting through the layering at cross angles.

Chapter 2. Structural, Tectonic, and Geospatial Aspects of the Sterling and Franklin Zinc Mines, Sussex County, New Jersey

Old, detailed mining records and maps are lacking for the surface and upper-level workings prior to the establishment of the NJZC which joined the Franklin and Sterling Hill Mines as part of a single enterprise (Dunn, 2002). The Franklin Mine produced 22 million tons of ore over the mine life, while the Sterling Mine is reported to have produced 11 million tons (Dunn, 2022). Edwards (1962) states that “At Sterling Hill, the New Jersey Zinc Company mines zinc ore, crushes and grinds the ore to size; and ships the powder to the Palmerton smelter for further treatment. Production in the 1962-65 period averaged 1000 tons per day. Company estimates as of December 1st, 1965 indicate an ore body of 4,750,000 tons of proven ore, averaging 20.1% zinc.” Please see Dunn (1995) and Wilkerson (1962) for a comprehensive review of the mine histories and mineralogical review.

The plan maps and cross sections (stope sections) acquired for this study were compiled by geologists, miners, and draftsmen employed by the NJZC using various mining and cartographic techniques at the two separate facilities over time. Detailed maps and sections of the Franklin Mine were first drafted in February 1908 with ore volumes tallied at the -1150 ft subsurface level. At that point in time, exploratory drilling and shaft construction had been completed and the first detailed records of ore stoping were compiled for mining conducted at the bottom of the fish-hook shaped ore body where it's the flattest, thickest, and widest (figs. 5, and 9 to 11). Mining at Franklin continued upward toward the surface through systematic, shrinkage stoping, mining of the pillars by top-slicing, and backfilling (Haight and Tillson, 1917) until mining ended in July 1954. The first subsurface work noted on the SHM stope maps are dated September 1932 with records compiled through May 1986 (fig. 9). Edwards (1962) summarized the mining methods at Sterling as “horizontal cut and fill for stopes and square sets for pillar recovery; all excavated openings are refilled with gravel.”

The bedrock geology of the mined area is well mapped and documented by many workers including Hague, Baum, Herrmann, and Pickering (1956), Baker and Buddington (1970), and Volkert and Monteverde (2013). A NJZC cross section constructed by Bob Metsger in 1975 details the structural nature of the Franklin-Sterling Hill syncline in which the zinc-ore resides (fig. 12). The section is based on rock coring across the valley and depicts a tight, upright syncline with a hinge area cut by the steep, southeast-dipping Zero fault. As noted by Hague and others (1956), both ore bodies occur within the Franklin marble positioned between the siliceous Cork Hill and Median Gneiss layers at horizons favorable for mineral replacement and growth during metamorphism. They also report a general composition of Franklin ore being 40% franklinite, 23% willemite, and <1% zincite with the remainder of gangue silicates and carbonates. The ore mineralogical proportion at Sterling Hill is reported at 33% franklinite, 16% willemite, and ~1% zincite, with the remaining gangue calcite. These values closely agree with an earlier assessment by Palache (1929). Both ore bodies have hook-shaped keels in cross section (figs. 5, and 9 to 11).

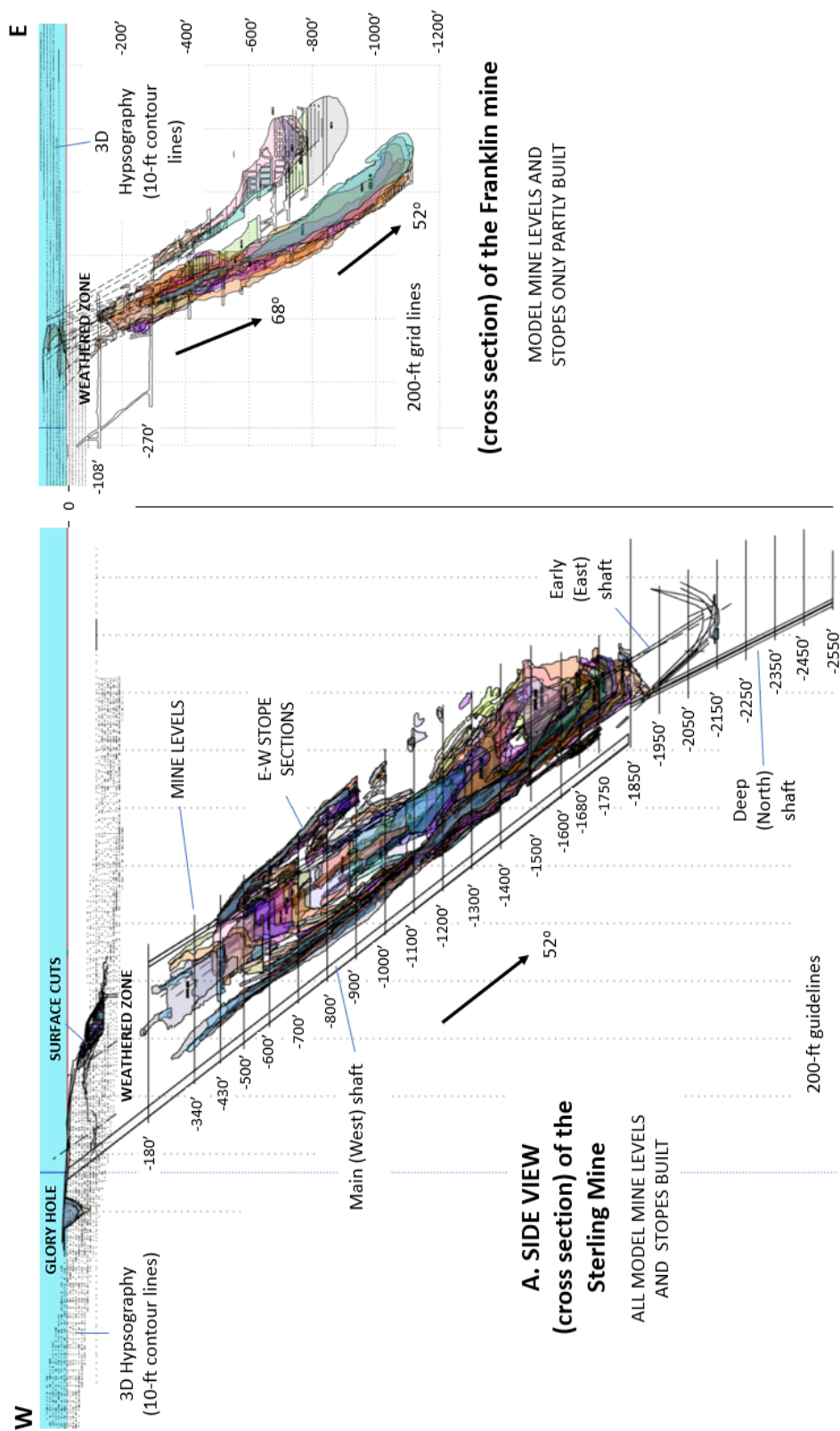
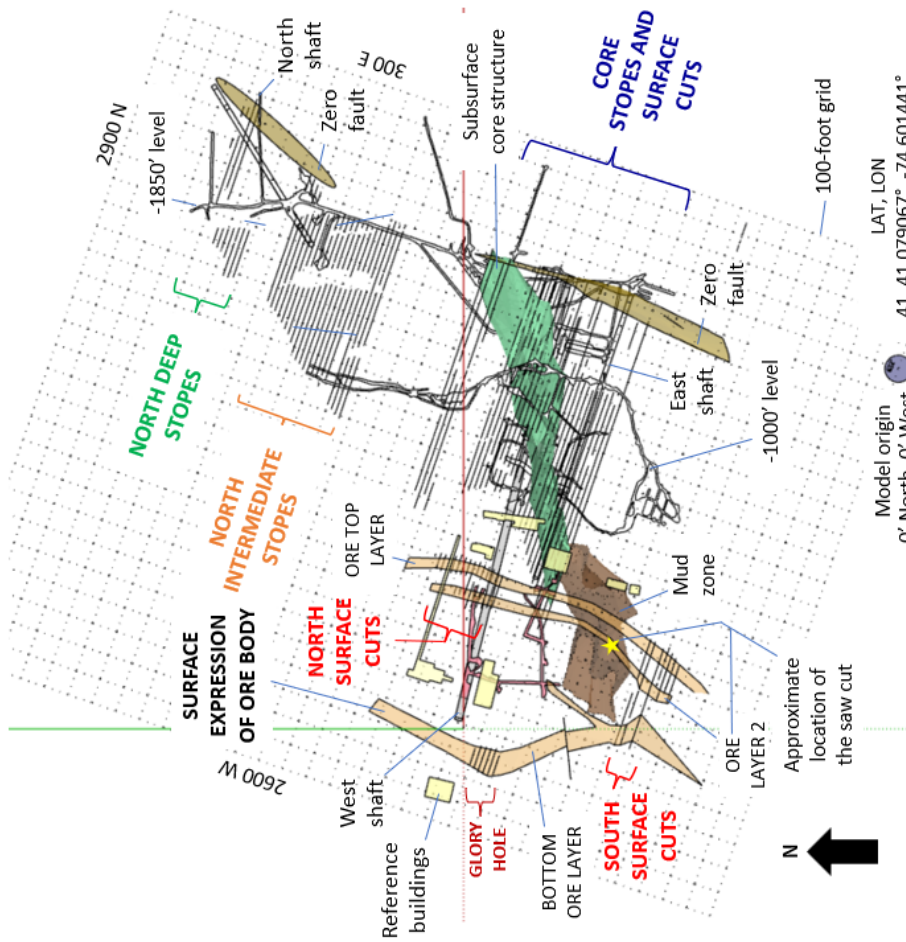


Figure 5. Cross-section views of the (A.) Sterling Hill and (B.) Franklin mines looking north at the same scale. Notable features are labeled and discussed further in the text. Please note that the Sterling Hill model used all available maps and stope sections whereas the Franklin model used only a fraction of the total archived. Both ore bodies occur in the hinge area of an upright syncline that's cut by the steeply southeast-dipping Zero fault as detailed in figure 8.

A. TOP VIEW (map) of the Sterling Mine



B. TOP VIEW (map) of the Franklin Mine

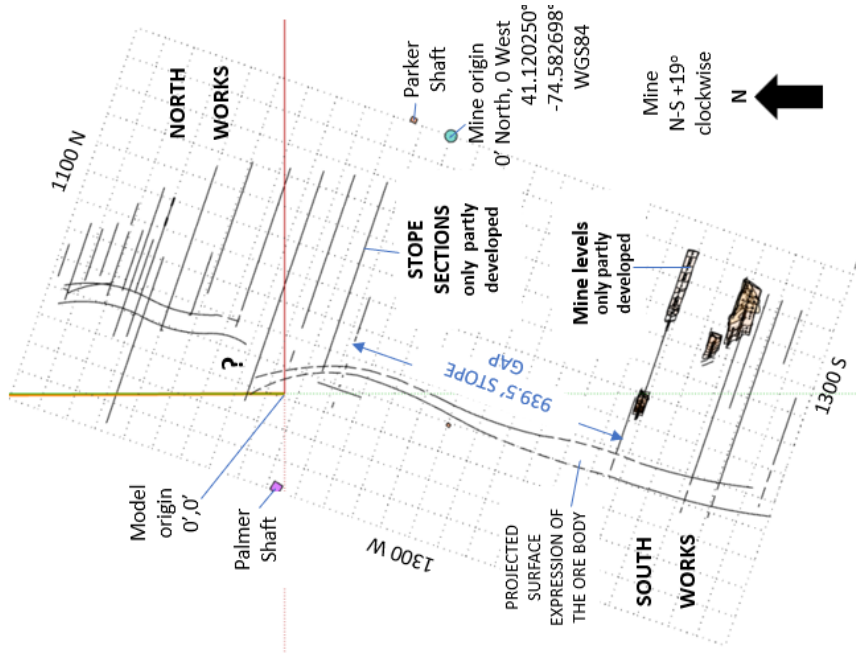


Figure 6. Maps of the (A.) Sterling Hill and (B.) Franklin mines at the same scale. Notable features are labeled and discussed further in the text. The ore body at Franklin is offset and noted using a question mark.

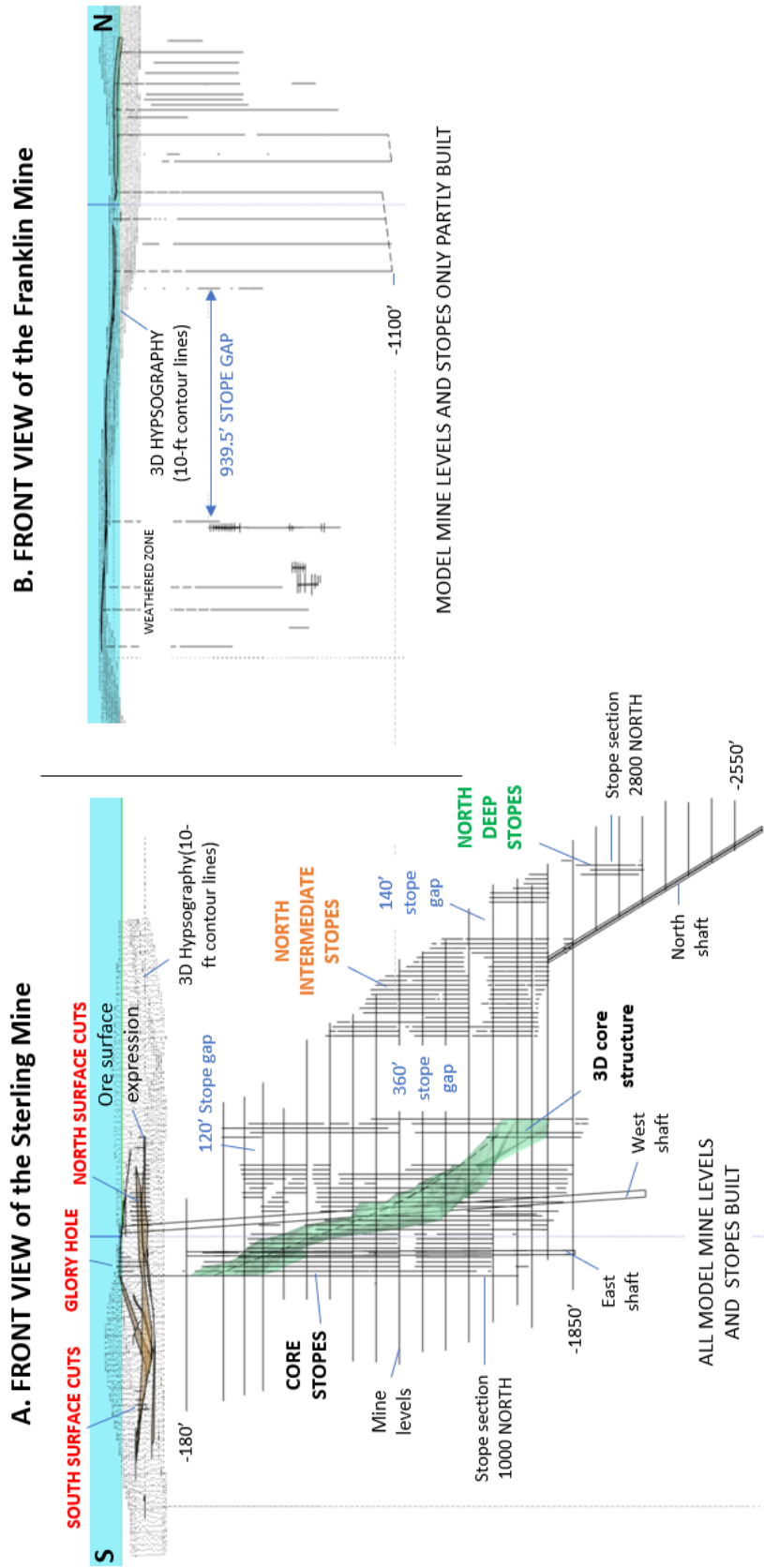


Figure 7. Front views (longitudinal sections) of the (A.) Sterling Hill and (B.) Franklin Mines at the same scale. Notable features are labeled and discussed further in the text. Please note that the Sterling Hill model used all available maps and stope sections whereas the Franklin model used only a fraction of the total archived. The spatial density of stope sections for both the north and south cluster of stopes at Franklin are developed most in the upper right corner as an example of representing only part of the available information.

There is a focused cluster of stopes and surface cuts at Sterling Hill situated in the structural core of the ore body where the zinc ore accumulated along the margins of a fattened, ovoid, dike-like structure striking about 080° (figs. 13 to 16). This core structure is what Hague and others (1956) refer to as a “cross vein”. Metsger, Tennant, and Rodda (1958) describe it as a complicated “cross member” that’s greatly thickened in its middle portion, and they indicate it joins the west and east limbs. Outcropping structural aspects of the core structure are detailed in the field guide.

A long-standing misconception about the Sterling Hill structure is that the ore resides in an overturned syncline, such that the east and west ore layers were once coplanar but now form an isoclinal fold wrapped around a marble and gneiss core structure. But a NJZC cross section that was constructed through the area by Bob Metsger in 1957 disproves that (fig. 12). This is partly the basis for a fault-mediated hydrothermal-plume origin proposed for the ore body as depicted in figures 14 through 16. At both locations the ore bodies thicken at depth and to the south, and

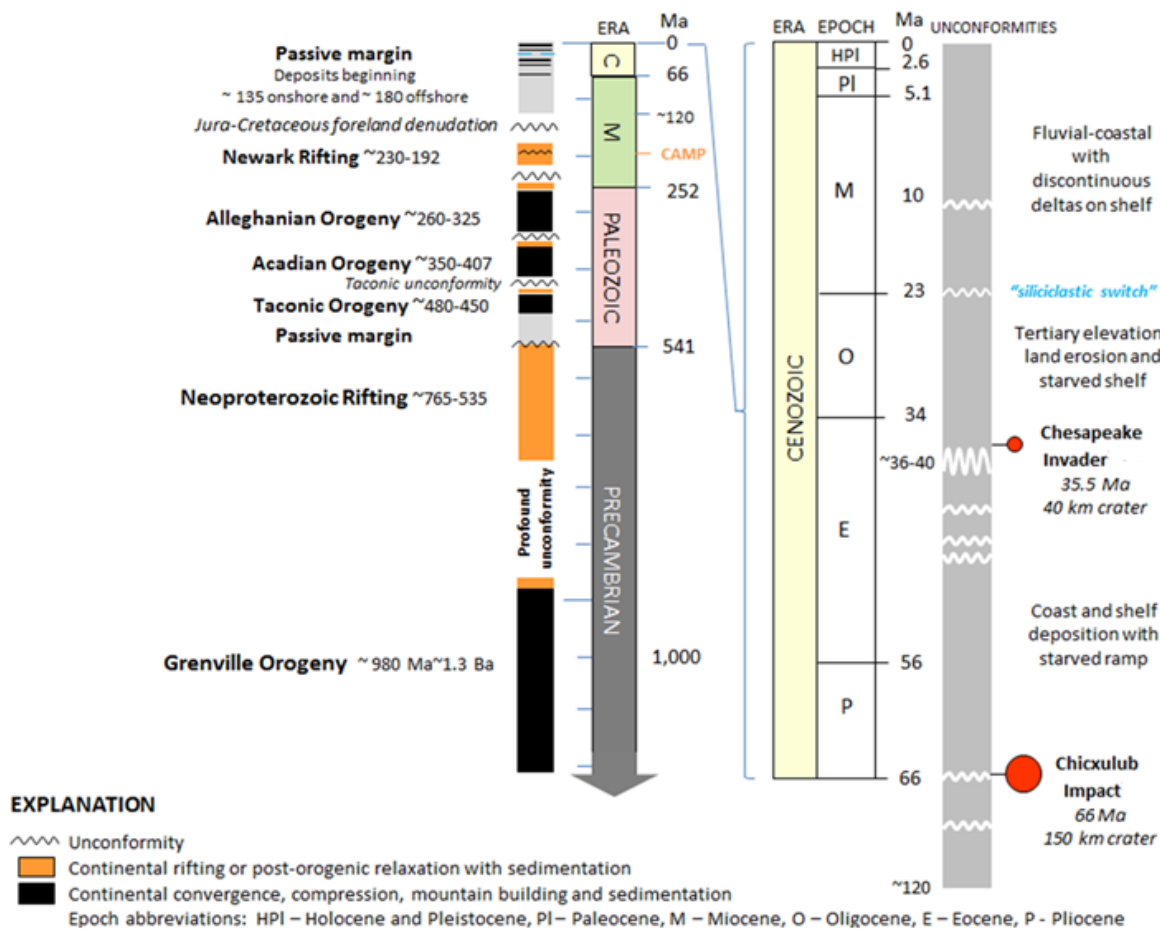


Figure 8. Chronology of Appalachian tectonics in the New Jersey part of the central Atlantic region of North America (adapted from Herman, 2015).

taper to the west. The original dips of the infiltrated strata are unknown, but the beds were originally deposited with sub horizontality. They were then folded and faulted during Mesoproterozoic compression and subsequent extension (figs. 15 and 16). The current attitude of the ore bodies is likely not the same as during infiltration. At Sterling Hill, a portion of this core structure is composed of black willemite, which under high magnification appears to be composed of colorless willemite peppered through with minute inclusions of highly magnetic

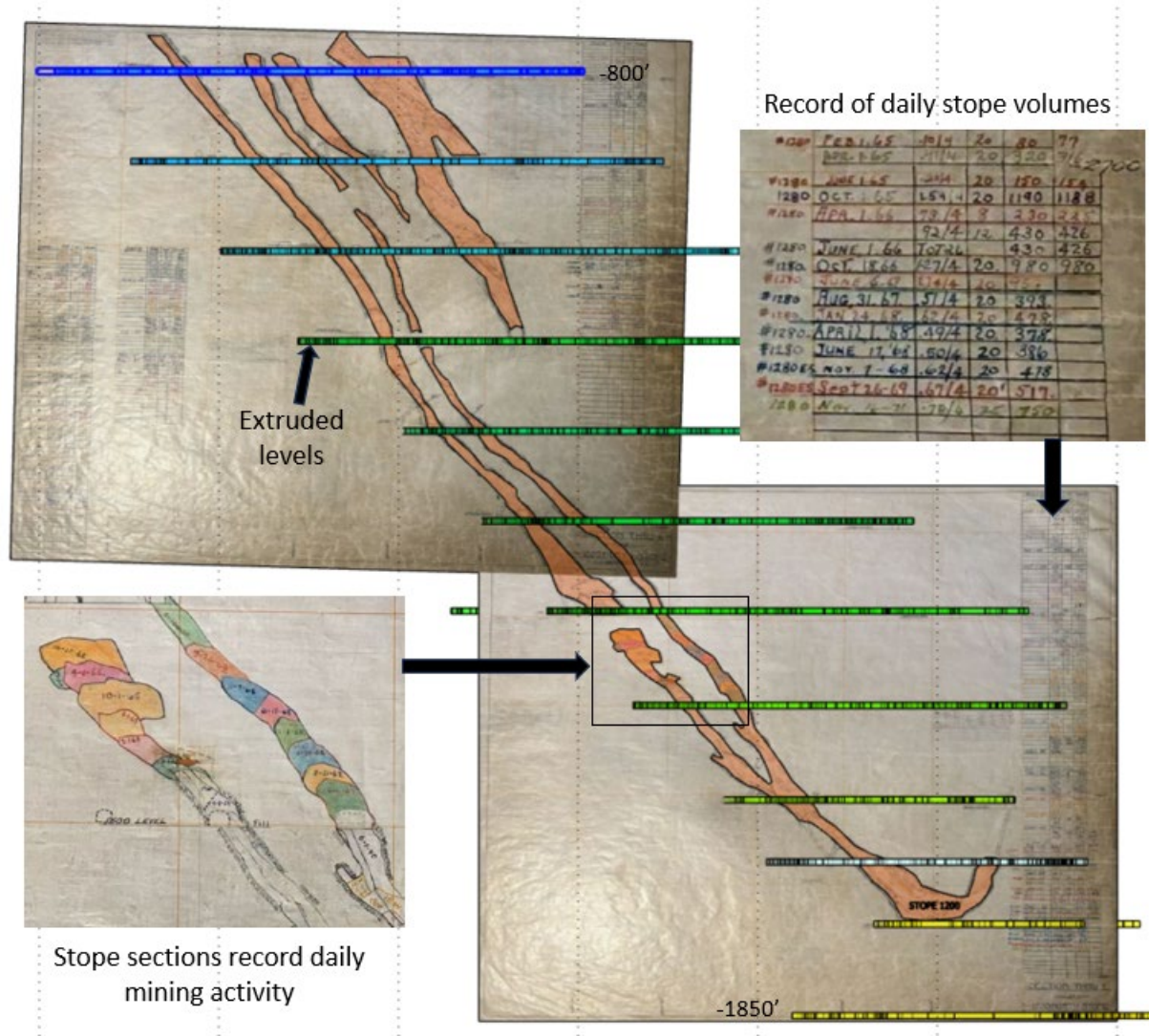


Figure 9. Captured screen views of the 1200 North stope section of the Sterling model showing two registered and overlapping stope sections with an example of how the ore-mining records were kept. The orange polygons are 2D vector-based faces that were manually digitized from the raster imagery. The digitized polygons of the multi-colored mine levels were also extruded seven feet vertically as shown. The slight clockwise rotation of the top raster image shows how small ($<1.5^\circ$) angular rotations were introduced from using a hand-held smartphone camera to digitally photograph the stope records.

black franklinite that approaches magnetite in composition (Metsger and others, 1958). So, it appears that the heaviest minerals crystallized along the core structure and basal sections of adjacent, infiltrated layers. (figs. 14 to 16).

THE STERLING HILL AND FRANKLIN COMPUTER MODELS

This section details the methods and tools used to build and share the mine models. The CAD models were built using the SketchUp Pro (SUP) 2024 3D design software by Trimble, Inc. SUP is powerful and versatile architectural-design software that includes geolocation tools for positioning models in geographic space using the WGS84 reference system. The models use imperial feet as the standard unit of measure. The representative accuracy is estimated to be ± 10 ft both vertically and horizontally for both models. The models were exported using a *.dae file format for model output that was exported as 3D objects into Google Earth Pro (GE) for additional visualization as detailed in the last section.

However, these results only illustrate a fraction of the information that the mine maps provide. My focus was on building a 3D mine model and using it to portray the structural position

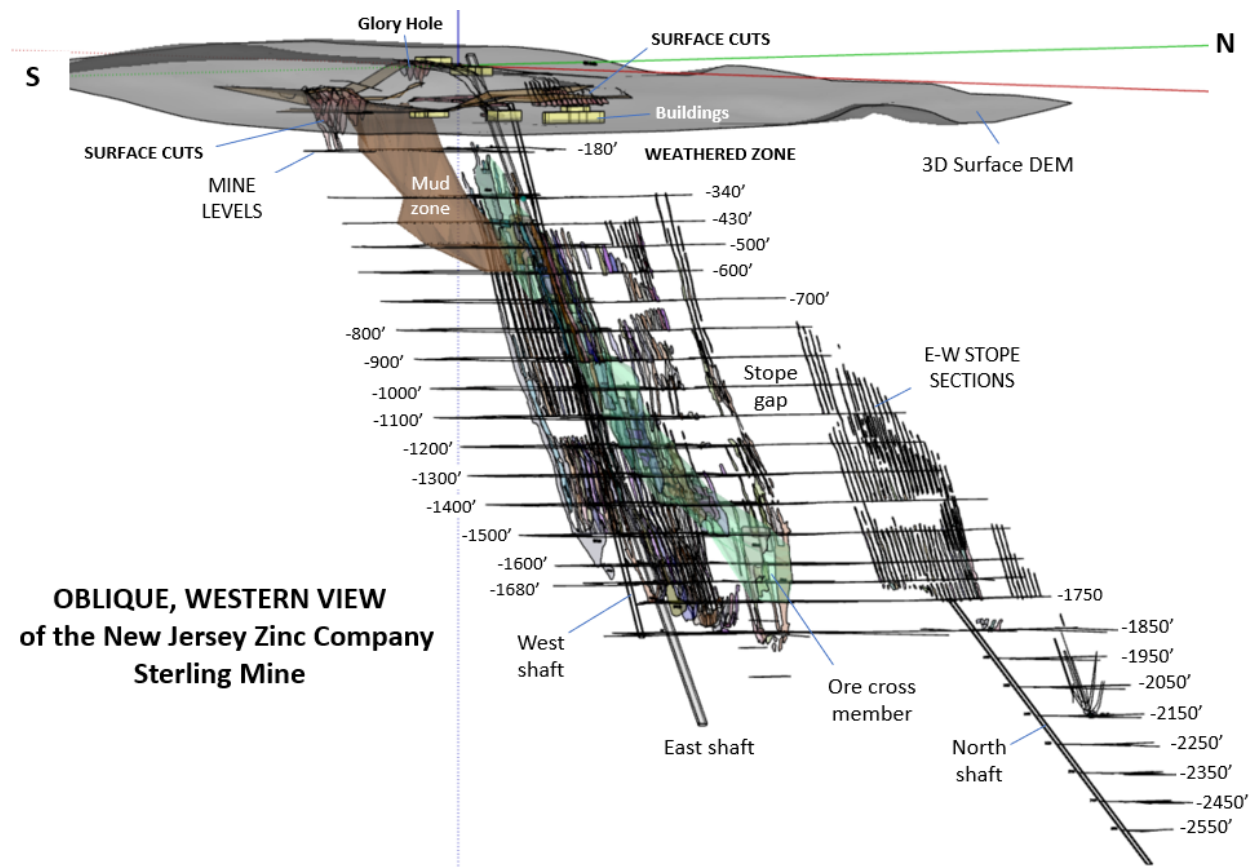


Figure 10. Western view of the NJZC Sterling Mine SUP model.

and complexity of the ore body including the primary metamorphic layering with metalliferous banding that is cut by many secondary structures resulting from many tectonic episodes throughout geological time (fig. 8). I also considered building geometric envelopes around groups of stoped sections as part of the model in order to calculate extracted ore volumes, but upon building one and comparing the resulting volume with those recorded on the stoped sections, there was 99% agreement between the two (fig. 17), so I didn't need to develop those further because the historical records are available that include amounts and dates of extraction. These records can also be used to reconstruct the working history of the mines if one is compelled to do so.

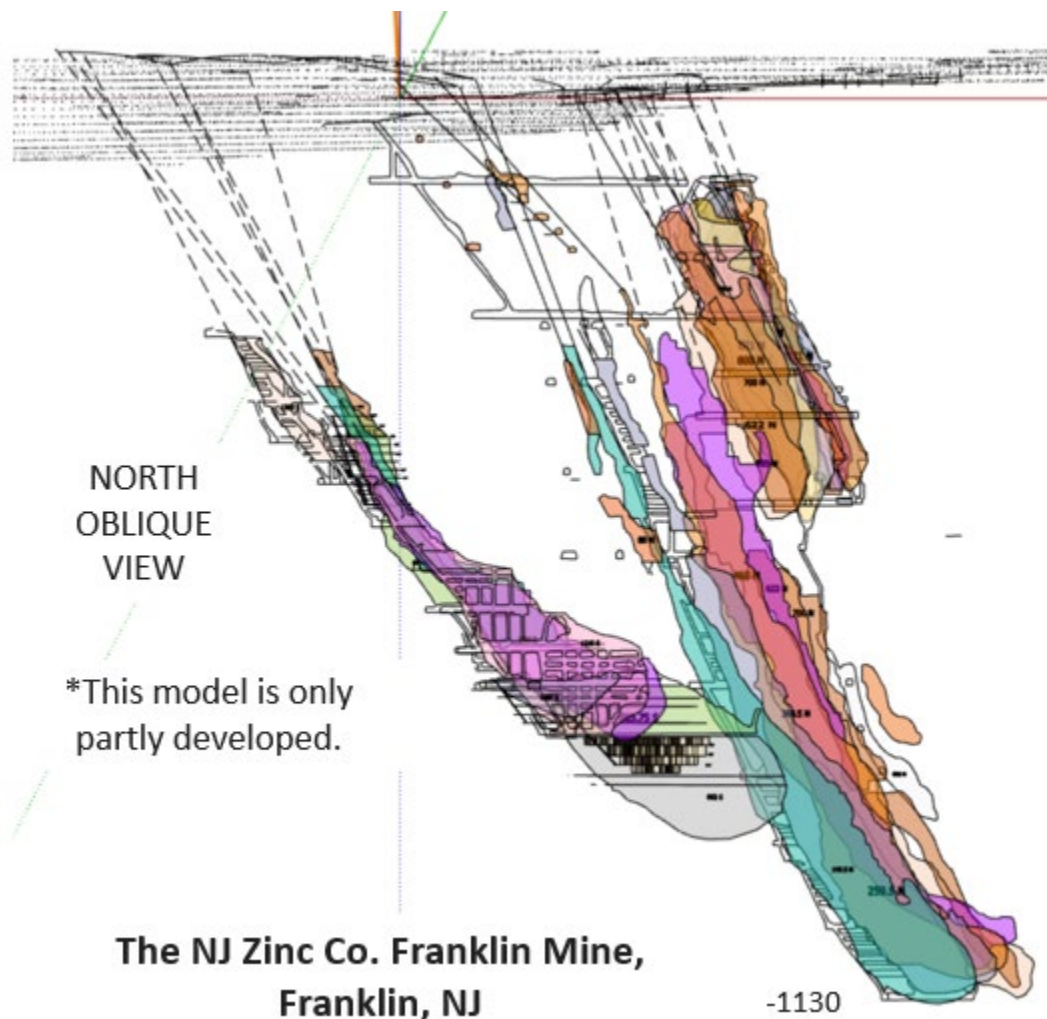


Figure 11. North view of the Franklin mine SUP model with semitransparent stoped sections.

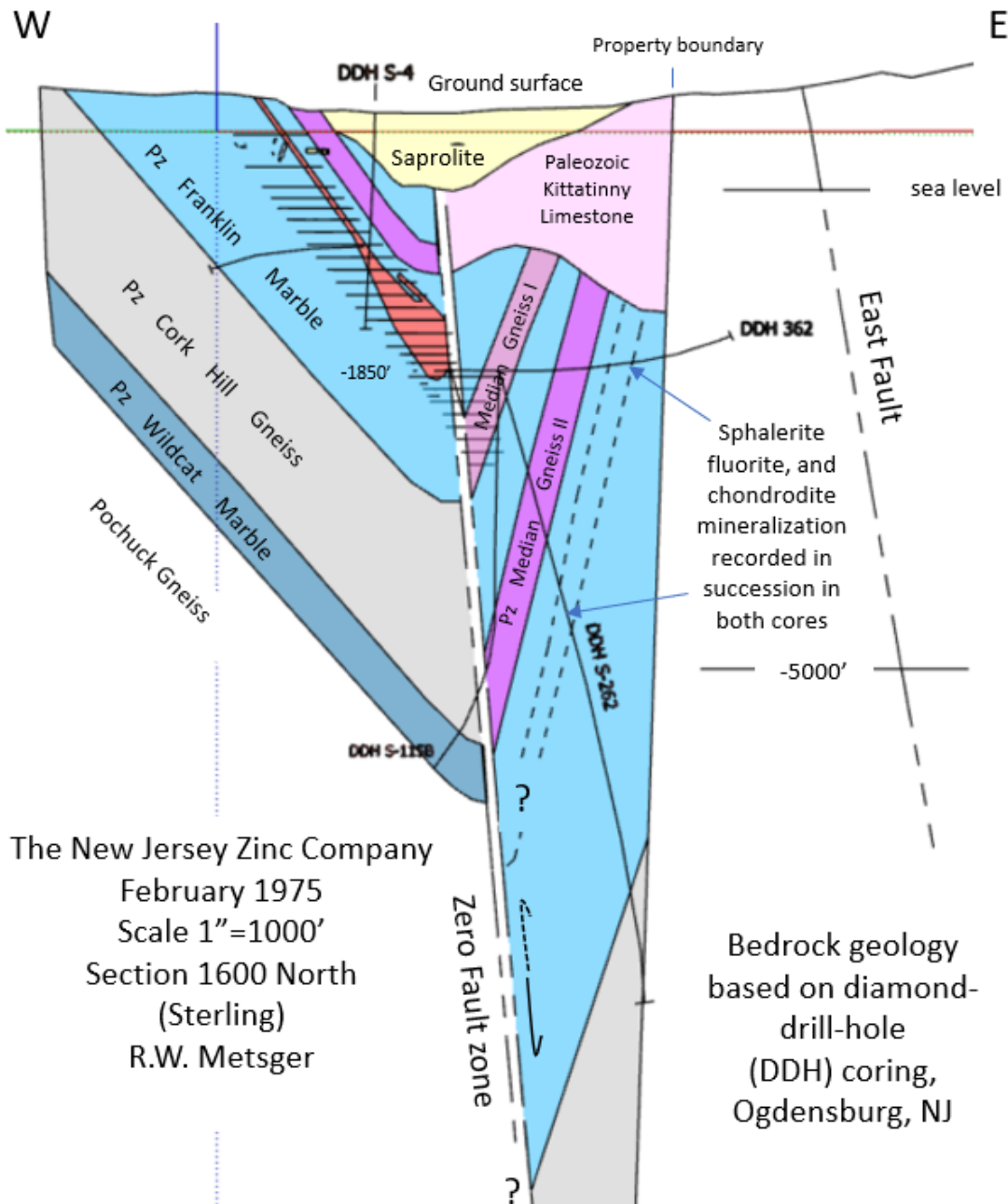


Figure 12. A formerly proprietary NJZC cross section constructed by Bob Metsger in 1975 is now part of the New Jersey State Museum Metsger collection, and is reproduced and augmented here. Please see the section below about the museum collection. The cross section, constructed along the 1600 north stope, details the structural nature of the Franklin-Sterling syncline in which the zinc-ore resides. It's based on five rock cores (labeled DDH) that were drilled to over a mile underground. This confirms that the mines are developed in a synclinal hinge cut by the steep, southeast-dipping zero fault. The dissected fold limbs are upright and dip moderately to steeply toward one another. The Sterling ore deposit is depicted to thicken in the fold hinge area. The location and length of core DDH S-262 is listed in table 1, and the core resides in the Rutgers University core repository.

Table 1. Locations (feet) and lengths (feet) of rock core from the Sterling (S) and Franklin (F) Mines and where they are kept. Written communication from Dr. Earl Verbeek, June 24, 2025.

Hole #	North	West or East	Elevation	Length	Rutgers	Sterling Hill
S-33	1200	806 W	-2088	212		212
S-56	1200	179 W	-2394	426	426	
S-58	900	490 W	-2393	259		259
S-109	1335	764 W	-1696	450		450
S-110	1211	574 W	-1894	250	250	
S-138	1049	899 W	-1513	27'	273	
S-144	950	1084 W	-1336	277	277	
S-153	2772	103 E	-3146	182	182	
S-154	2860	544 E	-2838	1791		1791
S-155	2791	282 W	-2845	483		483
S-156	2858	550 E	-2838	4784		4784
S-240	1570	645 W	-2087	91		91
S-250	2526	486 W	-2386	1005		1005
S-257	1639	534 W	-2186	70		70
S-262	1588	305 E	-2186	4652	4652	
S-263	1559	153 W	-2850	71		71
S-286	1200	267 W	-2092	150		150
S-288	2997	175 W	-2090	70		70
S-290	1320	356 W	-3498		410	
S-292	1319	356 W	-2692	142		142
S-300	960	825 W	-2096	340		340
S-304	801	944 W	-1594	275		275
S-308	1300	447 W	-1993	376	376	
S-343	2946	325 E	-3442	166	166	
S-351	1640	254 W	-2389	97		97
S-363	1023	257 W	-2393	259		259
S-401	1140	189 W	-2496	110		110
S-402	1340	681 W	-2189	155		155
S-403	1444	494 W	-2185	159		159
S-404	1444	496 W	-2184	155		155
S-405	1550	438 W	-2189	89		89
S-421-2	1540	379 W	-2491	176		176
S-424	1300	256 W	-1796	120.5		120.5
S-427	1498	108 W	-2708	97	97	
S-432	1460	93 W	-2708	111.5-150		38.5
S-449	1037	1008 W	-1598	45-91		46
S-450	1045	1005 W	-1598	56-82		26
S-451	1037	1005 W	-1598	49-88		39
S-452	1020	1034 W	-1515	63-101		38
S-453	1020	1034 W	-1512	63-134		71
S-454	1360	741 W	-1790	57-76		19

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S-455	1335	927 W	-1790	93-221		128
S-457	1335	927 W	-1790	60-220		160
S-459	1300	554 W	-2287	43-112		69
S-460	1540	544 W	-2186	90-148		58
S-461	1444	495 W	-2183	81-130		49
S-462	990	1091 W	-1424	60 -100	40	
S-463				85-113		28
S-465				101-208		107
S-466				56-126		70
S-467				85-125		40
S-468				95-132		37
S-115-b	1589	298 E	-2849	2992	2992	
F-155	750 S	2727 E	663	1965	1965	
F-156	1744 S	1680 E	607	1686		1686
				Total	12106	15952

Subsurface mining of the main ore bodies started below 180 ft at Sterling Hill and below 100 ft at Mine Hill owing to deep weathering of the Franklin marble (figs. 11 to 12). The larger mining gap across the weathered zone at Sterling Hill prohibited a well-constrained interpretation of how the surface cuts connect with the mined sections below. Other mining gaps occur between clusters of stope sections at both mines presumably because of ore degradation or bedrock instabilities stemming from even deeper weathering occurring along brittle cross faults that strike parallel with those observed in and around the Newark Basin as seen in historical aerial imagery and LiDAR (fig. 18 and Herman, 2009; 2015).

The Franklin model only includes a subset of level maps and stope sections that capture the mining approach and its 3D spatial arrangement in two separate north and south areas separated by a 930.5 ft horizontal gap in the mining works for unknown reasons, but likely owing to deep weathering and structural instabilities stemming from late-stage, brittle cross faulting. Weathering beneath the Passaic Pit extends downward to nearly 700 ft (Kroth, 1993) where the mineralized marble layers are reduced to a mud zone that has the width and inclination of the deeper ore body (fig. 6). Ore mining therefore was generally focused below the -600 ft level at Sterling Hill (fig. 5).

The ore surface drifts, saw cuts, high walls and stope sections at Sterling Hill helped constrain the model so that the interpretation of the ore body is compiled and represented as best possible given the limitations. I'm satisfied with the results when portraying the structural complexity of the ore body stemming from multiple tectonic episodes as discussed in more detail below in the following sections.

Mine Locations

Accurately locating the Sterling Mine model proved challenging until May 2025 when I met Earl Verbeek. He used and shared a detailed site map by Kroth (1993) to map faults and slickenlines of the Sterling Mine (chapter 3). Kroth's map includes the mine-coordinate system, the tunnels used for the SHMM mine tour near ground level, and some upper mine levels that are projected to the surface, thereby allowing accurate placement and rotation of the Sterling Mine model relative to true north (fig. 20).

Registration of the Franklin model relied upon a set of roads depicted at ground surface on the southern group of stope sections. In particular, section 842N includes a drafted surface trace running across Nestor, LaRue, Main, and Mill Streets in Franklin Borough that limited the position of the model and constrains its accuracy to the width of LaRue Street (rather, Larue in GE) that runs approximately normal to the ground-surface trace (fig. 20). The two adjacent mines use the same vertical datum but different horizontal datum (fig. 6).

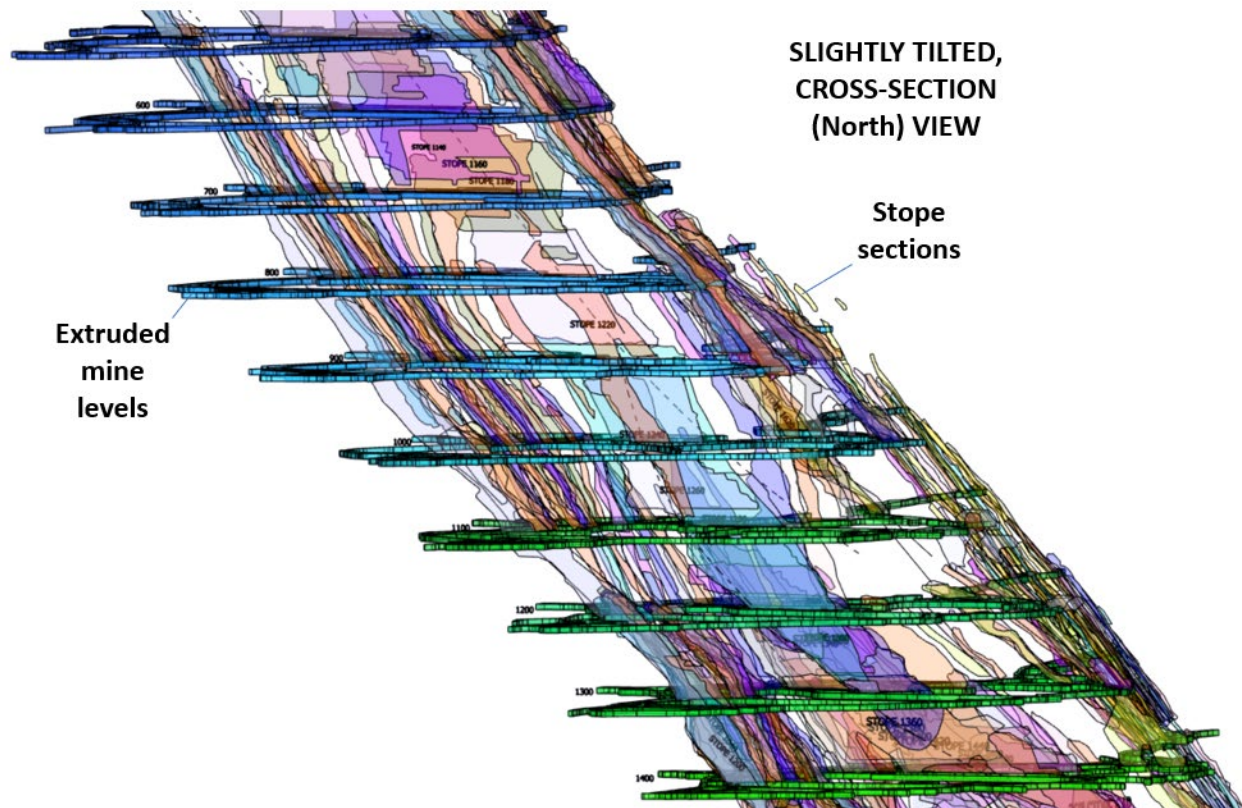


Figure 13. North view of part of the Sterling Mine model showing sets of semi-transparent stope sections and mine levels that exemplify the mine workings and structural complexity of the ore body.

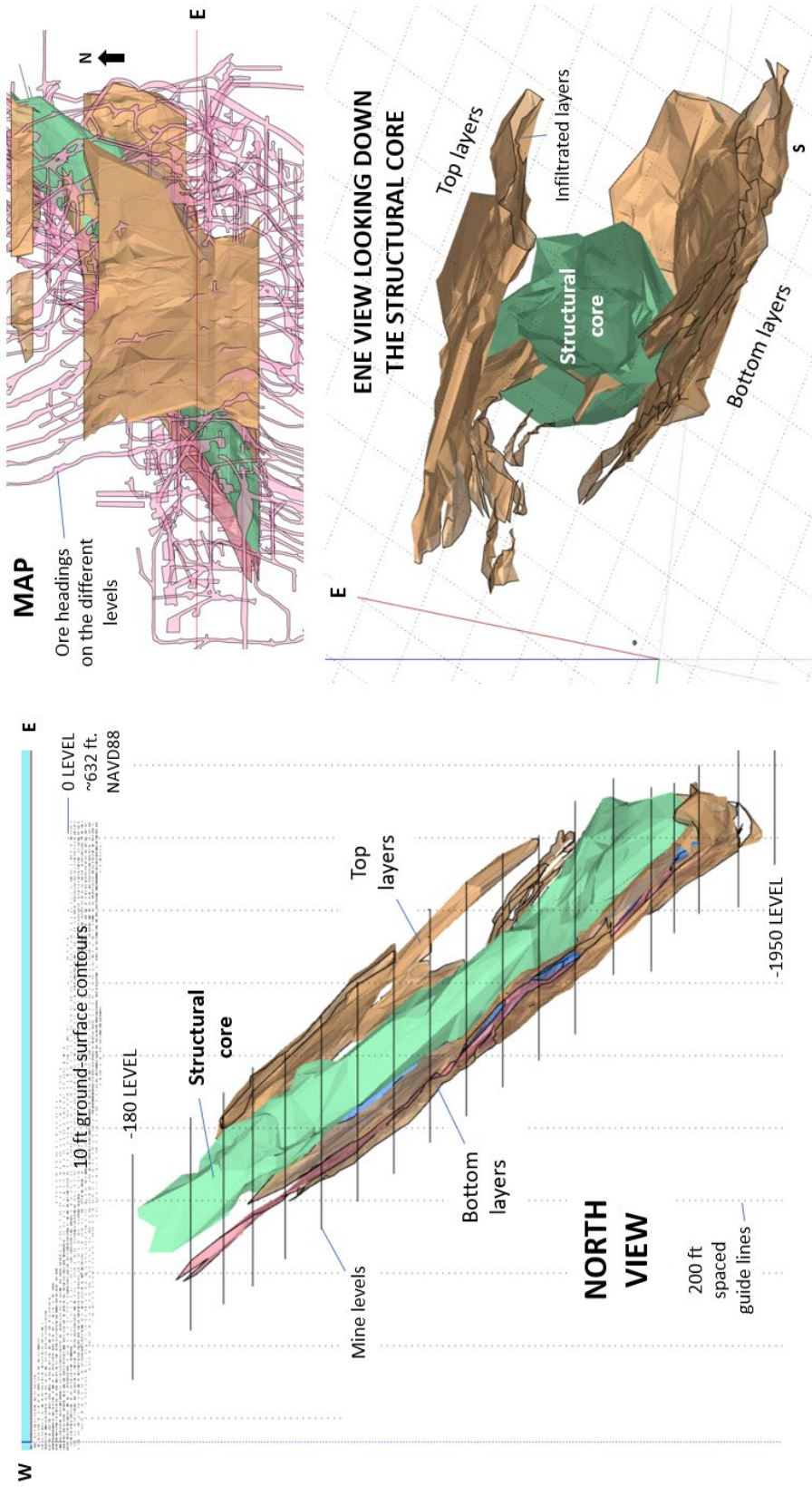


Figure 14. TIN surfaces were manually built around the structural core (green) and along the tops and bottoms of ore layers (light brown) defined by the set of core slope sections in order to visualize the main part of the Sterling ore body (fig. 6). Mine-level polygons are colored pink. The structural core is a round- to oblong-shaped, elongate structure that fed metallic fluids into adjacent top and bottom layers. Zinc-enriched fluids preferentially invaded the hinge zone of an upright syncline along this dike-like core structure that could strike parallel to the paleo-tectonic compression axis (fig. 15). The bottom, hook shape of the ore body arose from several tectonic episodes involving both reverse and normal faulting on the bounding zero fault system (fig. 8).

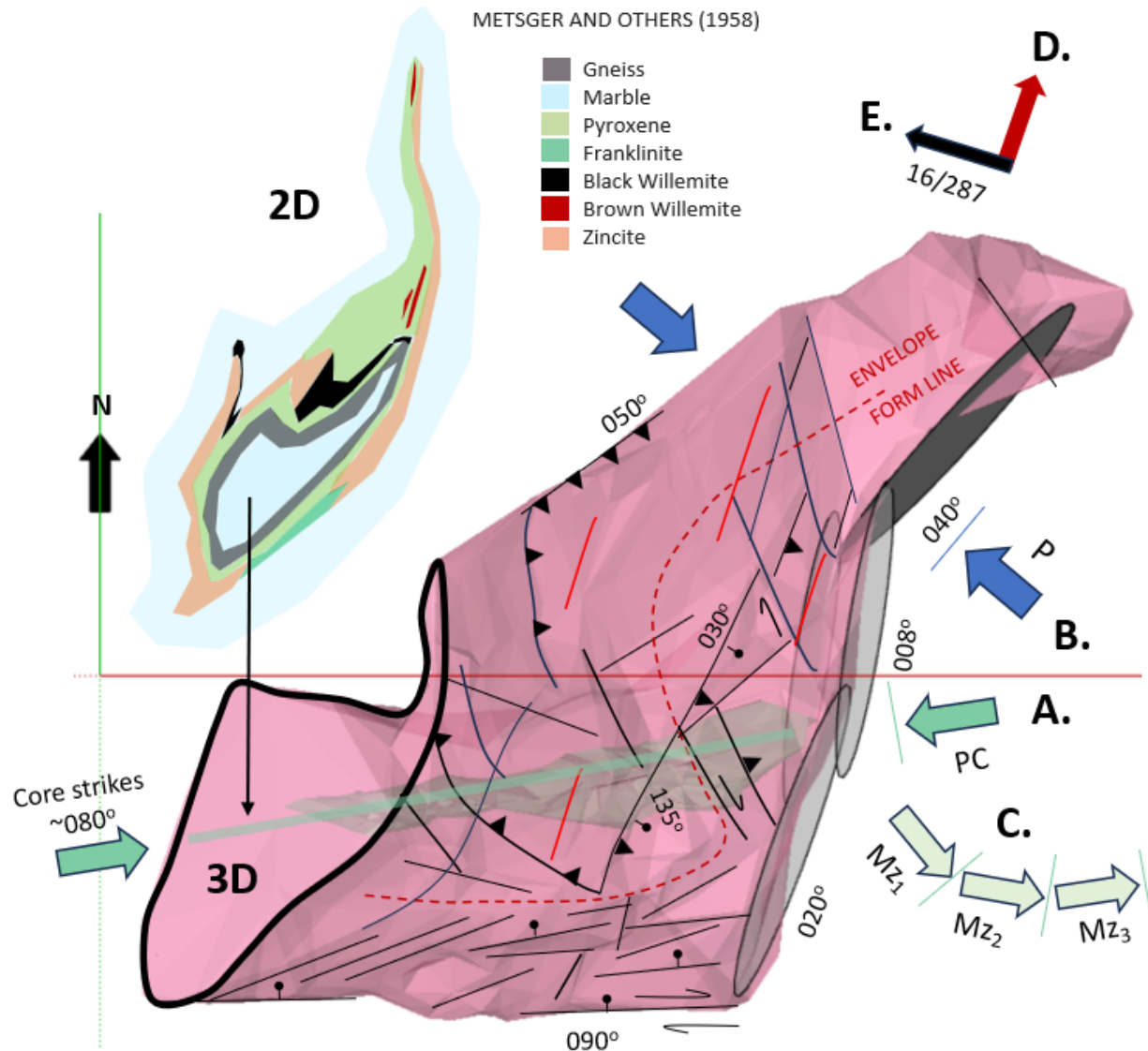


Figure 15. Map view of the Sterling Hill ore body in 2D on the upper left and in 3D to the lower right. The Metsger and others (1958) 2D map demonstrates mineralogical heterogeneity in the ore body (layers colored by primary mineralogy). The 3D diagram shows an enveloping surface constructed around the ore body that highlights its structural creases and flexures resulting from incremental tectonic strains. A.) The ore body was first emplaced during Mesoproterozoic compression (Precambrian-PC) along faults feeding Fe-Zn-Mn rich fluids into the Franklin Marble. B.) The mineral deposit was then deeply buried before ductile-brittle compression and shearing during Paleozoic (P) Appalachian Mountain building that raised it towards ground surface. C.) Mesozoic (Mz) incremental stretching segmented the ore body and displaced it downward during continental rifting, of which there were at least three incremental stretching phases. D. and E.) Two phases of Cenozoic compression have also impacted the region (Herman, 2015) including compression and uplift down range of the Chesapeake Invader meteorite impact (D.) and current compression stemming from passive drift toward the NW (E., 16 mm/year toward azimuth 287°).

Data Input and Processing

The models were built in stages as the data were acquired. The SHMM had previously digitized the twenty-six levels of mine workings so these files were received as individual Adobe Portable Document files (PDFs) that were converted to raster images using the TIFF file type. Many of the longer maps were split in half in order to preserve image resolution because SUP dithers imported images, with larger images losing a greater degree of definition. Altogether, forty-four map images of the mine levels were digitized as closed 2D polygons that were later extruded seven feet for rendering 3D levels (figs. 9 and 13). An iPhone 14 was then used to photograph the stope sections and resulted in the introduction of small, angular rotations that required adjustments within the vectorized model (fig. 9). The JPG file-image format was used for working with stope-sections raster imagery. The integrated levels and stope maps detail the 3D form of the ore body and reveal the nature and orientations of secondary structures within and bounding the ore bodies (figs. 13 to 15).

The following list summarizes the data gathering, processing, and interpretive steps in building and sharing the Sterling model. Many of these steps were then followed when building the Franklin model. An iPhone 14 was used to photograph the level and stope maps for Franklin. The location of the Franklin Mine Palmer and Parker shafts were located and added using Sanborn (1920) maps.

- 1) Established a model origin from which 100-ft reference grid and 200-ft spaced vertical guidelines were constructed to aid in the 3D positioning of the imported level maps and stope sections as raster images (figs. 5, 6, 9, and 10).
- 2) Converted the PDF files for the twenty-six mine levels into forty-six raster images using TIFF image format supported by SUP. Many of the PDF maps were split into halves in order to preserve image clarity for manually digitizing the line traces (fig. 19).
- 3) Positioned the model in geographic space (WGS84) using the SUP geolocation tools using a set of reference buildings and the location of the headframe of the main shaft to constrain the alignment of the model and imagery (fig. 3). The SUP geolocation tool includes an option for generating a 3D digital-terrain model (DTM) that more than doubled the file size of each mine model.
- 4) Generated 3D hypsographic contours from the imported DTM using the SUP courbes de niveaux plugin (ver. 1.1.4) downloaded from the online SUP Extension Warehouse.
- 5) Manually digitized the line tracings of the ore body on each mine level as closed 2D polygons constrained to the XY model plane (fig. 14 and 21).

- 6) Extruded each level polygon seven feet vertically along the z-axis to construct multicolored 3D levels (figs. 9 and 13).
- 7) Added the zero fault where it cuts the deep levels as portrayed in NJZC glass-box model (fig. 22)
- 8) Rotated the model 19° clockwise relative to true north (figs. 6 and 20).
- 9) Digitized Kroth's (1993) 2D polygons of the mud zone at the 0 (ground), -340, -430, -500, and -600 levels in and below the Passaic Pit (fig. 23). Digitized Kroth's (1993) 2D polygons of the current tunnels used for the SHMM mine tour (fig. 23). These were constrained using a set of surveyed benchmarks embedded in the tunnel walls that Picatinny Arsenal recently used for robotic tests.
- 10) Digitized the NJZC cross section of the area constructed at the 1 in: 1000 ft scale (fig. 8; Metsger, 1975).
- 11) Assembled and digitized part of the zero fault and some associated, footwall shear zones mapped in the NJZC report detailing the geologic nature of the sheared, southeast limb of the ore body at the 1 in: 100 ft scale (figs. 24 to 26; Baum and Williams, 1947).
- 12) Digitized Kroth's (1993) 2D polygons of the current tunnels used for the SHMM mine tour (fig. 23). These were constrained using a set of surveyed benchmarks embedded in the tunnel walls that Picatinny Arsenal recently used for robotic tests.
- 13) Digitized the NJZC cross section of the area constructed at the 1 in: 1000 ft scale (fig. 8; Metsger, 1975).
- 14) Assembled and digitized part of the zero fault and some associated, footwall shear zones mapped in the NJZC report detailing the geologic nature of the sheared, southeast limb of the ore body at the 1 in: 100 ft scale (figs. 24 to 26; Baum and Williams, 1947).

Data Interpretation

- 1) Manually constructed 3D TIN surfaces around the core structure and top and bottom infiltrated layers (fig. 14). The volume of the core structure as interpreted is 28,059,466.73 ft³.
- 2) Manually constructed a 3D triangulated integrated network (TIN) surface that envelopes the mapped ore body with a volume of 779,881,868.92 ft³ (figs. 14, 15, and 18).
- 3) Identify and digitize representative geometric breaks in the 3D envelope reflecting localized faulting and offset of the ore body (figs. 15 and 18).

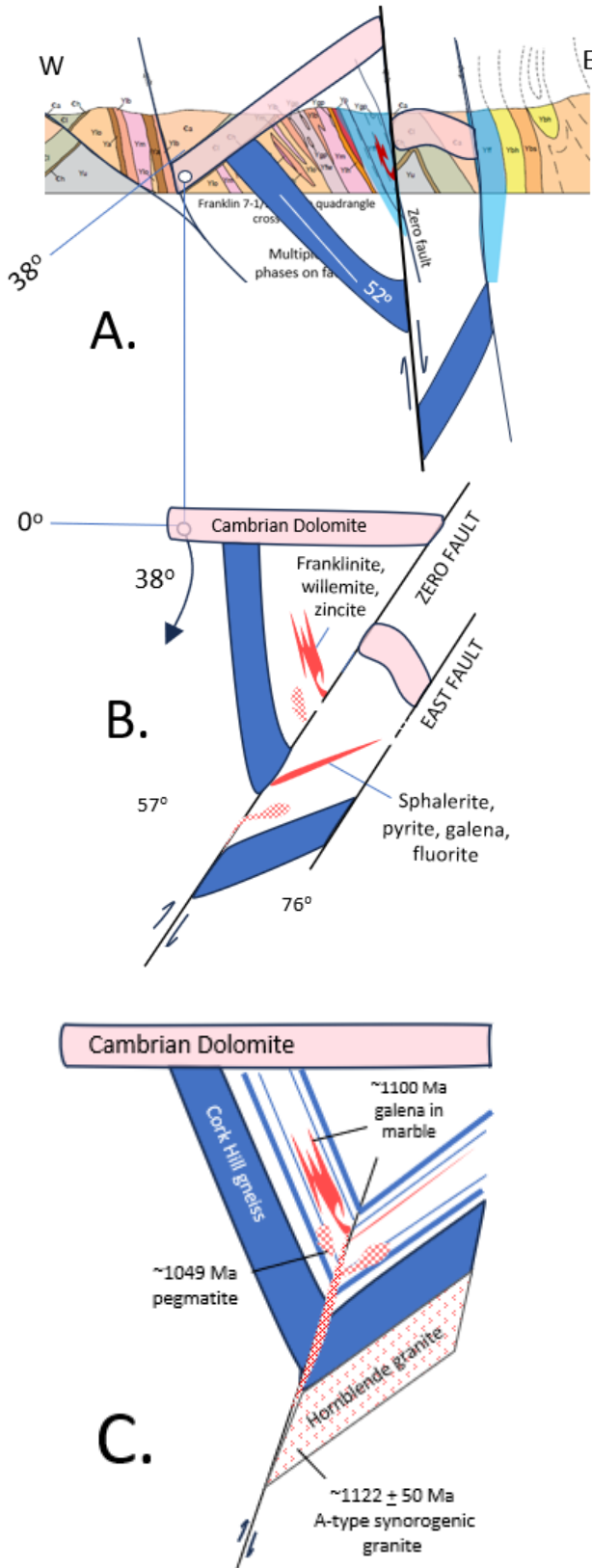


Figure 16. Structural restoration of the basal Cambrian dolomite to horizontal shows how the zero and east faults probably originated as northwest-dipping reverse faults during early Grenville tectonism. A.) Shows the current structure based on cross section A-A' of Volkert and Montverde (2013) as modified by details included on the NJZC cross section of figure 10. B.) If we assume that Proterozoic-age faults rotate with the overlying Paleozoic strata during subsequent tectonism, then upon restoring the Cambrian dolomite to horizontal, the zero fault restores to a reverse fault and a fault-propagation fold in Mesoproterozoic strata holding the ore deposits. The fold symmetry shows eastward vergence with the western fold limb dipping steeper than the east. C) Structural restoration of Mesoproterozoic strata into an open, upright syncline depicted with little offset of the ore body across early fault slip on the developing zero fault. The restored geometry is consistent with the structural grain observed in underlying Proterozoic basement in exploration seismic-reflection data (Herman and others, 1997).

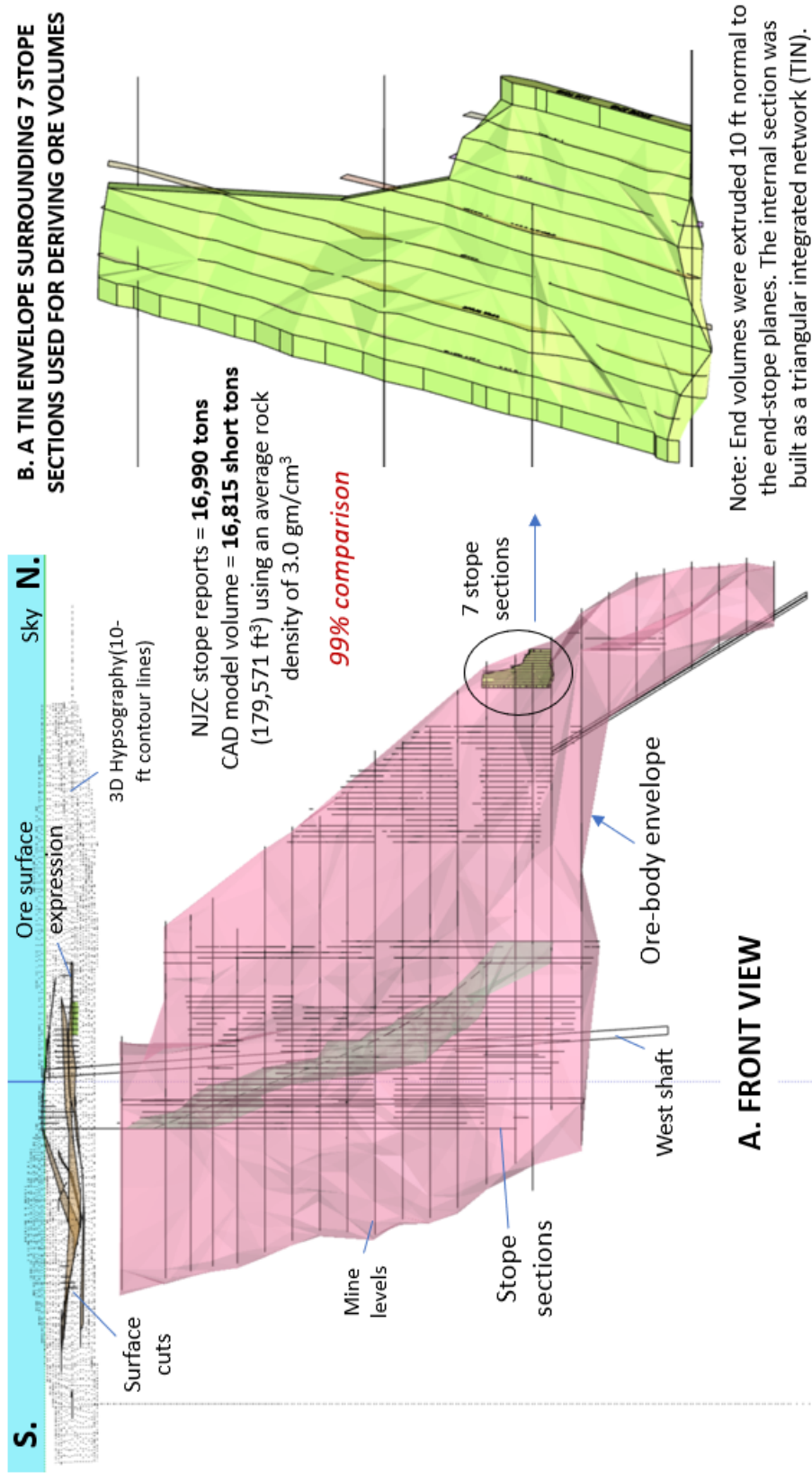


Figure 17. Longitudinal views of the Sterling Mine. A.) A pink-colored geometric envelope was built around the Sterling Hill ore body in order to compute its volume and provide geometric insights into its structural nature. B.) A comparison of the volume of ore removed from an area covered by seven stope sections was also modelled using a triangular integrated surface (light green) that resulted in a 99% agreement with the ore volume reported by NJZC.

- 4) Insert and scaled 3D ellipses corresponding to interpreted faults (fig. 15).
- 5) Export the SUP mine model to an AutoCAD drawing exchange file (rev. 12; DXF file extension) that was imported into the QGIS (ver. 3.28.12) geographic information system. The QGIS Line Direction Histogram plugin (Tveite, 2015) was then used for azimuthal representation of the ore headings and cross cuts (fig. 21).

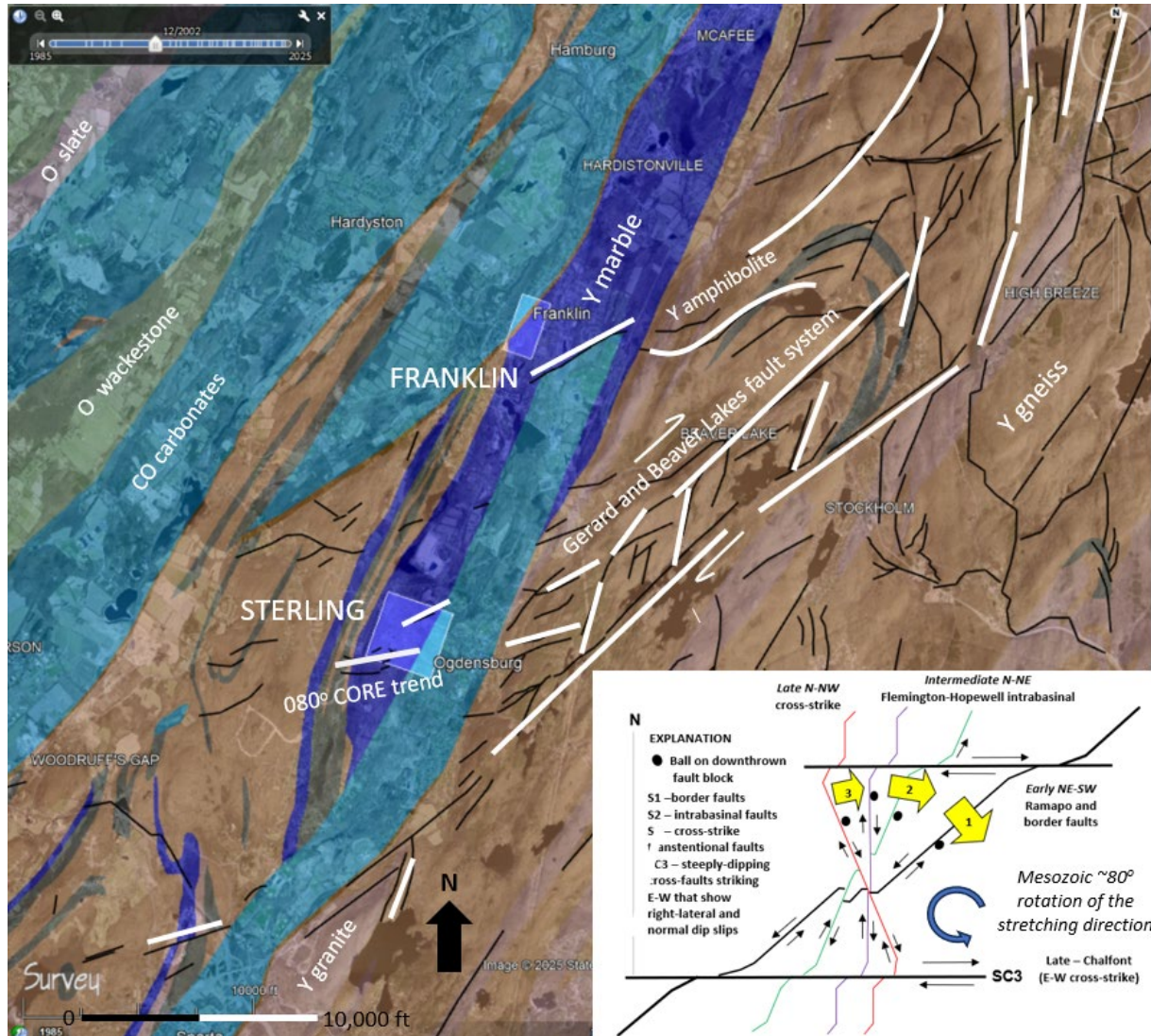


Figure 18. GE Pro was used to overlay the U.S. Geological Survey digital bedrock theme for New Jersey on a 2002 aerial image of part of the NJ Highlands covering the Sterling and Franklin Mines. A fault system crossing through Gerard and Beaver Lakes corresponds with topographic creases following surface drainage. This old fault system isn't depicted on bedrock geology maps, and strikes parallel to rift-related faulting of Mesozoic age in the Newark Basin to the southeast as summarized in the lower right panel (Herman, 2015). Ore metals may have been carried by fluids flowing through these faults that cross Mesoproterozoic bedrock through the Franklin Marble along the core trend.

STRUCTURAL AND TECTONIC ANALYSES

Despite having a constrained sense of how these zinc deposits have been repeatedly tectonized and strained throughout Appalachian history, questions remain as to how the protolith for the body of ore was originally structured. The nature of Grenville-age folding and faulting of the Franklin Marble and associated gneisses and ore bodies is complex. Hague and others (1956) summarized the nature of folding seen in these Mesoproterozoic rocks:

- Minor folds are small-scale, generally isoclinal folds observed in many of the gneisses throughout the area. Their amplitude ranges from a few inches to several tens of feet.
- The trace of the banding in places forms a serpentine map pattern, reflecting small-scale undulatory folds whose axes plunge nearly down the dip of the banding. The axes of these folds are oblique to the mineral lineation, and the folds were probably formed after the main period of deformation.
- Cross folds are present in the Lake Lenape syncline, in the Pimple Hills syncline, at the north end of Mount Eve, and elsewhere. Analysis of the attitude of folds in the area shows that the average bearing of major fold axes is N40°E and the average bearings of the two sets of cross-folds are north-south and N70°E. If the cross-folds are related to the major folding, the major compressive forces probably directed from the southeast to the northwest, probably had minor components of force directed so as to produce cross-folds oriented at roughly 30° to the major folds. If the formation of the cross-folds postdated the major folds, the cross-folds may have resulted from compressive forces from the northeast and southwest, roughly at right angles to the major compressive forces, or from horizontal movement along northeast-southwest shears.

Metsger (1980) proposed that the shape of the ore body is that of “an inverted diapir whose shape may have been influenced both by gravity and tectonics at an early stage of formation.” The evidence offered are:

- Ore textures grade from massive granulose and gneissose to disseminated "pepper and salt." The appearance of the gradation suggests that the ore minerals as well as the adjacent calc-silicates were friable masses which became disaggregated within an extremely plastic or, in part, even fluid carbonate.
- The shape of the ore body itself suggests a huge flow pattern influenced by a broken band of brittle gneiss fragments which it has engulfed. Where the sharply angular gneiss blocks are near ore, the ore banding is bent around them. Where they are isolated in marble, the flow pattern is revealed by contorted silicate and graphite bands (fig. 2).

- When the average density of the entire body (approximately 3.02) is considered together with the visual evidence for the plasticity of the enclosing marble ($d = 2.75$) it seems almost a certainty that the complex fold pattern of the ore body is due to its movement through the marble. It has therefore been proposed (Metsger and others, 1969) that the body acquired its present shape as it sank through the limestone as “an inverted diapir”, or density flow.
- Marble “dikes” are common in the gneiss and granulite associated with the metamorphic sequence. They were formed when the mobile carbonate flowed into fissures in the more brittle rocks. One such dike was observed in a pyroxene granulite fragment in the core of the Sterling ore body. The dike contained a vein of galena which occupied a fracture in the marble. The lead age of the galena, manifestly of more recent origin than the surrounding rock, was 1100×10^6 years.

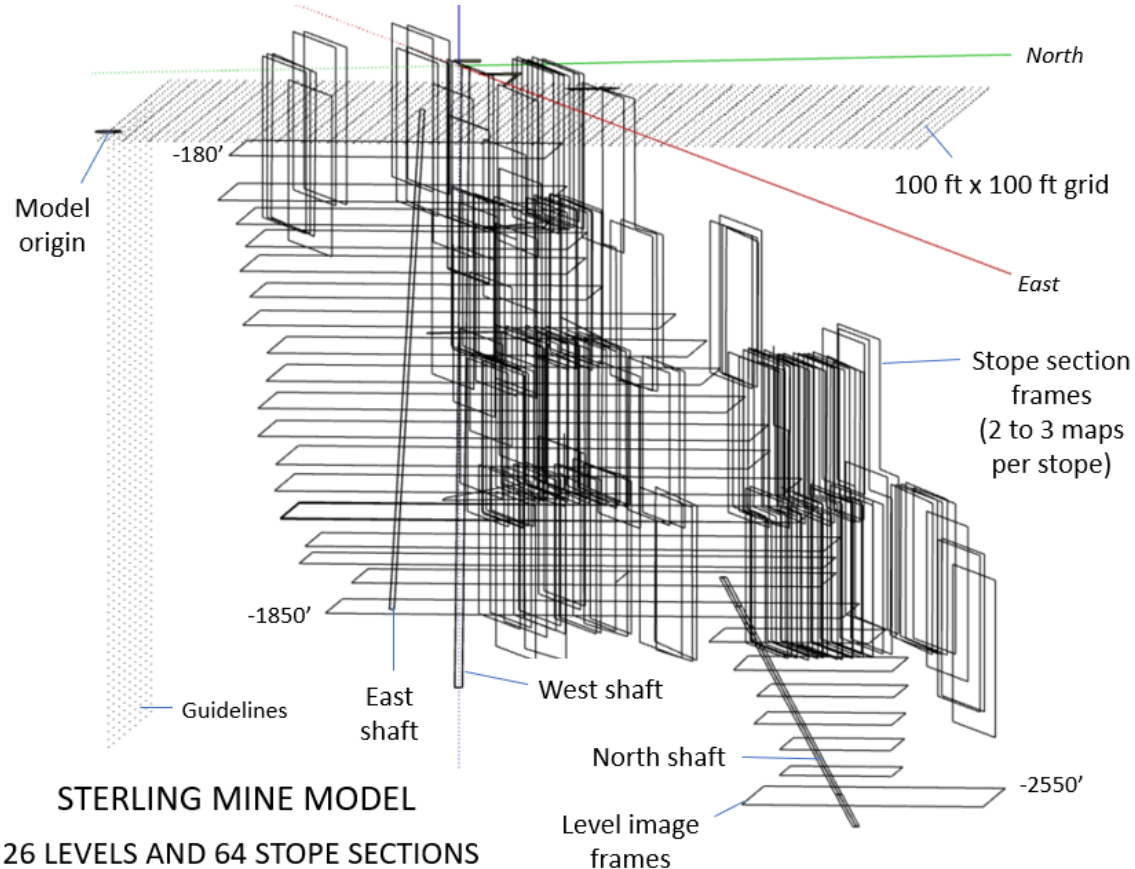


Figure 19. 3D tilted west view showing some model components including polygonal frames that were drawn around each registered TIFF and JPG image used to digitize the vector polygons. The frame borders were saved in the model to facilitate image reinsertion into the model. A total of 26 images of the level maps and 200 photographs of the stope sections were placed into the model using a horizontal mine grid with 100 ft cells and 200 ft vertical guidelines.

Matt, Peck, Mathur, Hurtgen, and Godfrey (2022) noted that the Sterling Hill deposits are layered with respect to chemical and isotopic composition and stated that “the absence of isotopic homogenization indicates a lack of pervasive fluid flow during metamorphism”. This is consistent with a scenario in which an iron and zinc-infused, hydrothermal plume emanated from a fault zone and infiltrated a mixed sedimentary assemblage prior to regional metamorphism (fig. 16). A central feeder structure formed beneath the contact of gneissic layers of greater compressive resistance than the adjacent carbonate protoliths. It’s possible that the core structure parallels the paleo stress direction and is an integral part of the old fault system seen transecting the highlands from west to east (fig. 18).

As seen in the mine models, the ore bodies at Franklin and the Sterling north sections are structured as a single, tabular sill-like body that is structurally segmented and offset along

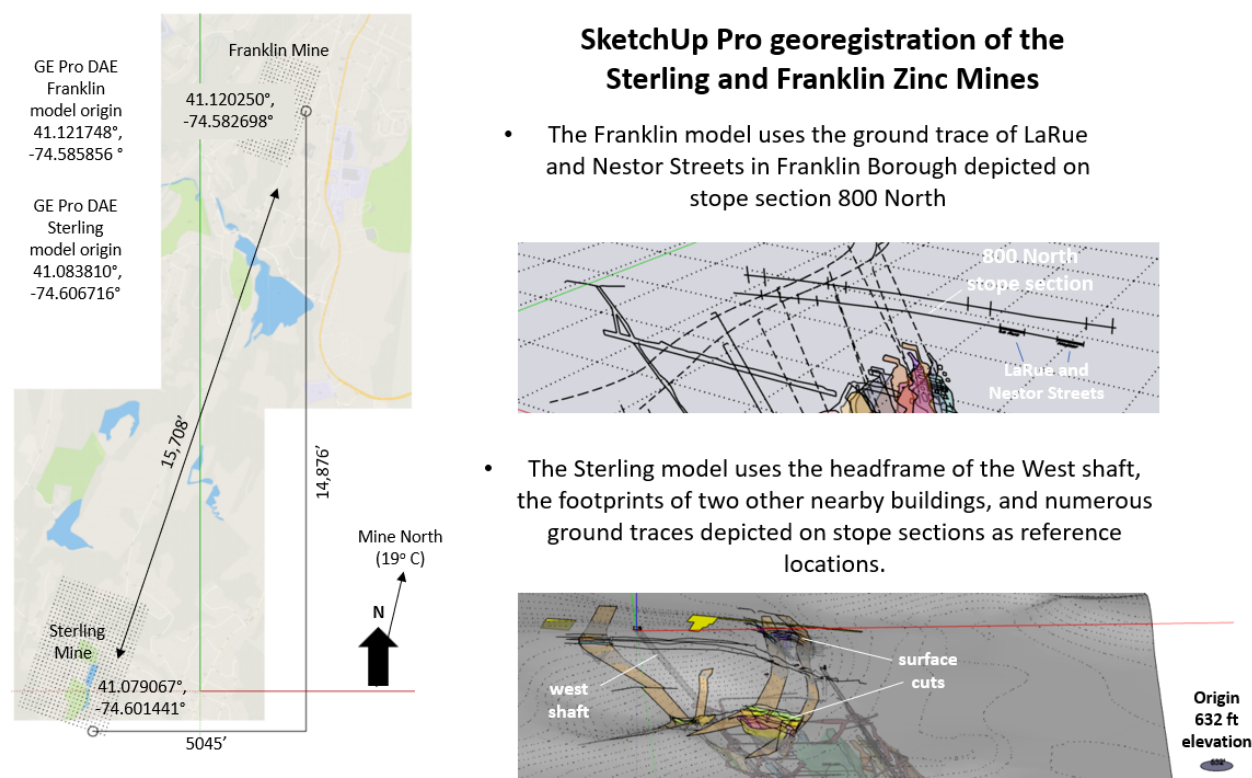


Figure 20. SketchUp Pro geolocation of the Sterling Hill and Franklin Mines relied on various criteria. The Franklin model is precisely located using the traces of LaRue and Nestor Streets in Franklin Borough as depicted on the cross section of the 800 North stope. The Sterling Hill mine used a set of reference buildings (yellow polygons) including the headframe of the west shaft, and a site map by Kroth (1993). The diagram on the left summarizes the arrangement of the two sites in geographic space (WGS84). Note the 19° clockwise (C) rotation of the mine-coordinate grids relative to true north.

strike (figs. 6, 7, and 11). But the core structure at Sterling Hill appears to have originated as an intrusive, metalliferous, fracture-and-fault-mediated hydrothermal plume with ferrous fluids infiltrating the carbonate layers, now located in the footwall fault block of the zero fault beneath the median gneiss (figs. 14 and 16). Tarr (1929) noted the necessity to assume that the ore protolith was originally a tabular mass within the limestone that may have developed “along a fissure of some type, or along some readily replaceable bed, either of which possibilities would (or could) permit the development of the tabular character, of the deposit.” He also noted that a branching bed at Sterling could be readily explained as a branching fissure structure.

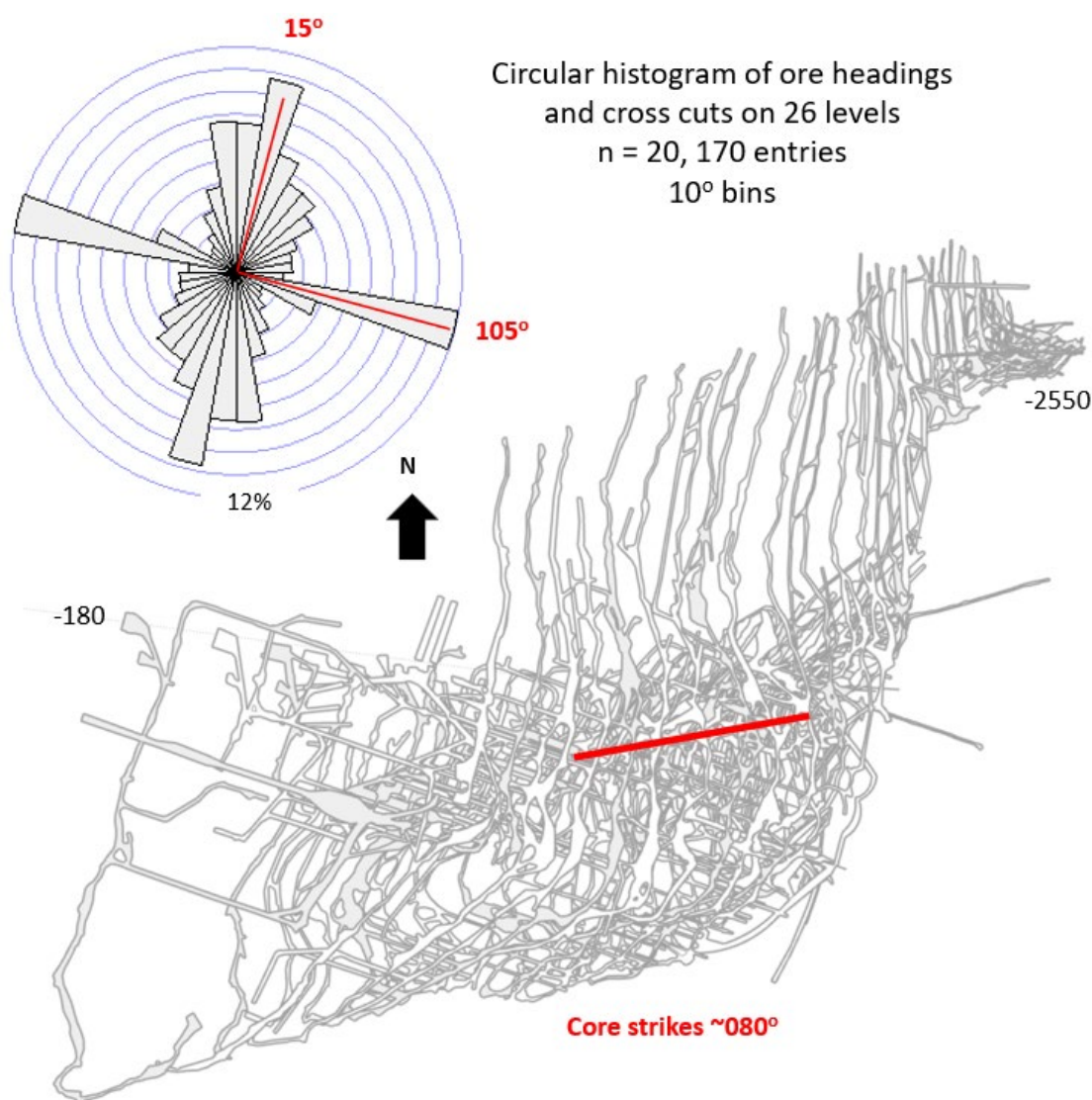


Figure 21. 2D polygons of the ore headings and cross cuts for the twenty-six mine levels of the Sterling Mine that were exported from SUP as a 2D AutoCAD DXF file and added to QGIS as a vector layer. The circular histogram is a plot of all of the headings for all of the different levels. The two dominant azimuths are 015° and 105°. The structural core of the ore body strikes ~080°.

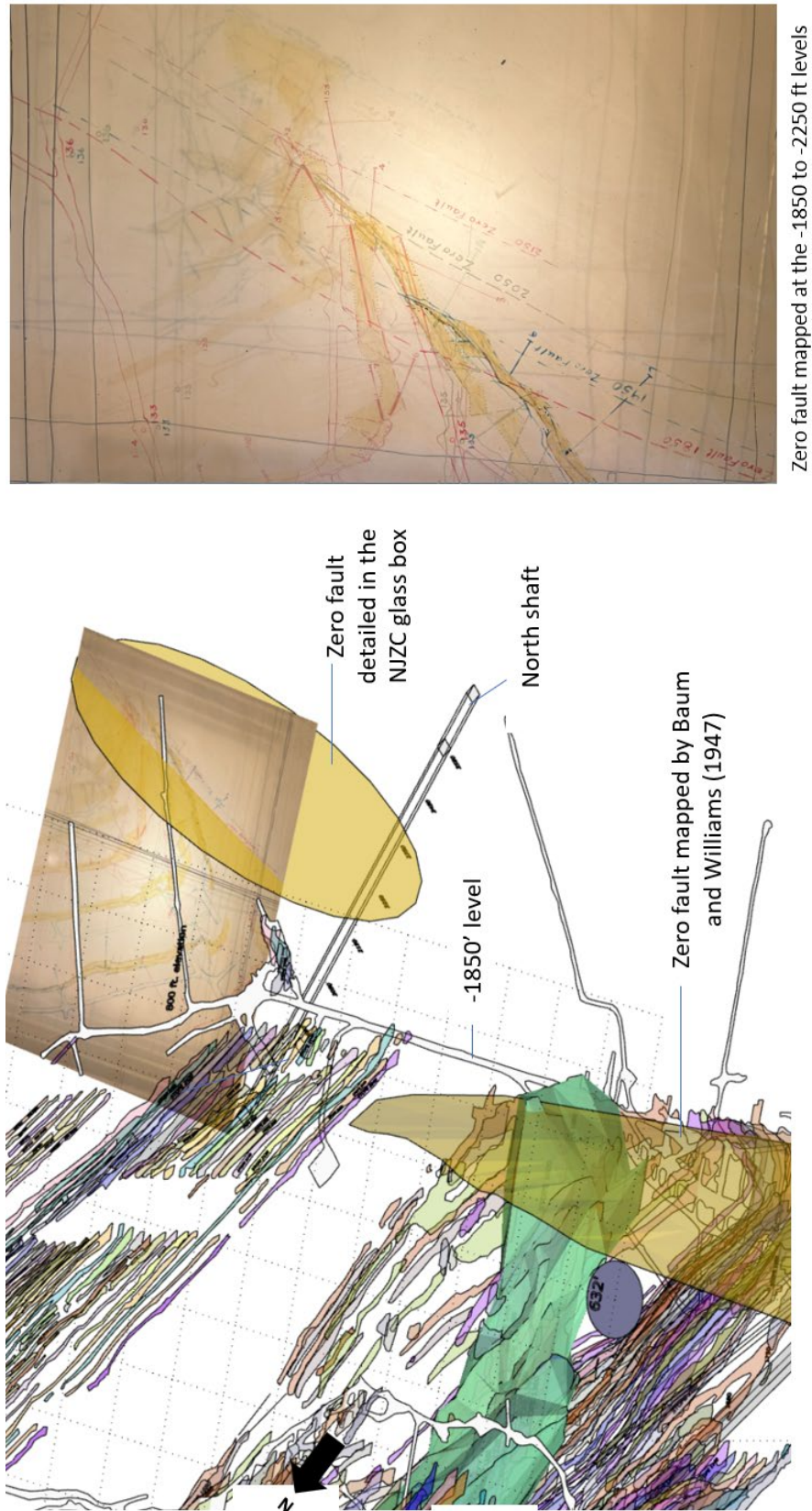


Figure 22. The zero fault was added into the Sterling model lower levels (left) based on its expression in the NJZC glass-box model (right photograph).

Rocks of the Losee arc predate the earliest Grenville tectonism and are characterized as a mobile arc complex, with the Franklin and Sterling zinc deposits likely originating in a back-arc basin (fig. 27 and Volkert, 2004). So, this was a tectonically active and thermally vigorous setting with concurrent igneous plutonism and faulting that helped drive crustal hydrothermal processes (fig. 16). The evidence compiled herein supports a metasomatic origin for these ore deposits that likely formed by infiltration of the Franklin Marble protolith by magmatically spurred, hydrothermal fluids discharged along an old reverse fault system that also cuts synorogenic type-

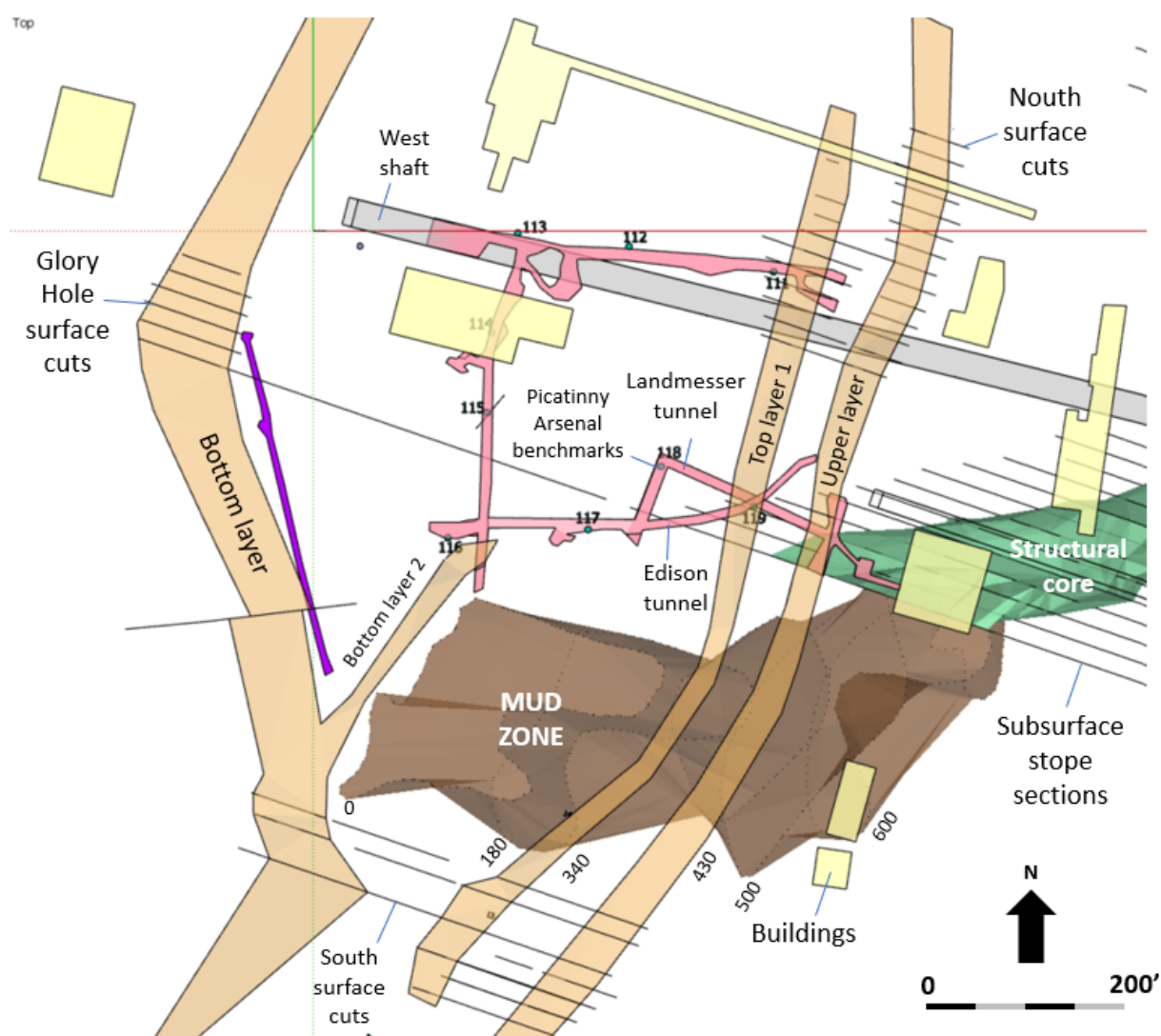


Figure 23. Top view (map) of the Sterling SUP model showing the mud zone relative to the structural core along with the tunnels used for the SHMM mine tour (pink). Other model elements include some SHMM buildings and subsurface features including the structural core (green TIN). Note where the sets of surface cuts occur.

A magmatic plutons (fig. 16). Puffer (2023) demonstrated that magmatically spurred anatectic melting and mineral fractionation occurred along the zero fault and other “penetrating structures” in the area where pegmatites associated with the Mt. Eve Granite occur. Metsger’s galena age (1100 Ma) overlaps with radiometric ages for the Byram and Lake Hopatcong A-type granite suites in the NJ Highlands (Volkert, Aleinikoff, and Fanning, 2010), and volcanism of the distant mid-continental rift (fig. 27). This must have been a huge tectonic event.

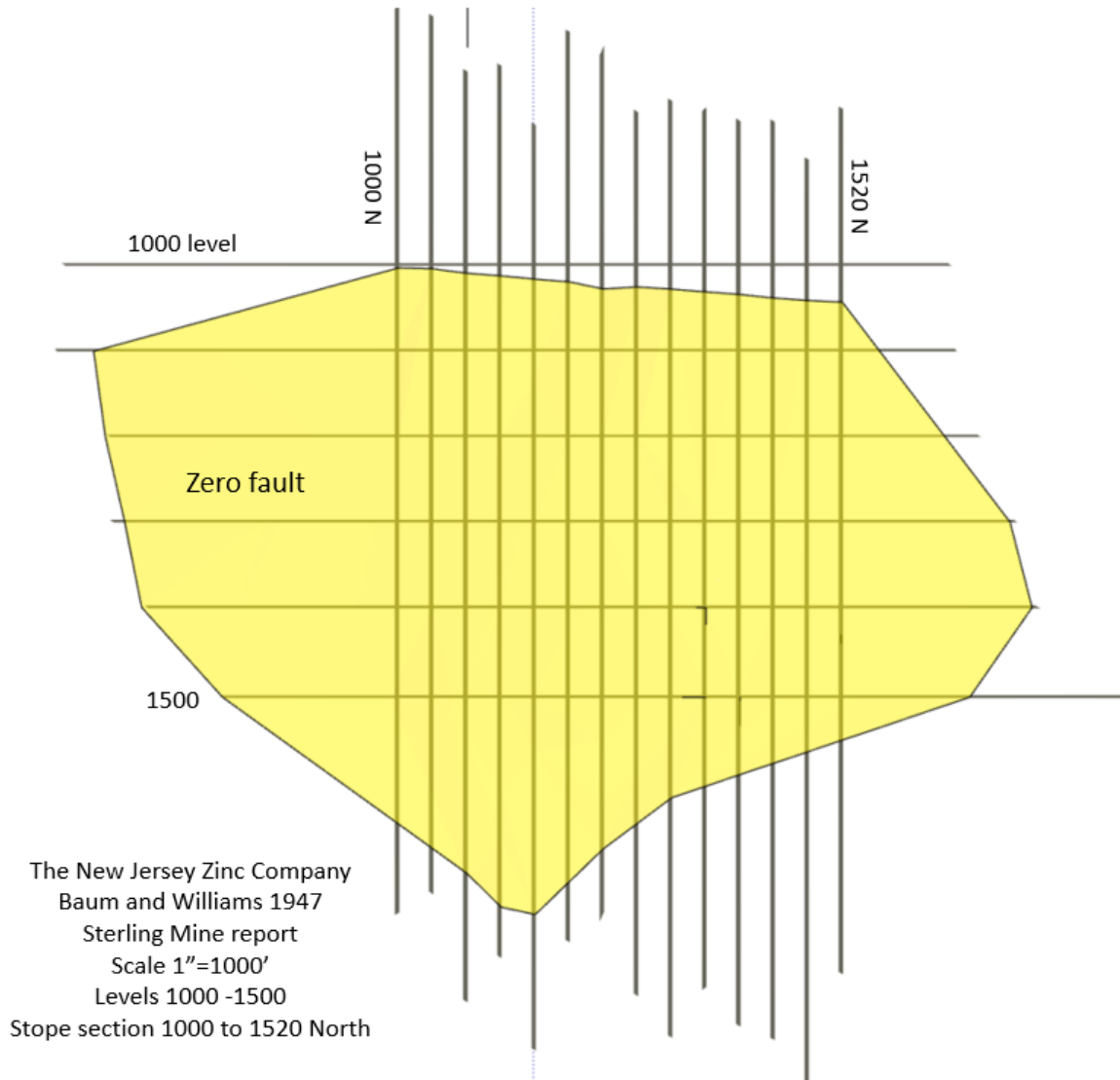


Figure 24. A NJZC internal report by Baum and Williams (1947) includes twenty maps and sections providing geological details on the structural and stratigraphic nature of the Sterling ore deposits for a 500 cubic-ft region of the deposit subject to faulting and shearing in the footwall of the Zero fault where the ore is spotty and lean (<8% bulk). The yellow area represents the Zero fault in longitudinal section based on its occurrence in the different levels and stopes.

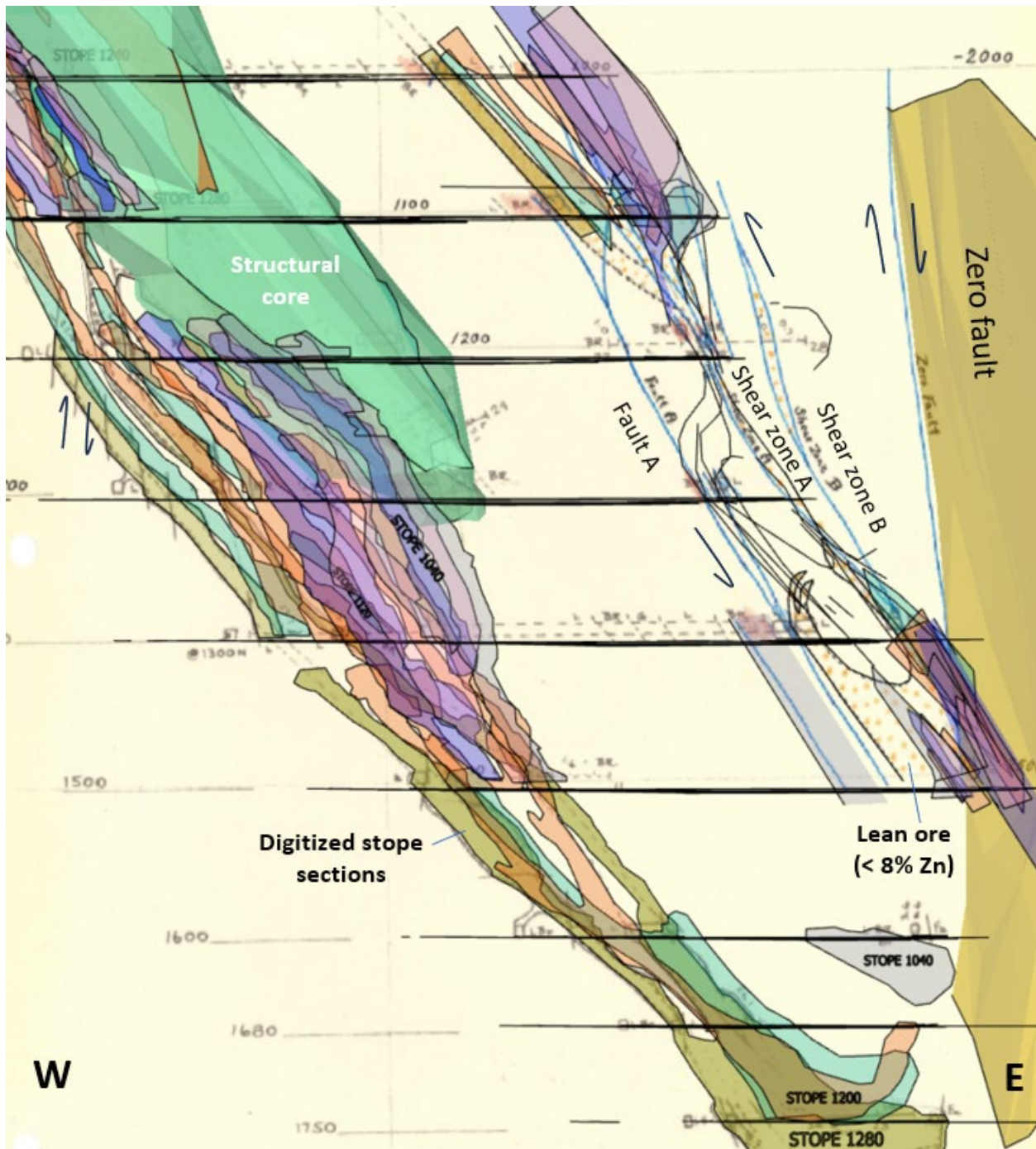


Figure 25. Part of the 1280 North stope section from the Baum and Williams (1947) Sterling report is shown with respect to some of the digitized ore layers and the structural core. The faulting history here is complex with reverse shear zones being subsequently stretched and down dropped along normal faults. The Zero fault likely has had several episodes of tectonic slip. Also note the faulting to the west that drops the ore layer down to the east, and the BR (black rock) layering beneath the upper ore.

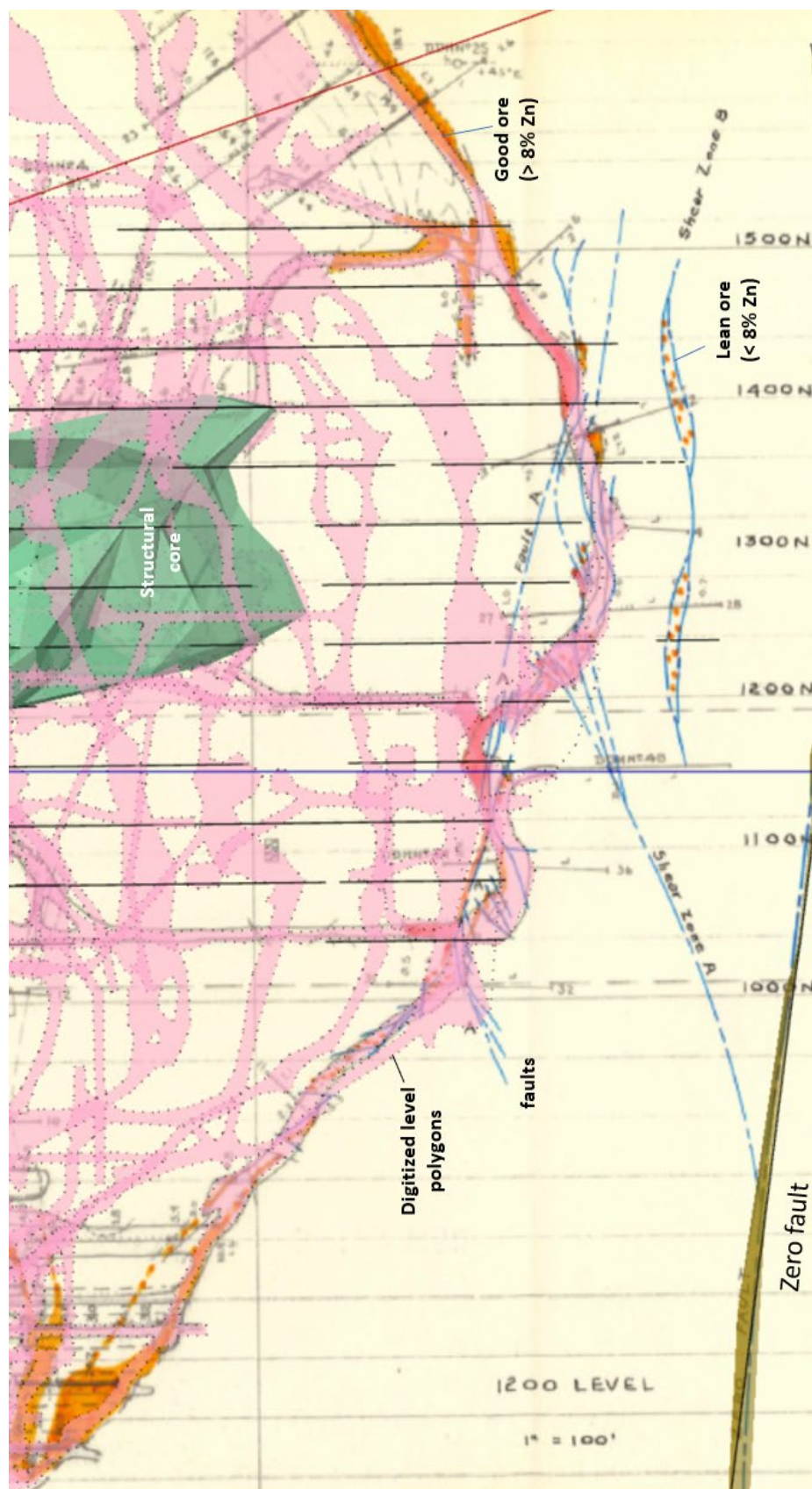
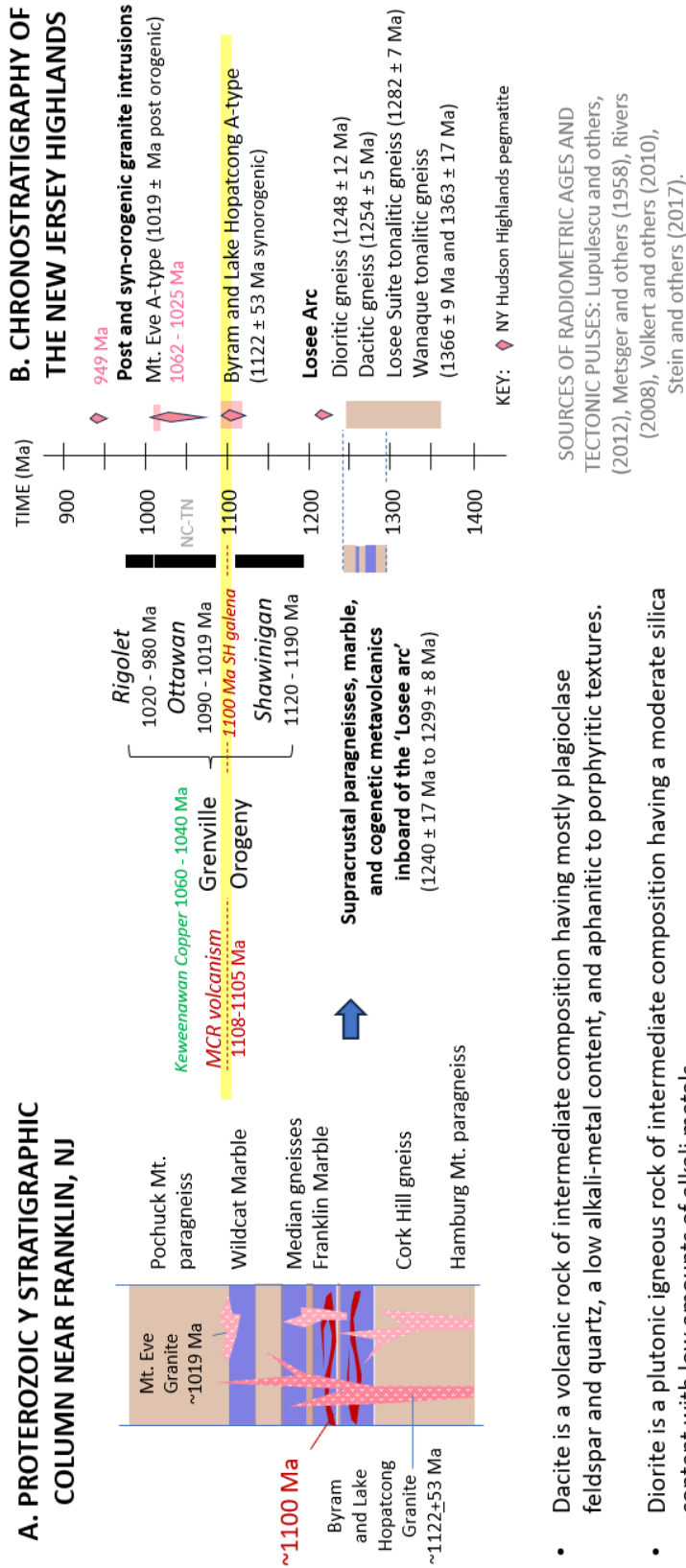


Figure 26. The 1200 level map from the Baum and Williams (1947) Sterling report shows how the upper, southeast layers of the ore body are locally sheared and stretched adjacent to the zero fault that has a complex movement history including reverse, normal, and oblique slips. The pink polygons are the digitized mine-levels, and the structural core (green TIN) is labeled. An 8% bulk concentration of zinc represent the cutoff between good (orange) and lean (orange stippled) ore. Drill and core holes are also noted on these maps in addition to smaller faults.



- Dacite is a volcanic rock of intermediate composition having mostly plagioclase feldspar and quartz, a low alkali-metal content, and aphanitic to porphyritic textures.
- Diorite is a plutonic igneous rock of intermediate composition having a moderate silica content with low amounts of alkali metals.
- Tonalite and Trondhjemite are plutonic, leucocratic igneous rocks of felsic compositions and phaneritic textures. Their bulk component is plagioclase feldspar with more than 20% quartz and less than 10% alkali metals. Amphiboles and biotite can be minor components with apatite, magnetite and zircon accessories. Trondhjemite is a tonalite with oligoclase.

Figure 27. Chronology of the Grenville tectonic cycle with respect to Mesoproterozoic (Y) stratigraphy near Franklin, New Jersey.

A mapped fault system shown in figure 18 cuts across the nearby northern highlands along the strike of Gerard and Beaver Lakes with ductile-brittle shear-zone geometry of possible Grenville origin. The angular gneiss blocks noted by Metsger and others (1958) that are entrained along the contacts with the hydrothermally charged marble makes sense when placed into a context of ductile-brittle, reverse shearing that is seen cutting across the highlands including the Franklin Marble where the ore occurs. The metalliferous plume likely flowed along and discharged from component faults in this system into the compressed and sheared footwall hinge zone of the Franklin-Sterling Hill syncline. This locally involved ductile flow of the marble protolith with entrained, brecciated blocks of a suprajacent, dark-gray protolith (figs. 12 and 16). Overall, the mineralized stratigraphic succession now holds dike-and-sill-like structures that were subsequently buried, compacted, metamorphosed, further sheared and tightened, then stretched and segmented by normal faults (figs. 15, 16 and 26) before Cenozoic exhumation.

The fluid nature of the ore infiltration can be directly observed near an excavated ore layer in the Passaic Pit where a webwork of franklinite weaves through dolomitic marble (fig. 28 and (field guide STOP 1). If Metsger's (1980) 1100 Ma age of the galena deposit within fractured marble is the age of initial mineral infiltration, then that phase of tectonism occurred after the first compressive pulse of the Grenville tectonic cycle (Shawinigan; figure 27). Grenville-age rifting also occurred in the area as evidenced by the hypabyssal, diabase dikes that crop out just a few miles south of Sterling Hill (Volkert and Montverde, 2013; Volkert and Puffer, 1995). But it's unlikely that the observed plasticity associated with the ore development would arise from post-orogenic relaxation and crustal stretching accompanying dike emplacement. It is however possible that another mineralization phase accompanied the post-Shawinigan rift event because there is more than one zinc-mineralization event at Sterling Hill as seen in figure 4 and reported by Verbeek and Grout (2018; 2025). An Alleghenian zinc-mineralization phase is also possible from fluid mobilization accompanying ductile shearing of the ore body as seen in the Baum and Williams report where the ore is lean. The Franklin-Sterling Hill ore deposit therefore appears to consist of metalliferous layers, and various cross-strike feeder structures that were emplaced then buried deeply, compacted and metamorphosed to sillimanite grade prior to uplift and partial surface exposure preceding deposition of the Cambrian Hardyston alluvium. Metsger (1980) noted the rubbly, weathered nature of the Precambrian erosion surface. Episodic hydrothermal alteration of these deposits has also repeatedly occurred here (Verbeek and Grout, 2018) and will likely occur again.

The structural form of the stope sections and outcropping structures also provide insights into the nature of probable Paleozoic orogenic strains that further shaped the ore body. For example, the Sterling and Franklin stope sections repeatedly show three- to twenty-foot subhorizontal, top-to-the-northwest offsets of the ore body that provide a measure of fault slip resulting from the brittle shear zones that permeate the region during Late-Paleozoic Alleghenian

orogeny (fig. 29). The sheared and slickenside-covered hanging wall of the ore excavation at field STOP 1 in the field guide exemplifies these reverse shear zones that later compacted and thickened the sequence during Alleghenian Mountain building and northwestward crustal translation (Herman, 1992;2002). Structures in the southern highwall of the Sterling Noble Pit (field STOP 4) also shows this. The samples of smeared-out mylonitic ore in the Zobel Hall museum attest to the ductile component of the brittle-ductile incremental strains that accompanied Appalachian orogenesis after final crystallization of the marble and ore (fig. 30). This is congruent with what is seen elsewhere in the region; Alleghenian-age orogenesis prior to the onset of Mesozoic Newark rifting leading to the opening of the Atlantic Ocean basin (Herman, 2002; fig. 8). Nevertheless, all of the faults are of uncertain ages until radiometrically dated and of uncertain slip distances unless directly measured using offset indicators. No such indicators were observed in outcrop, but some can be traced in aerial imagery (see field guide). Structural interpretation only offers hypothetical solutions that can be tested and modified if necessary.

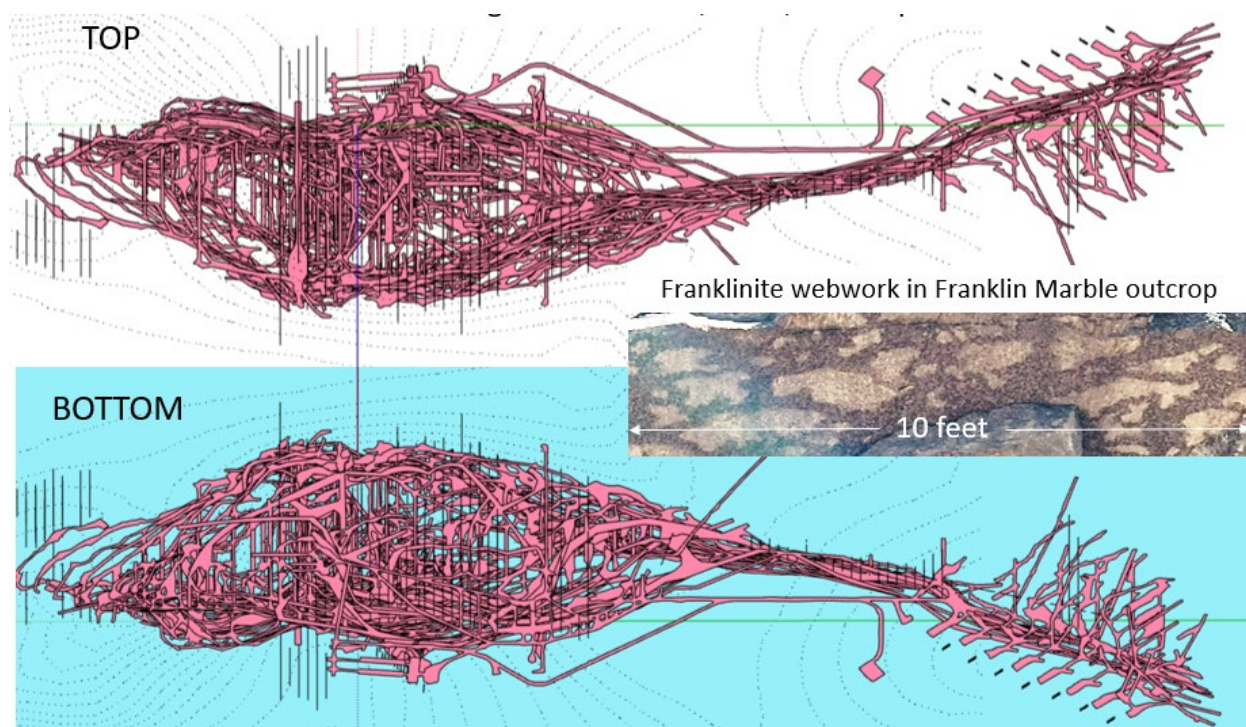


Figure 28. Top and bottom views of the composite Sterling Mine works including the digitized ore drifts and cross cuts on all levels, and the stope sections (thin black lines vertical lines). 3D hypsography is shown as thin dotted lines using 10-ft contours. The inset diagram shows the mineral-infiltration pattern of franklinite in marble as seen on the underside of a marble layer at field STOP 1. These analogous patterns suggest that the mineral complex was compressed and squeezed again after infiltration in a direction normal to these elongate mineralized layers. The deepest workings correspond to the fishtail on the right.

Please see chapter 3 of this volume by Verbeek and Grout (2025) for more information about the nature of faulting at Sterling Hill.

The southern high wall in the Noble Pit is an ore-bounding fault that's likely a Newark-age normal fault (figs. 3, 6, 15 and field guide STOP 3). Other, similar faults also offset the Franklin ore body in places as portrayed in figure 6B. These too are probable, Mesozoic faults that strike parallel to those involved in Newark rifting to the east (fig. 18). Extension through this region was extensive, with Jurassic dikes emplaced even further westward into Pennsylvania along the northern Susquehanna River Valley (Herman, 2013). Rodger Faill (2003) also recognized the widespread nature of mid-Atlantic Mesozoic rifting, but the importance and extent of widespread tectonic stretching only became more apparent recently with the advent and use of LiDAR and virtual globes like GE that bundle historical imagery into their visualization tools. In particular, their 2002 aerial imagery (fig. 18) is very good at revealing geologically induced topographic breaks along known Newark trends throughout the northern New Jersey region with north-to-south striking fault blocks that are inherited from a late stretching phase directed eastward (Herman, 2015). Accordingly, the mine and work gaps together with the offset of the

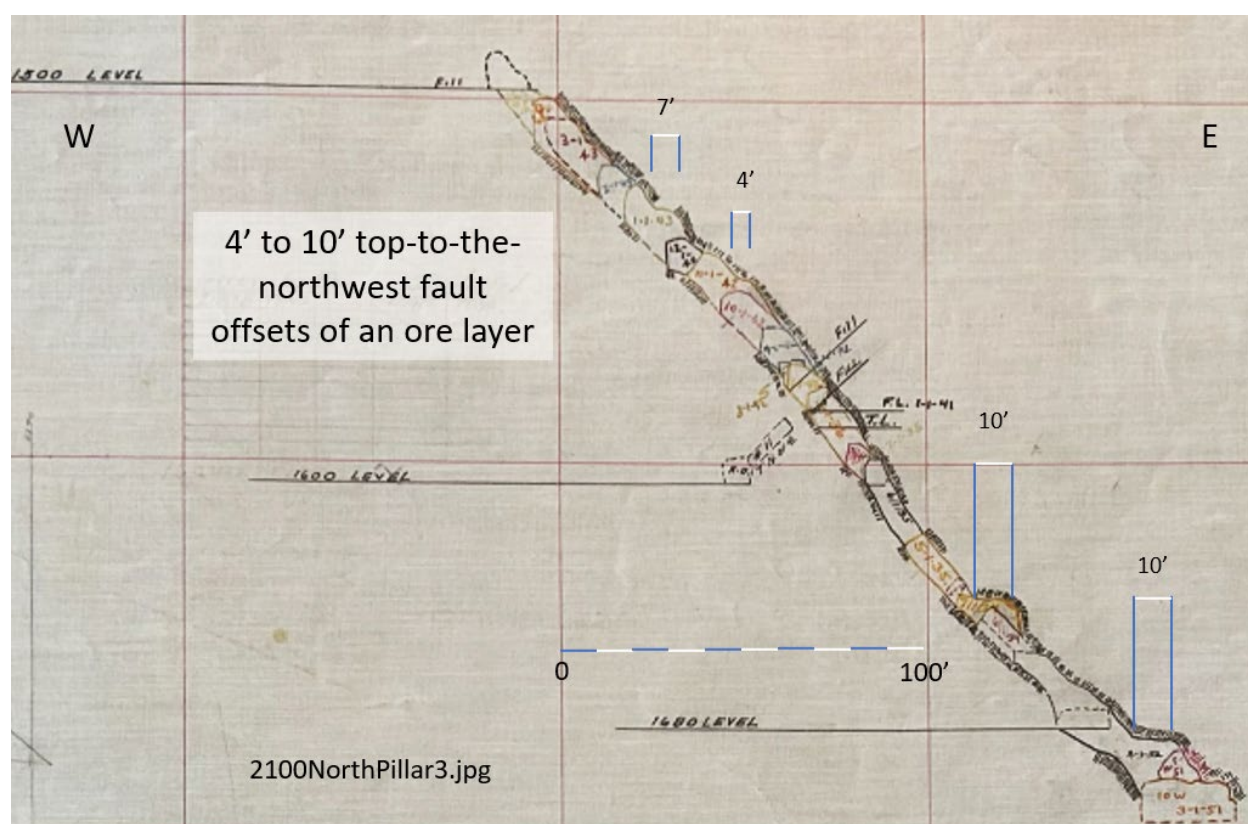


Figure 29. A photograph of the 2100 North Pillar stope section is used to illustrate how the ore layers are pervasively sheared with top-to-the northwest offsets. These offsets are likely Alleghenian faults that contracted, thickened, and elevated the New Jersey region during the Appalachian orogeny.

ore bodies between Sterling and Mine Hills probably results from breakage and weathering along faults resulting in Mesozoic rifting and wrenching of the crust immediately prior to birth of the Atlantic Ocean. Altogether, the stope gaps and structural fragmentation and jostling of the ore body reflects incremental brittle and ductile compressional strains accumulated during bulk shearing and translation before segmentation and stretching with brittle normal faulting.

THE NJ STATE MUSEUM METSGER ESTATE COLLECTION (NJSN NH2013.15)

Most of the contributors to the GANJ 41 guidebook and conference proceedings met on May 4, 2025 near Franklin to begin coordinating activities. Earl Verbeek told us then that part of the NJZC information was given to the New Jersey State Museum (NJSN) in the late 1980s by the estate of Bob Metsger. I subsequently planned a trip to the museum on Friday June 27, 2025 to meet Rodrigo (Rod) Pellegrini, Registrar of Natural History, to review the NJZC materials. I drove there with J. Mark Zdepski and also met with Mike Di Maio and Julia Vastano, NJSN assistant curator for Natural History. We spent a few hours together combing through the archived samples, thin sections, maps, and documents that are now housed in the natural history specimen storage areas of the NJSN. We photographed select materials and learned about how the museum had begun cataloguing the collection. The collection has a preliminary index that was shared by the museum and is available on the GANJ/2025 website. Please see Rod Pellegrini's abstract at the front of this volume for more information about the NJSN Metsger collection.



Figure 30. Mylonitized zinc ore in Zobel Hall, Sterling Hill Mining Museum.

Despite having time to only glance at about half of the NJSM holdings, we located and copied two important internal documents during this visit that have a significant bearing on this study. The first one is a deep cross section of the area constructed along the 1600 North stope that is based on exploratory rock coring (fig. 12). It illustrates the bedrock geology of the Ogdensburg area to over one mile beneath the ground surface and shows the Mesoproterozoic rocks folded into a tight, upright syncline that is cut by the zero fault that dips steeply east through the hinge area, and offsetting the opposing fold limbs. One core hole shown on this section transects the hanging wall of the zero fault and now resides in the Rutgers core repository (table 1). The locations and lengths of other rock core hole from Sterling Hill and Franklin that are included in table 1 require confirmation. A second document of note is a 1947 internal report by John 'Jack' Baum and William Williams, geologists for Sterling, titled "The nature of ore occurrence and structure in the lower portion of the East vein at Sterling". Jack Baum was the NJZC chief geologist (1950 to 1981) before Bob Metsger (1981 to 1988) and was involved in exploration and mining there and elsewhere for decades. No other information was found about Mr. Williams from a cursory Internet search using his name and employer. This report includes structural and stratigraphic details of the sheared-out eastern limb of the regional syncline between the -1000 and -1500 levels and the 1000 to 1520 north stope sections (figs. 25 and 26). The maps are at 1 in: 100 ft scale and include some bulk zinc concentrations of specific ore layers that range from 8% to over 30%. Layers of dark gneiss labeled "black rock" were also mapped in drifts cutting the marble. The black rock is reported as having originated as siliceous and aluminous interbeds of clastic and possibly igneous origin within an impure limestone (fig. 25). The layers of black rock comprise less than half of the bulk of the Franklin Marble and are situated beneath the Median Gneisses, of which there are two (fig. 12). Ore mineralization is associated with the black rock where haloes occur around fragments floating within the marble, and in the marble adjacent to thick black-rock layers (fig. 25). They point out that the entire complex was folded during the process of ore emplacement, and then the beds were further distorted through faulting and drag folding resulting in the distortion of horizons favorable for ore. They illustrate the overall distortion of the ore body from late tectonic stretching. The stope sections show that the structure of the limestone and black layers form interlayered marble and gneissic lenses with favorable ore horizons developed in the carbonate-rich layers.

SHARED COMPUTER-MODEL FILES

The SUP and associated files used to build the Sterling Hill and Franklin models are available on the Internet as free downloads from the 2025 GANJ website at the URL www.ganj.org/2025/data/. The following list summarizes the respective shared files:

File (file size and date)

SketchUp Pro (SUP) files (rev. 2024)

2025-07NJZCSterlingMineR19.skp (377,789 KB 07-28-2025)

2025-06NJZCFranklinMineWODTM.skp (42,456 KB 06-07-2025)

2025-07NJZCSterlingMineBaumandWilliamsZeroFaultR19.skp (14,942 KB 07-06-2025)

Compressed ZIP files of level and stope raster imagery

NJZCSterlingMineLevelMaps.zip (170 MB, 07-13-2025)

NJZCSterlingMineStopeSections.zip (116 MB, 07-13-2025)

NJZCFranklinMineStopeSections.zip (138 MB, 07-13-2025)

Google Earth Pro KMZ file

2025GANJ41NJZCSterlingHill&FranklinMines.kmz (4,019 KB, 07-18-2025)

MS Excel file

SomeVerbeek&Grout2025StructuralDataGCH09-26-2025.xlsx (51 KB, 09-26-2025)

Using the SUP models requires a proficient level of familiarity with the software. Users assume all risks and responsibility for their access and use. It's advised to download the original file, copy it, and rename it before implementing any further changes. The associated sets of raster imagery that the models were built from are also shared as compressed ZIP files. The ZIP files must first be decompressed into their individual files before reinserting them into the SUP models using embedded image frames (fig. 19). File types for Sterling Hill include TIFF and PNG but only PNG files for Franklin.

A derivative GE KMZ file is also shared that includes selected elements for each model that were imported and georegistered in GE as Collada objects (DAE files; figs. 31 and 32). These models can be interactively displayed and manipulated by anyone using the program. As a reminder, the Franklin Mine model is only partly developed in comparison with the Sterling Mine model. The Sterling DAE derivative model includes only subsets of model objects including TIN surfaces, 2D level polygons, 3D shafts, and cross sections of the surface cuts. The objects can be manipulated in 3D space in GE by accessing the model after loading the KMZ file, and adjusting its elevation in the following manner:

Open the KMZ file listed above, expand the folder to access an embedded *.dae object (MineHillFranklinR19C.dae or 2025SterlingMineR19CTINS.dae). Then, using a computer mouse, touchpad, or control arrows and <Enter> keys,

- 1) Activate a DAE model by checking its box and select a DAE object. The background will be blue when selected and active.
- 2) Right-click <Properties> or left click <Edit><Properties>.
- 3) With the object active and highlighted by green handles, click on <Altitude> and adjust its height from <Clamped to ground> to <Relative to ground>, and then use the slider or enter a desired elevation to raise and lower the model vertically.

A METHOD FOR CONVERTING STERLING HILL MINE FEATURES HAVING NORTH AND WEST COORDINATES (FEET) INTO GEOGRAPHIC DECIMAL DEGREES (WGS84)

This section summarizes a method for accurately calculating geographic coordinates (WGS84 - decimal degrees) of point-based mine features using north and west coordinate feet and the Sterling Mine grid (figs. 6 and 19). The methodology uses directional sines and cosines programmed into a Microsoft Excel spreadsheet to convert mine coordinates based on a reference grid that's rotated about its origin point 19° clockwise relative to true north (fig. 33). The north and west offsets of a point location are first converted to longitude (LON) and latitude (LAT) decimal degrees and then added to the geographic coordinates of the model origin point to compute its rotated location. The methodology uses the four equations below:

$$\text{Equation 1. } \text{WEST}_r = \text{WEST} * 0.94551857 + \text{NORTH} * 0.32556815$$

$$\text{Equation 2. } \text{NORTH}_r = -\text{WEST} * 0.94551857 + \text{NORTH} * 0.32556815$$

$$\text{Equation 3. } \text{LON}_r = \text{LON}_0 + (\text{WEST}_r * 0.00000368)$$

$$\text{Equation 4. } \text{LAT}_r = \text{LAT}_0 + (\text{NORTH}_r * 0.00000276)$$

The coordinate transformation is thus completed in two steps: Equations 1 and 2 calculate the north and west offsets resulting from the 19° grid rotation (fig. 33). Equations 3 and 4 compute the rotated geographic coordinates (LON_r, LAT_r) by adding the results derived from the first two equations to the geographic origin of the mine grid (LON₀, LAT₀). The trigonometric method is diagramed in figure 33 together with the charted results of a methods test using the ground-level field stations of Verbeek and Grout (2025; chapter 3). A MS Excel workbook containing the mathematical solutions for deriving rotated mine coordinates is included in this year's data downloads page on the internet (see file details listed in the prior section). The impetus behind deriving these relationships was to visualize the Verbeek and Grout (2025) fault data (Chapter 3).

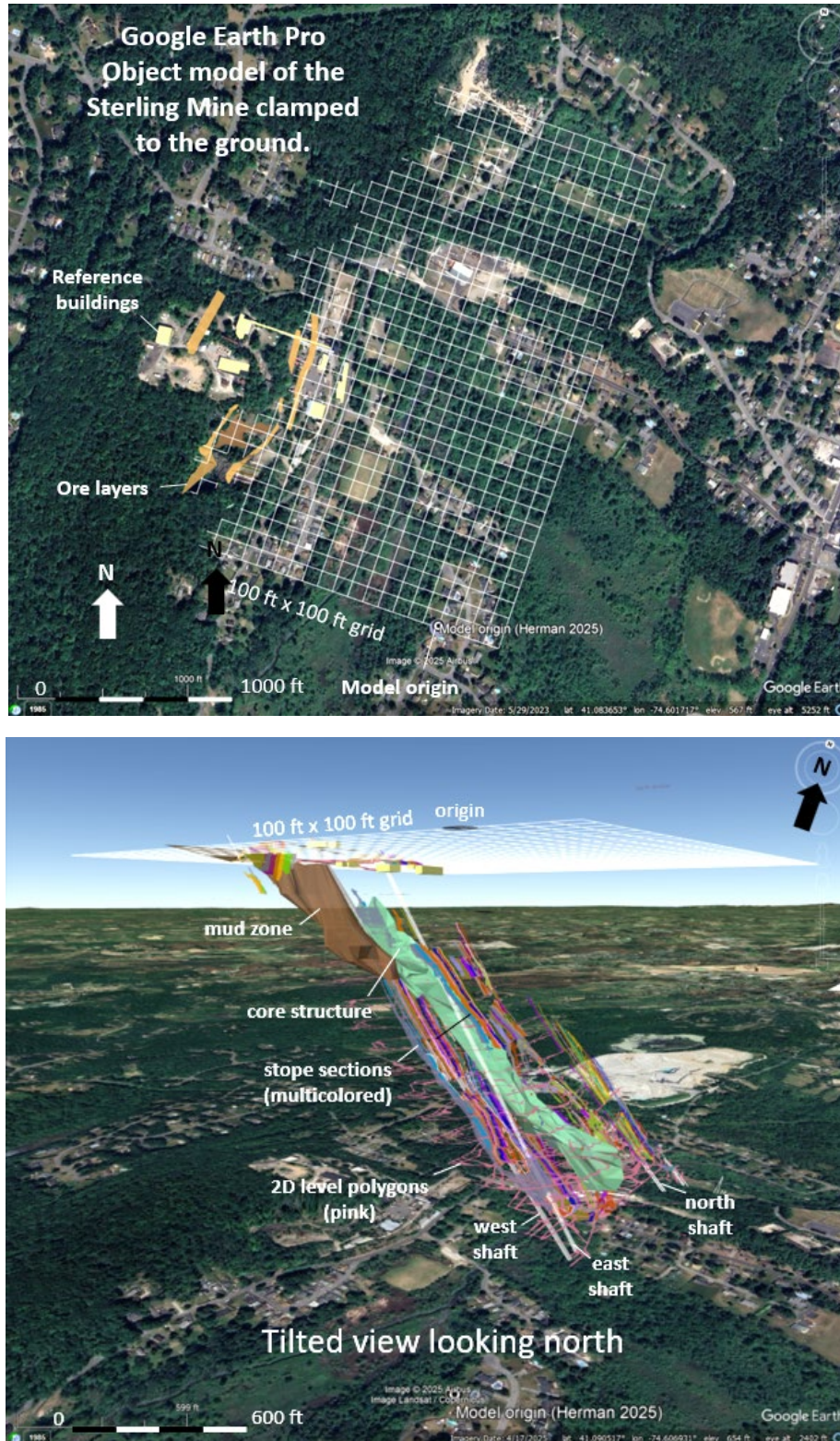


Figure 31. Map (top) and oblique, north view (bottom) of part of the Sterling Mine model that was added to a GE KMZ file as a Collada object (*.dae file). The map view has the model clamped to the ground. The bottom view shows the model raised 600 m (~1968 ft) vertically above ground. Only select components of the SUP model were exported as the DAE object model including the mine grid, reference buildings (yellow), and surface cuts in the ore body (multicolored). Ore layer surface traces appear as orange stripes in the map view. TIN surfaces of the structural core (green) and mud zone (brown) are shown below along with stope sections (multicolored), 3D shafts (white), and the twenty- six level polygons (pink).

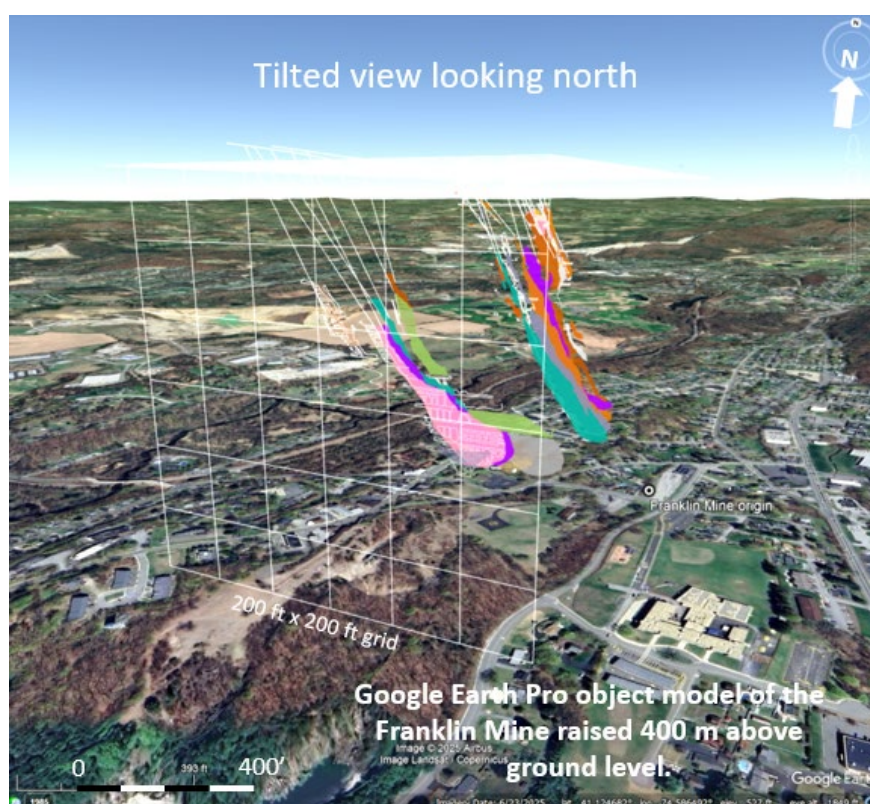


Figure 32. Map (top) and oblique, north view (bottom) of part of the Franklin Mine model that was added to a GE KMZ file as a Collada object (dae file). The map view has the model clamped to the ground. The north view shows the model raised 400 meters (~1312 ft) vertically above ground. This object model includes the mine grid, some multicolored stope sections, and line projection of the ore body to the surface.

Their observations and measurements constrain the location of reverse and normal-fault systems that help shape the ore body as illustrated using the aforementioned 3D CAD models. Discreet representation of 3D faults is made possible with the GE Pro virtual globe that can display oriented, colored, and scaled geological symbols to portray their orientations in geographic space relative to geological contacts and other mapped features (fig. 31, 32, and 34). Figure 34 features a GE Pro KML file of 308 oriented and scaled red ellipses generated from the near-surface fault data by Verbeek and Grout (2025 and Chapter 3). The KML was generated using the online geology tool www.impacttectonics.org/GeoTools/exceltoKML.html. This KML is only a subset of their report that details the mineralogy and slip directions of 1362 faults measured in the mine levels from -1200 ft to the surface before the mine eventually filled with groundwater.

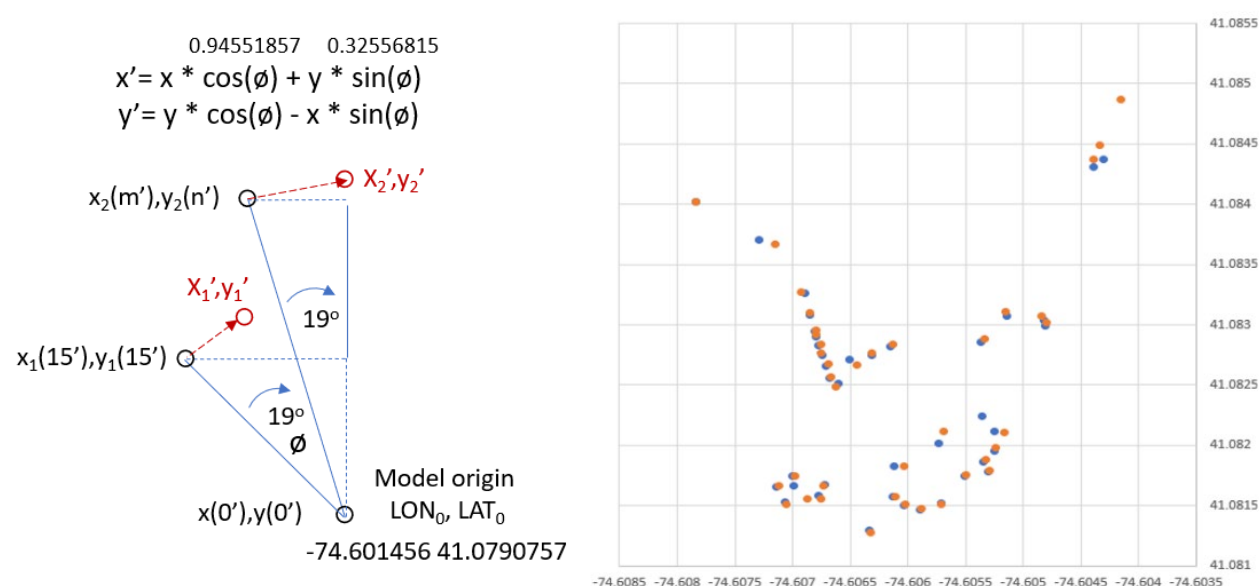


Figure 33. Left diagram illustrates the geometry of rotating 2D points 19° clockwise from the Sterling Mine model origin located at coordinates zero north and west, to the corresponding geographic coordinates. The scatter plot to the right compares the locations of thirty-nine, ground-level field stations recorded by Verbeek and Grout (2025) using the Kroth (1993) map (blue dots) in comparison to those derived using equations 1 to 4 to calculate geographic coordinates for each field station based on listed mine coordinates (orange dots). Local discrepancies arise from arbitrarily digitizing a point location for stations collected on a traverse having multiple fault readings. The MS-Excel spreadsheet included in this year's data downloads contains the conversion formulae and graph above for some of the Verbeek and Grout (2025) faults mapped near ground surface.

SUMMARY COMMENTS

- 1) The ore could have originated as a metalliferous, magmatically spurred hydrothermal plume of Mesoproterozoic age that was discharged from a fault zone into the Franklin Marble protolith (fig. 16).



Figure 34. A 3D plot of 308 fault planes mapped at Sterling Hill near ground surface by Verbeek and Grout (Chapter 3) on a 2002 aerial image in GE Pro. Each red ellipse is scaled at 10-m strike and 6-m dip length (5:3 aspect ratio). The symbols were generated using WGS84 geographic latitude and longitude coordinates and structural dip /dip azimuth notation. The top diagram is a map whereas the bottom view is tilted and rotated clockwise. Further refinements can include variable scaling of smaller and larger faults. The yellow building is a reference building for aiding in geolocation of the associated 3D CAD model that was imported into GE as a Collada (*.dae) object model (fig. 32). The light orange stripes are the ore layers projected to ground surface.

Chapter 2. Structural, Tectonic, and Geospatial Aspects of the
Sterling and Franklin Zinc Mines, Sussex County, New Jersey

- 2) The Gerard and Beaver Lakes fault system mapped to the east is a candidate source for the ore fluids because it cuts across Mesoproterozoic protoliths in the Sterling Hill and Franklin areas (fig. 18).
- 3) The ore body has sill and dike-like segments including a thick, long, and internally complex core zone striking about N80E around which the mining efforts at Sterling Hill were focused (figs. 13 and 14).
- 4) The structural core thickens to the east where it butts up against the Zero fault in the N1600 to N1680 stopes where the east and west limbs nearly connect.
- 5) The structural core branches into mineralized layers lying above and below it.
- 6) The mineralized structural core strikes ~N80E, the adjacent, mineralized layers strike ~N20W to N20E and average ~ N-S, and the mineralized cross layers, or members, strike ~N20E to N50E.
- 7) The ore body in the Franklin Mine has a sill-like form with a fattened eastern termination and an upturned, curved shape similar to the northern ore body at the Sterling Mine (figs. 5, 10, 11, 31, and 32).
- 8) Crystallization of the ore minerals occurred after emplacement of the iron and zinc-rich fluids, but before ductile-brittle shearing and brittle stretching of the ore body, because there is no indication of preferred crystal alignment from dynamic movements accompanying crystallization (fig. 4).
- 9) Metal cations were fractionated and segregated upon emplacement before deep burial, compaction and crystallization of the ore bands because the three primary ore minerals occur in different strata, and there is lack of evidence for extensive fluid exchange accompanying regional metamorphism.
- 10) The franklinite and black willemite layer at the bottom of the Sterling Hill ore body is about 30 ft thick in the west high wall of the Passaic Pit (see field guide STOP 5).
- 11) The first layer above the mud zone and structural core at Sterling Hill is comparatively thin (~12 ft), with a basal franklinite layer a few feet thick underlying willemite and zincite layers in the rock pillar with the saw cuts in the Passaic Pit (see field guide STOP 3).

- 12) The uppermost, eastern ore layer at Sterling Hill no longer crops out and seems to have been thoroughly mined and/or sheared out near ground surface.
- 13) The early mining approaches at Franklin used systematic arrays of pillars to shore up level roofs. Ore was first extracting ore from many small, excavated chambers (fig. 35) before removing the pillars by top slicing before backfilling the excavations. Mining at Sterling benefited from the experience gained at Franklin as they were able to confidently open up larger stopes using the same mining methods (figs. 5, 9, 10, and 13).
- 14) The highest-grade ore lies in the structural core and adjacent, infiltrated layers away from areas that have been repeatedly sheared and faulted during successive tectonic events, especially in the footwall of the zero fault where ore is spotty and of lower grade.

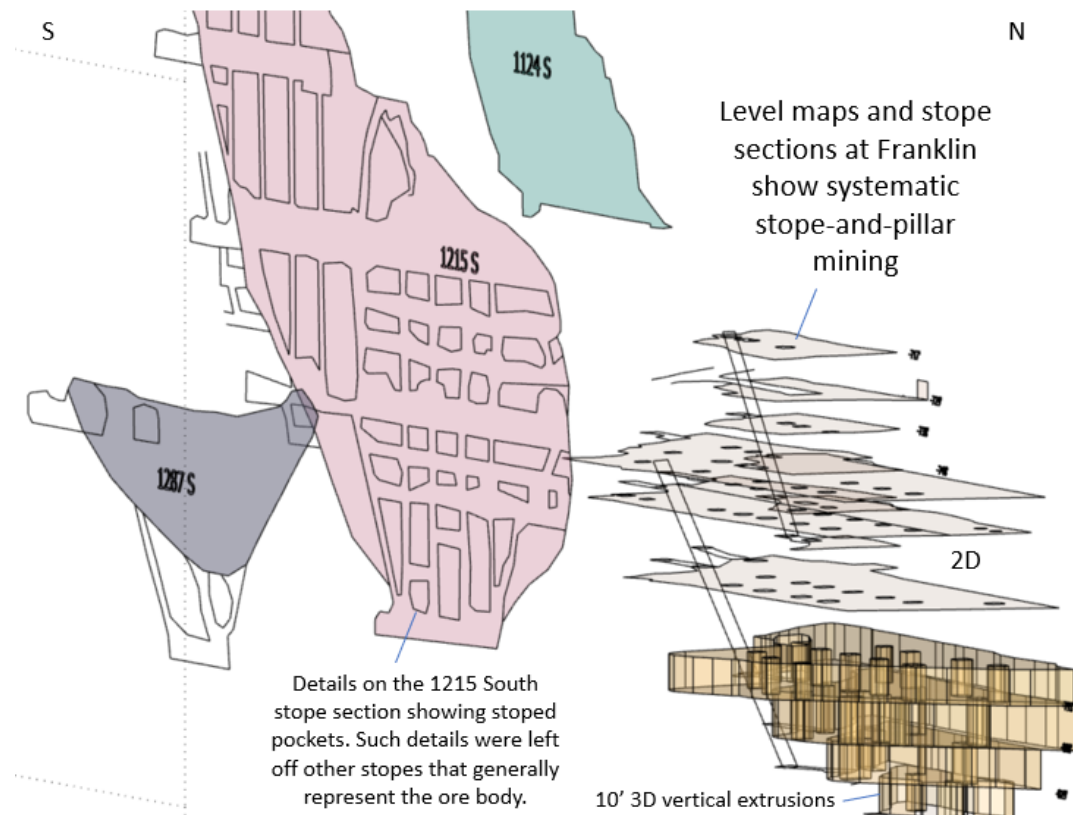


Figure 35. An oblique, WNW view of part of the Franklin Mine showing representative 2D and 3D polygonal elements including three 2D stope sections (left and top) and 12 level maps on the right, with four extruded 10 ft vertically to illustrate aspects of the shrinkage, stope-and-pillar mining method. The details captured on the stope sections are only shown for the 1215 South (S) stope section.

- 15) The ore body was compressed, structurally thickened, and thrust westward during Alleghenian orogenesis that imparted brittle-ductile structures striking about $\sim 040^{\circ}$ to 060° , at an acute angle to Mesoproterozoic ones striking about E-W (fig. 15).
- 16) The ore body was structurally segmented by normal faults and dropped downward during Triassic-Jurassic regional rifting (fig. 18). Old reverse faults may have been reactivated with normal and oblique movements during east-and north directed stretching. The ore body was compressed again, sheared northward, and uplifted to the surface during the Eocene that resulted in a regional, Oligocene unconformity (fig. 8). The orientation of fault identified by Verbeek and Grout (2025; chapter 3) as set 4 may stem from this tectonic pulse.
- 17) The ore body was compressed again, sheared northward, and uplifted to the surface during the Eocene that resulted in a regional, Oligocene unconformity (fig. 8). The orientation of fault identified by Verbeek and Grout (2025; chapter 3) as set 4 may stem from this tectonic pulse.

After digitizing the set of raster imagery for the Franklin stope sections and extracting vector-polygon representation of the respective mine components, and then upon returning the maps to the SHMM map room and appropriate drawer, I saw another map folder that held all of the level plans. Apparently, some of the level maps that I digitized from the stope-section folder had been used and then misplaced back into the wrong folder prior to this effort. The amount of information that remains to be added to the Franklin model is robust.

Upon learning that some of the diamond-drill-hole (DDH) rock core from the Franklin Mine is now curated by the Yale Peabody Museum, I emailed Dr. Stefan Nicolescu, Collection Manager of Mineralogy & Meteoritics. After further correspondence he sent some representative samples of the coring records in their collection (fig. 36). We requested a complete listing of core held by Yale but have yet to receive one.

We have recently learned that the NJSM holds many maps and reports detailing core-hole locations and records, including those in the aforementioned Baum and Willams (1947) report. But much work remains to be done in preserving the legacy of this historic, geological treasure. A worthwhile goal would be to add the diamond-drill-hole core traces into the model that have core samples preserved in the Peabody Museum, the Rutgers University core repository, or any of those held by the SHMM (table 1).

Some stope sections for the Sterling Mine include DDH locations but such aspects need further development in these mine models. Such efforts would be appreciated by many as these

K. STERNLOF		LITHOLOGIC LOGGING SHEETS		PAGE 1 OF 4	
LOGGED BY 6/11/85		DDH NO. 4 (24-A)		?	
DATE		HOLE LOGGED		ORIENTATION/LENGTH OF HOLE	
INTERVAL	LITHOLOGIC DESCRIPTION	CORE QUALITY	SAMPLES TAKEN	REMARKS	
0' - 2'4"	GARNET RICH ZONE -- GAR + WT AT TOP, GAR + ft + SPWT IN CALCITE TO NEAR PURE MARBLE IN MIDDLE, ABUNDANT ft + GAR w/ CALCITE & NO WT AT BOTTOM, CALCITE FLUORESCENT PINKISH (APPARENTLY GAR IS REALLY GARNITE)	RECOVERY IS SPOTTY HARD TO PINPOINT DEPTHS	F4(24A)-5": WHAT IS FLESH COLORED, TRANSLUCENT SPECIES? F4(24A)-2'3": GARNITE, CALCITE, ft + WHAT IS NON-FLUOR. LUT. LOOKING MINERAL	BOXES DIVIDED INTO ZONES; DEPTHS WILL BE MEASURED FROM NEAREST BLOCK ABOVE, WITH LOST CORE ASSUMED TO OCCUR AT THE BOTTOM OF EACH BRACKETED ZONE	
2'4" - 11'	RELATIVELY PURE MARBLE, PINKISH TO GRAY ON FRESH SURFACES. SCATTERED SMALL INCLUSIONS OF FT. A BOUND TO GREENISH PHYLLOSILICATE (BIOTITE), AND A VITREOUS, SEAGREEN SILICATE NOT SHOWING ANY GOOD CLEAVAGES	SMALL TO LARGE PIECES	F4(24A)-10'6": REPRESENTATIVE		
11' - 12'4"	HIGHLY ALTERED LOOKING, DARK GREENISH HUE, VERY FINE GRAINED. CONTAINS CALCITE IN MATRIX, BUT NOT PRE-DOMINANT. LOOKS LIKE FRACTURED ZONE, SOME EVIDENCE OF BRECCIATION, SOFT SERPENTINIZED(?), CHLORITE ALTERATION, SOME CUBES OF PYRITE SEEN. SOME CHUNKS OF K-SPAR & QUARTZ, ALL SiO ₂ AT BOTTOM.	CHUNK	F4(24A)-11'8": REPRESENTATIVE		
15' - 15'4"	MARBLE w/ INCLUSIONS OF BIOTITE(?) ft.	ONE PIECE	NONE		
15'4" - 18'11"	A MASSIVE, FLESH-PINK, LARGELY MONOMINERALIC ROCK EXHIBITING ONE GOOD CLEAVAGE -- RHODONITE. SEEMS ALTERED ALONG FRACTURES ROUGHLY PARALLEL TO CORE AXIS CONSTITUTING OF DARK GREEN (SERPENTINIZED?) CORE w/ LIGHT GREEN (ALTERED RHODONITE?) BOUNDARIES. SOME CUBES OF PYRITE PRESENT	GOOD, LONG PIECES	F4(24A)-18': REPRESENTATIVE		

4 Parker, Tonking = No 24 A		Franklin	
1100 level Elev.		Sept 20 1934	
152 N	Bearing N 86°-30' E	Franklin D.R.	
229 W	Dip	TR. MK. REG. U.S. PAT. OFF.	
Date: Dec 1903		Pilled into NW opposite first x-cut N from Parker Winze.	
0 - 1/4	1/4	Gr. WT. G. 99% Fe	
1/2 - 1 1/2	1	Calc G. + ft. sp. wt.	
1 1/2 - 10	7	WT + Pink LC. T. 1/2" + G	
		+ Fe from 2 1/4" down to 2" G + Eld at 7. Loc. P. + Cdt.	
10 - 11	1/4	P. + Q. Mass.	
11 - 13	1/4	Wt. No. 1/4	
13 - 14	1/4	Mass. P. + Q.	
14 - 15	1/4	Mass. G.	
15 - 15 1/2	1/4	Wt. P. + cdt	
15 1/2 - 19 1/2	4	P. + Red Eld. P. + Gr. M.	
		Mass. P. + cdt. + Gr. M.	
19 1/2 - 56	23	Gt. Wt. Loc. cdt + P.	
		Loc. 13rd Gt. 50-56.	
56 - 57	1	Wt. + abt. 1/2	
57 - 93	18	Wt. + sp. Loc. cdt. Gt. 1/2.	
93 - 95	11/2	Mass. P. + P. 1/2" + cdt.	
95 - 103	7	Same as 57-93	
103 - 105	2	Well bnd. Gt. 1/2	
105 - 117	3	Gt. 1/2 Wt.	
117 - 160	30	Wt. Well bnd. Gt. 1/2 + 50-55' Loc. Cr. 1/2 + 135 + 136	
160 - 210	36	Lt. Gr. L. Bnd. Loc. Gt. 1/2 cdt.	
		Loc. Amp. 165. Loc. Cr. 1/2 + P. at 188-189. Gt. 1/2	
210 - 245	35	Lt. Gr. L. Gt. 1/2. No Amp. cdt. abt.	
245 - 258	8 1/2	Same	
258 - 287	28 1/2	Same + Loc. cdt. + Loc. bnd. Gt.	

Figure 36. Two examples of mining records for the Franklin Mine held by the Yale Peabody Museum that accompany the curated rock core. The upper example dates from 6/11/1985 and the bottom record is from 9/20/1934.

mines warrant any efforts to preserve their legacy. Moreover, if the curated core can be placed into spatial context with the core and adjacent, infiltrated layers at Sterling Hill, then further insights into the mineralogy, petrology, and genesis would be forthcoming by employing modern geophysical instrumentation isotopic characterization and radiometric dating.

The surface expression of the ore bodies as mapped and modelled here also needs more work (fig. 6). The six half days spent photographing and mapping outcropping structures at Sterling Hill were enough to assemble a tentative representation of the surface expression of the ore body and generate material for a few-hour field trip, but this map rendition can be vastly improved with more surface mapping. Though it's worth noting here, that no large meso-scale folds were seen in any of the high walls or surface cuts in the Passaic or Noble pits. Only one recognizable, small-scale fold set was seen in the Passaic pit at STOP 1. A small rock bridge located in the roof of the ore excavation holds fault-propagation folds in the footwall of the slickensided fault plane of probable Paleozoic age (field STOP 1).

The tectonic nature of the Gerard and Beaver Lakes fault system is uncertain. The geometry is clear, but the tectonic impetus behind its occurrence is speculative. I collected fault and slip measurements on this fault system 40 years ago at the outset of my career with the NJGS along NJ Route 23 at about the time that the NJZC began closing the Sterling Hill mine. This crustal shear zone has both ductile and brittle features seen in outcrops along. Epidote and chlorite coat slickensided fault surfaces and a complex strain history is indicated by various, reverse, normal, and oblique-slip kinematic indicators. This Grenville-age fault system cuts across the highlands of New Jersey and exhibits ductile-shear geometry with a right-lateral reverse slip sense (fig. 37). Similar fault systems cut the Hudson Highlands of southern New York (Gates, Valentino, Gorrington, Chiarenzelli, and Hamilton, 2001). This raises the prospect that the core structure is a massive, old tension gash accompanying sudden, regional wrenching and shearing. The topographic expression of this old fault system is clear, and the resulting zinc deposits in the Highlands appear to only occur within the Franklin Marble where component faults of this old system cut across it (fig. 18). In summary, early, Mesoproterozoic faulting and folding in the area include reverse faulting with east-verging, upright folding of a layered sequence of carbonate and clastic that may include some volcanic layers. These ductile-brittle faults were originally moderate- to steeply northwest dipping with a component of right-lateral ductile shearing upon structural restoration involving clockwise rotation in profile, such that the overlying, northwest-dipping, Paleozoic dolomite beds are returned to horizontal.

This exquisite structure is the most complex one that I have studied and portrayed in such detail. To realize that its geological history spans a billion-plus years, and then to ponder its origin, deep burial and metamorphism, and subsequent uplift to the surface through time gives one pause. We see evidence for its fluid-driven genesis during early tectonism, then subsequent

brittle-ductile cataclasis and mylonitic faulting before brittle segmentation and offset. We also see evidence of episodic, hydrothermal alteration and modification of the original ore body (Verbeek and Grout, 2018). When one considers that the entire region was structurally elevated and unroofed during the Cenozoic period resulting in three to five kilometers of erosion, one can then suppose there may be a couple of more tectonic episodes represented (fig. 15). Much of the late uplift likely stems from crustal compaction and thickening from tectonic far-field strains occurring down range of the large-bolide impact crater buried beneath the mouth of Chesapeake Bay, Maryland, USA (Herman, 2015; Mathur and others, 2015). Also please note that current plate drift in this region invokes low-level, spotty seismicity that is temporally distributed throughout the region, so this ore deposit continues to be subject to neotectonic strains.

The mining techniques and operations utilized in identifying and retrieving the ore, and documenting the associated activities are impressive. I am also amazed how lucky the NJZC was in encountering the thickest and richest ore bodies at depth. They must have been thrilled upon prospecting below the 10 to 30 ft-thick ore layers mapped up top to discover unweathered core structures at depth that span several hundred feet in length and thickness. They must have been very pleased with the bounty of resources discovered beneath their feet. Sadly though, scores of miners perished executing their duties; Dunn (2002) verified at least 77 deaths prior to 1913, with an average of one per year based on records compiled from 1917 to 1984.

My interpretation of the ore genesis as fault-mediated, metalliferous fluids that infiltrated a siliciclastic sequence echoes the work of Palache (1937) who proposed metasomatic

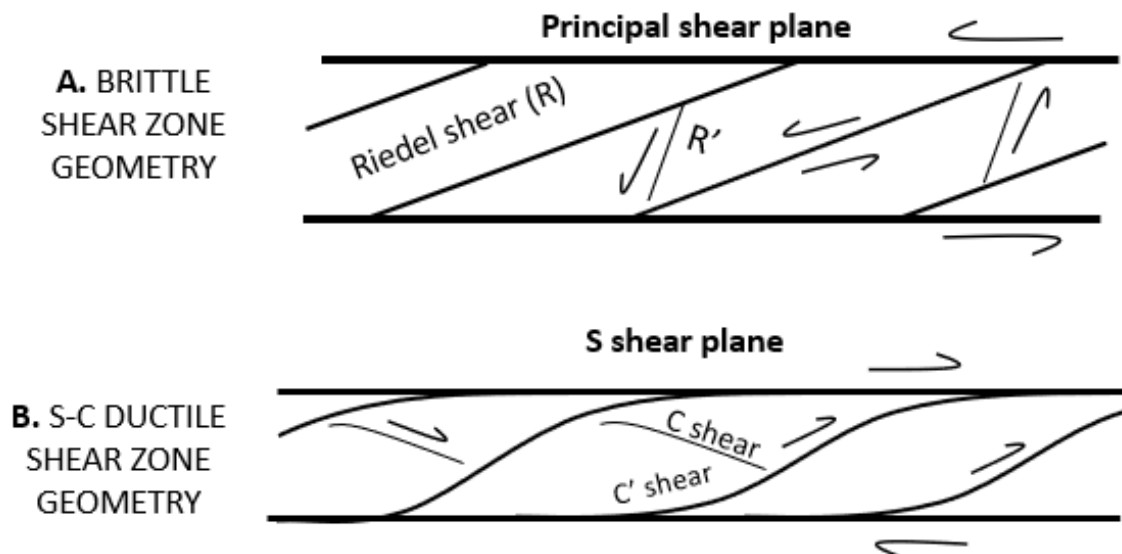


Figure 37. The contrasting geometry of brittle (A) and ductile (B) shear zones with left-lateral slip.

emplacement as the most probable explanation for the source fluids. He believed that they “were deposited near the surface under oxidizing conditions, and that they probably consisted largely of the hydrous zinc silicate, calamine, together with hydrous oxides of iron and manganese and perhaps carbonates of zinc and manganese.” He also considered the depositing solution to have derived its metallic contents from the products of oxidation of a previously existent mass of mixed sulphides. He provides analogous proof from a zinc deposit in Moresnet, Belgium where vast accumulations of sphalerite underwent profound oxidation, and the soluble products were transferred to the nearby dolomite where *they accumulated in synclinal folds that halted the circulation*. At Sterling Hill, the ferrous fluids appear to have been flushed into the Franklin Marble protolith along a cross-strike core structure and then gathered, or pooled along a steeply-dipping reverse fault, with some mineral fractionation and perhaps differentiation occurring in the upright fluidized column in the N1600 – N1660 stope area. Having the faulted, synclinal hinge as a hydraulic barrier to subsequent, cross-strike fluid migration helps explain why the zinc-lead-sulfide seen across the fault to the east within the same stratigraphic section as that on the west wasn’t subsequently oxidized. But the New Jersey mines extracted highly oxidized ore that was subsequently buried deep and subject to regional dynamothermal metamorphism, unlike that in their proper position with respect to the ore body so that geochemistry can be used to further interpret the ore petrogenesis. Palache (1937) also neglected to provide a mechanism for introducing the “depositing solutions”, which I suggest here to be fault-mediated flow during folding of the Mesoproterozoic rocks along the E-W striking shear zone and core structure where it pooled against the Zero fault on the western side, and likely along strike of the fault.

The structural core at Sterling Hill is probably more complex than portrayed here, or possibly larger than represented in the model because of what the Baum and Williams (1947) report shows. Their work includes mapped ore concentrations within stratiform layering based on exploratory drilling in the heart of the Sterling ore deposit. A cursory examination of the mapped chemical isograds shows that the highest ore grades occur along the margins of the structural core, and in parts of the bottom, synformal keel. Their report also shows that the zero fault has complex splays of reverse and normal displacements, both of which likely contribute to the down-warped, synformal shape of these ore bodies at depth. In other words, the upturned, synformal keel is also likely shaped by sagging into extensional grabens of probable Newark age.

Although much of the aforementioned is speculative, what this work provides with certainty is a virtual foundation upon which a more thorough understanding of these unusual ore bodies can be attained. The computer models reflect the assembly of unbiased data, and the only interpretations embedded in the Sterling Mine model are the TIN surfaces built to encompass the structural core and adjacent. Infiltrated layers. How the ore accumulated and was distributed in the fold hinge can be further explored now using the CAD models to place specific core holes into

To conclude, this has been a very interesting and fulfilling project that has resulted in new friendships and has laid a foundation for future research into this unique geological phenomenon. I hope that the computer models will be used by others in this scientific pursuit. I'm excited to see how the archived core fit into the model and how future efforts will continue to resolve this magnificent mineral deposit.

ACKNOWLEDGEMENTS

This work was spurred on, approved, and aided by Mike Di Maio, this year's GANJ president. He was my sounding board throughout the process, and looking back, he experienced a barrage of ideas and requests for favors. Through it all he remained helpful and excited, and for that I acknowledge his attention and friendship. Jim Peterson, Don Monteverde, and Steve Spayd and Mark Zedpski accompanied me on different field days examining outcrops around Sterling Hil. It is honor and pleasure to have been aided by such knowledgeable gentlemen. Mark, Mike and I also combed through the NJ State Museum Metsger collection. Mark's career familiarity of the metal-extraction industry provided many insights into the various mining methods and the nature of the archived maps. David Kaminski and James Brown reviewed and commented on early drafts of this manuscript that improved its clarity. I am also very grateful for the institutional support given by the SHMM and NJSM. In particular, Denise and William (Bill) Kroth's help in gaining access to the SHMM field pits and internal records, and Rod Pellegrini's help in accessing the NJSM Metsger collection. It's rare to gain access to caches of old, detailed records to characterize such a unique geological phenomenon. I also acknowledge the help and advice provided by Earl Verbeek, resident geologist for the SHMM and curator at Franklin, NJ Mineral Museum. His knowledge about, and commitment to studying the Sterling and Franklin ore deposits are remarkable. His attention to details during the compilation and editing of these proceedings was extraordinary. I also acknowledge the GANJ geological professionals and board members as listed in the front of the guidebook. Their dedicated commitment to the production and dissemination of geological research in the New Jersey region made this work possible. Their time spent on coordinating this event and programming the website is very much appreciated. Lastly, I thank Trap Rock Industries, Inc. for my employment and their support of my geological research in the New Jersey region.

REFERENCES

- Baker, D.R. and Buddington, A.F., 1970, *Geology and Magnetite Deposits of the Franklin Quadrangle and Part of the Hamburg Quadrangle, New Jersey*: U.S. Geological Survey Professional Paper 638, 71 pages.
- Baum, J. and Williams, J., 1947, *Nature of the Ore Occurrence and Structure on the Lower Portion of the East Vein at Sterling*: New Jersey Zinc Co. internal report. 43. p., 22 plates, scale 1"=100'.

Chapter 2. Structural, Tectonic, and Geospatial Aspects of the
Sterling and Franklin Zinc Mines, Sussex County, New Jersey

- Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1996, Bedrock geological map of northern New Jersey: U.S. Geological Survey Miscellaneous Investigation Series Map I-2540-A, scale 1:100,000, 2 sheets.
- Drake, A.A., Jr., Aleinikoff, J.N., and Volkert, R.A., 1991, The Mount Eve Granite (Middle Proterozoic) of northern New Jersey and southeastern New York, *in* Drake, A.A., Jr., ed., Contributions to New Jersey Geology: U.S. Geological Survey Bulletin, 1952-C, p. C1-C10.
- Dunn, P. J., 2002, Mine Hill in Franklin and Sterling Hill in Ogdensburg, Sussex County, New Jersey: Mining History, 1765-1900, Franklin Mineral Museum, Franklin, NJ, 1102 p.
- Faill, R.T., 2003, The early Mesozoic Birdsboro central Atlantic margin basin in the Mid-Atlantic region, eastern United States. Geological Society of America Bulletin, vol. 115. P. 406-421 doi:10.1130/0016-7606(2003)115<0406:tembca>2.0.co;2
- Gates, A.E., Valentino, D.W., Gorrington, M.L., Chiarenzelli, J.R., and Hamilton, M.A., Bedrock geology, geochemistry and geochronology of the Grenville Province in the western Hudson Highlands, *in* Gates, A.E., editor: Geology of the Lower Hudson Valley, 2001 New York State Geological Association Guidebook, p. 177-198, www.nysga-online.org/wp-content/uploads/2019/06/NYSGA-2001-3-Bedrock-Geology-Geochemistry-and-Geochronology-of-the-Grenville-Province-in-the-Western-Hudson-Highlands-New-York.pdf
- Hague, J.M., Baum, J.L., Herrmann, L.A., and Pickering, R.J., 1956, Geology and structure of the Franklin-Sterling area, New Jersey: Geological Society of America Bulletin, vol. 67. no. 4., p. 435-474. doi.org/10.1130/0016-7606(1956)67[435:GASOTF]2.0.CO;2
- Haight, C.M. and Tillson, B.F., 1917, Zinc Mining at Franklin: American Institute of Mining, Metallurgical, and Petroleum Engineers, AIME Transactions, New York, N.Y., p. 720-825.
- Herman, G. C., 1992, Deep crustal structure and seismic expression of the central Appalachian orogenic belt: Geology, vol. 20, no. 3, p. 275-278.
- Herman, G.C., 2009, Steeply-dipping extension fractures in the Newark basin, Journal of Structural Geology, vol. 31, p. 996-1011.
- Herman, G.C., 2015, Neotectonics of the New York Recess, *in* Herman, G.C., and Macaoay Ferguson, S., Neotectonics of the New York Recess: 32nd Annual proceedings and field guide of the Geological Association of New Jersey, Lafayette College, Easton, Pa., p. 80-151.
- Herman, G.C., Dooley, J. H., and Monteverde, D.H., 2013, Structure of the CAMP bodies and positive Bouguer gravity anomalies of the New York Recess, *in* Benimoff, A.I., editor, Igneous processes during the assembly and breakup of Pangaea: Northern New Jersey and New York

City: 30th Annual Meeting of the Geological Association of New Jersey, College of Staten Island, N.Y., p. 103-142.

Herman, G.C., Monteverde, D.H., Schlische, R.W., and Pitcher, D.M., 1997, Foreland crustal structure of the New York recess, northeastern United States: Geological Society of America Bulletin, v. 109, no. 8, p. 955-977.

Kroth, W., 1993, Composite site plan; Surface and sub-surface features: Sterling Hill Mining Museum, Inc., Ogdensburg, New Jersey. Scale 1":100'. Inset diagrams of the mud zone at 1":150'.

Lupulescu, M.V., Chiarenzelli, J.R., and Bailey, D.G., 2012, Minerology, classifications, and tectonic setting of the granitic pegmatites of New York State, USA: The Canadian Minerologist, vol. 50., no. 6., p. 1713-1728. doi.org/10.3749/canmin.50.6.1713

Mathur, R., Gold, D.P., Ellsworth, C.J., Doden, A. G., Wilson, M., Ruiz, J., Scheetz, B.E., and Herman, G.C., 2015, Re-Os isotope evidence an Early Tertiary episode of crustal faulting and sulfide-mineralization in Pennsylvania with probable ties to the Chesapeake Bay bolide impact in Maryland, USA, Chapter 3, *in* Herman, G.C., and Macaoay Ferguson, S., Neotectonics of the New York Recess: 32nd Annual proceedings and field guide of the Geological Association of New Jersey, Lafayette College, Easton, Pa., p. 68-79.

Matt, P., Peck, W.H., Mathur, R., Hurtgen, M.R., and Godfrey, L., 2022, Zinc isotope constraints on the formation of sedimentary exhalative (SEDEX) ore deposits: New evidence from the Franklin mining district: Ore geology reviews, vol 147., 8 p., doi.org/10.1016/j.oregeorev.2022.104970

Metsger, R.W., Tennant, C. B., and Rodda, J. L., 1958, Geochemistry of the Sterling Hill zinc deposit, Sussex County, New Jersey: Geological Society of America Bulletin vol. 69, p. 776-788.

Metsger, R.W., Skinner, B.J., and Barton, P.B., 1969, Structural Interpretation of the Sterling Hill Ore Body, Ogdensburg, N.J.: Econ. Geology (abstract), vol. 64, p 833.

Metsger, R.W., 1980, The geologic setting of the Sterling Hill zinc-iron-manganese deposit: Annual Meeting of the New York State Geological Association, vol. 52, p. 210-214.

Palache, C., 1929, Paragenetic Classification of the Minerals of Franklin, New Jersey, American Mineralogist, vol. 14, p. 1-18.

Palache, C., 1937, The minerals of Franklin and Sterling Hull Sussex County, New Jersey: U.S. Geological Survey Professional Paper 180, 135 p.

Puffer, J.H., 2023, The Zero Fault Pegmatite is Associated with Marble at Franklin, New Jersey, USA. The Canadian Journal of Mineralogy and Petrology, vol. 61, p. 1-18, doi.org/10.3749/2200030.

Chapter 2. Structural, Tectonic, and Geospatial Aspects of the
Sterling and Franklin Zinc Mines, Sussex County, New Jersey

- Rivers, T., 2008, Assembly and Preservation of lower, mid, and upper orogenic crust in the Grenville Province-Implications for the evolution of large hot long-duration orogens": Precambrian Research, vol. 167, nos. 3–4, p. 237–259. www.doi.org/10.1016/j.precamres.2008.08.005.
- Sanborn Map Company, 1920. <https://maps.princeton.edu/catalog/princeton-h415pd48g>.
- Tarr, W.A., 1929, The origin of the zinc deposits at Franklin and Sterling Hill, New Jersey: Journal of the mineralogical society of America, vol. 14, no. 6., p. 207-221.
- Tveite, H., 2015, The QGIS Line Direction Histogram Plugin. www.plugins.qgis.org/plugins/LineDirectionHistogram/.
- Verbeek, E.R. and Grout, M.A., 2018, Hydrothermal mineral deposition in a rock-dominated fluid system at Sterling Hill, New Jersey. The Picking Table, vol. 59, no. 2, p. 15-22.
- Verbeek, E. R. and Grout, M. A., 2025, Chapter 3. Fault History of the Sterling Zinc Mine, Ogdensburg, Sussex County, New Jersey, with Appendices, *in* Di Maio, M.P., Herman, G.C., and Verbeek, E.R., editors, Revisiting the Sterling Hill Orebody: Challenges in Understanding this Magnificent Deposit: 41st Annual proceedings and field guide of the Geological Association of New Jersey, The Sterling Hill Mining Museum, Ogdensburg, NJ, p. 117-140.
- Volkert, R.A., 2004, Mesoproterozoic rocks of the New Jersey Highlands, north-central Appalachians: petrogenesis and tectonic history: *in* Tollo, R. P., Corriveau, L., McLelland, J., and Bartholomew, J., eds., Proterozoic tectonic evolution of the Grenville orogen in North America: Geological Society of America Memoir 197, p. 697-729.
- Volkert, R.A., Monteverde, D.H., 2013, Bedrock geologic map of the Franklin Quadrangle, New Jersey: NJ Geological Survey Geological Map Series GMS 13-3, Scale 1:24,000, 1 sheet.
- Volkert, R.A. and Puffer, J.H., 1995, Late Proterozoic diabase dikes of the New Jersey Highlands - A remnant of Iapetan rifting in the north-central Appalachian: U.S. Geological Survey Professional Paper 1565-A, 20p. pubs.usgs.gov/pp/1565a/pp_1565a.pdf
- Volkert, R.A., Aleinikoff, J.N. and Fanning, C.M., 2010, Tectonic magmatic, and metamorphic history of the New Jersey Highlands: New insights from SHRIMP U=Pb geochronology, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., eds., from Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Memoir 206, p. 307-34.
- Wilkerson, A.S., 1962, The minerals of Franklin and Sterling Hill, New Jersey: New Jersey Geological Survey Bulletin 65, 80 p., www.dep.nj.gov/wp-content/uploads/njgws/technical-publications-and-reports/bulletins-and-reports/bulletins/bulletin65.pdf.



A photograph showing solution weathering of the Franklin marble on the eastern wall of the Passaic Pit that was temporarily cleared of foliage during surface grooming conducted by the Sterling Hill Mining Museum in 2006. Photo by Earl Verbeek received in written communication of June 6, 2025.

Chapter 3. Fault History of the Sterling Zinc Mine, Ogdensburg, Sussex County, New Jersey, with Appendices

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INTRODUCTION

The Zn-Fe-Mn deposit at Sterling Hill, together with the neighboring Franklin deposit about 2.2 miles north, constitute one of the world's most complex mineral localities, with more than 400 mineral species on record. The orebody consists of high-grade metamorphic gneisses composed principally of franklinite (ZnFe_2O_4), willemite (Zn_2SiO_4), and zincite (ZnO) in calcite matrix, interlayered with calc-silicate gneisses composed mostly of pyroxenes, amphiboles, feldspars, garnet, and calcite, with subordinate micas. The host rock of the orebody is the Franklin Marble, a generally coarse-grained, locally dolomitic marble with interbedded siliceous and aluminous layers.

The Sterling Hill orebody and the Proterozoic rocks enveloping it are extensively broken by fractures of multiple orientations and age. Nearly all of these fractures, many thousands of which are visible underground in the Sterling mine, originated as minor faults with total slips of several meters or less. Mineralization of these faults by hydrothermal fluids is responsible for much of the mineralogic complexity of the area, but to our knowledge, no detailed study of faults in the local Franklin-Sterling Hill area had ever been undertaken. Accordingly, in June 1989, shortly after acquisition of the Sterling mine property by the Hauck families (founders of the Sterling Hill Mining Museum), we proposed a study of the fault history of the mine, the upper half of which was still accessible, not yet flooded by rising groundwater. During this time, we were employed by the U.S. Geological Survey and were engaged in studies of regional fracture systems in Colorado, Utah, and Arizona. We began our fault study in November 1989 and concluded the main phase of data-gathering four years later, by which time only the adit level of the mine, plus the surface workings, remained accessible. Ultimately, we gathered data on 1,158 faults.

SLIP INDICATORS ON FAULTS

Slip indicators on faults in the Sterling Hill area are of various types, with the first three listed here being the most common. The features described here are not an exhaustive list but constitute the major types used in our study.

Graphite-Streaked Fault Surfaces

The Franklin Marble nearly everywhere is graphitic except in and near the Sterling Hill orebody. Individual graphite flakes intersected by faults and smeared onto fault surfaces during slip provided a ready means of determining slip directions (Fig. 1). Where slip amounts were small,

hand-lens inspection occasionally allowed individual graphite streaks to be traced back to the parent graphite grains, thereby allowing the polarity of the streaks to be determined and the slip vector reduced from two possible directions to one. In most cases, however, the streaks so much overlapped that this was not possible, and the sense of slip had to be determined by other means.

Fibrous Accretionary Minerals

Dilational openings that formed during slip along faults at Sterling Hill often contain fibrous minerals in overlapping, sheeted masses accreted to the fault surface (Fig. 2). Since each fiber connects two points of the fault that originally were in contact before slip began, the sense of slip can readily be determined where such fault openings are exposed in cross section. Where instead only one surface of a fault is exposed and the opposing surface has fallen away, one end of each fiber is attached to the wall rock (left side of fig. 2) and the other end is broken. The short, step-like fractures that mark positions where the fibers broke away face toward the direction of movement of the missing fault block.



Figure 1. Graphite-streaked surface of a small fault on the adit level of the Sterling mine.

Scratched/Abraded Fault Surfaces

Faults in rocks containing mechanically strong mineral grains (for example, norbergite in marble, franklinite in ore) in a weaker matrix (for example, calcite) commonly have scratched surfaces

that indicate slip directions. The sense of slip could locally be determined where parts of irregular fault surfaces are striated (those parts where the opposing walls of the fault were in contact during slip) while other parts are not.



Figure 2. Sheeted mass of fibrous to splintery zincite on a fault surface in high-grade, franklinite-zincite ore. Each zincite fiber is rooted to the wall rock along the left side of the specimen and is broken on the opposite end. The small steplike fractures produced by breakage of the fibers face to the right in this view, indicating the missing fault block moved in that direction. Franklin Mineral Museum specimen FMM-7909, 11 x 9 x 6 cm.

Corrugated Fault Surfaces

Faults exhibiting wavy surfaces composed of rounded, parallel ridges and valleys are fairly common at Sterling Hill. The wavelength of the corrugations is generally 0.5 m or less. Wherever independent indicators of slip directions were present, the corrugations were shown to be parallel to the slip vector of the earliest episode of slip on the fault. We did not use this as a primary criterion of slip direction but noted its presence where observed.

Drag Features

The sense of curvature of originally planar features (compositional layers, veins, other faults) adjacent to a fault was used as a shear-sense indicator wherever it was obvious that the curvature

was due to frictional drag on the fault surface (Fig. 3). The long axes of flattened mineral grains that originally were equant (e.g., franklinite) were used for the same purpose where the axes gradually curved into near-parallelism with the fault plane.



Figure 3. A small, nearly horizontal fault in Franklin Marble in the Sterling mine. Drag of the compositional layers (most obvious to right of lens cap) indicates top-to-the-left movement on the fault.

Intrafolial Folds

Intrafolial folds in mylonitic rocks of ductile shear zones are valuable shear-sense indicators but were exposed in few places during our study. S-C surfaces in the mylonites were used for the same purpose.

Fault Offsets

Some of the slip indicators mentioned above define only the line of slip but not its sense – i.e., whether up or down, right or left, etc. Observed offsets of compositional layers, veins, or other features on either side of a fault were used, where possible, to refine the two possible slip vectors to one (Fig. 4).



Figure 4. A willemite-calcite vein (brown, extending from upper right to lower left in photo) offset along a minor fault in ore exposed along the gravity tram in the Sterling mine. Red pencil lying in drill hole is 14 cm long.

PT Structures

Numerous faults in the Franklin Marble are composed of striated, *en echelon* surfaces at a low angle to the mean fault plane. At first these were assumed to be Riedel shears. However, diagnostic slip-sense criteria for dozens of faults in the Sterling Hill area show that these fractures dip in the opposite direction and are not Riedel shears, but probably correspond to the P surfaces of Petit (1987).

RELATIVE AGE INDICATORS OF FAULT EVENTS

Many of the faults observed during this study experienced more than one episode of slip and have slickenlines in two or more directions. In places it was possible to determine the relative age of the slip events by one or more of the following means.

1. The surfaces of fibrous accretionary minerals that formed within faults during an early slip episode occasionally were seen to bear numerous parallel scratches oblique to the fiber axes. The scratches represent abrasion by mineral grains in the wall rock during a later episode of slip.

2. Deposits of fibrous accretionary minerals in places were themselves faulted and plated over by a younger deposit of fibrous accretionary minerals. This was most commonly observed along faults in the Franklin Marble, where calcite is the dominant accretionary mineral. Color differences between the two generations of calcite accretionary fibers and the presence of shear surfaces within one generation of fibers but not the other can reveal their relative age.

3. Corrugated fault surfaces upon reactivation commonly display abrasion slickenlines on one side of the corrugations where the two walls of the fault were in contact, but not on the other side, thereby enabling the sense of slip during fault reactivation to be determined. This criterion was especially useful for faults in ore and gneissic rocks.

The most obvious and common means of determining the relative age of different fault sets is by observation of crosscutting faults (Fig. 5), but problems can arise in areas that experienced three or more episodes of faulting. Under such circumstances, renewed slip on an old fault can result in it offsetting a younger one, resulting in a misleading impression of relative age. Such “spurious” indicators of relative age are common in the Sterling mine and necessitated care in interpreting the results.

DATA TREATMENT

Our fault data, as noted above, were gathered primarily from 1989 to 1993, well before digital measurement and recordation of geological field data became the norm. We used manual Brunton compasses to measure orientation data and later transcribed our handwritten field notes into a computer file. Later, we converted our alphanumeric orientation data into right-hand-rule (numerical data only) files for computer analysis of the various sets of faults. Both the field and numerical data are presented in Appendix A. For many faults (48% of the total) we made redundant measurements so we could calculate slip vectors by two or even three different means as a way of judging the accuracy of the data. For that purpose, we regarded two slip vectors differing by a spatial angle of 5° or less as “excellent,” by 5°-10° as “good,” by 10°-20° as “fair,” and by more than 20° as “poor.” By that metric, 81% of the faults were regarded as good to excellent, 16% as fair, and (blessedly) less than 3% as poor (or missing, = incomplete data).

For each fault we recorded as much of the following information as possible: 1. Locality (including New Jersey Zinc Company mine coordinates), 2. Rock type, 3. Fault orientation, 4. Bearing and plunge (and/or pitch) of the slip vector, 5. Character of fault surface, 6. Minor structures associated with the fault (drag features, fault breccia, alteration zones, mylonitic foliation, etc.), 7. Mineralization history of the fault, and 8. Crosscutting and abutting relations

with other faults in the area. For various reasons (relocation, eventual retirement, re-employment, etc.) we returned to our Sterling Hill data only at widely spaced intervals, and it was not until November 2021 that we had converted all of our data to digital files and completed digitization of our field notes. The data have not yet been fully analyzed by any of the relevant computer programs such as FaultKin 8.1 (see Marrett and Allmendinger, 1990 and Allmendinger and others, 2011). What follows, then, is a *preliminary* interpretation of our fault data for Sterling Hill, subject to revision as further analysis takes place.



Figure 5. Crosscutting faults (to right of center) in the Sterling mine. The white deposits are calcite flowstone deposited by infiltrating water. For scale, the square plate of the rock bolt at right is about 5 inches on edge.

FAULT SETS

Figure 6, a plot of 1,135 poles to faults at Sterling Hill, shows a wide range in fault orientations but also reveals some general trends. Most obvious is the great number of poles in the NW and SE quadrants, showing that most of the local faults strike broadly NE but have a wide range in dip. Other faults strike NW and have moderate to steep SW dips, as reflected in a secondary concentration of poles in the NE quadrant. Beyond these broad generalities, attention to directions of slip vectors, the relative degree of brittle vs. ductile response of the rock during faulting, the ages of faults relative to other faults in the same area, etc., allow the recognition of genetic sets of faults that reflect discrete episodes of faulting in the Sterling Hill area. For example,

among the NE-striking faults, the faults of one set consistently have shallow to only moderate dips and show NW-directed slip vectors, while those of another, younger set are steeply dipping normal faults with the southeastern block downthrown. By these means, at least 777 faults (67% of the total) have so far been identified as members of known sets. Many of the remaining faults have orientations consistent with one of the known sets but were later reactivated and thus have slip vectors in other directions. Evidence of two or more episodes of slip on the same fault surface was documented for many faults during our work, a consequence of hundreds of millions of years of geologic history.

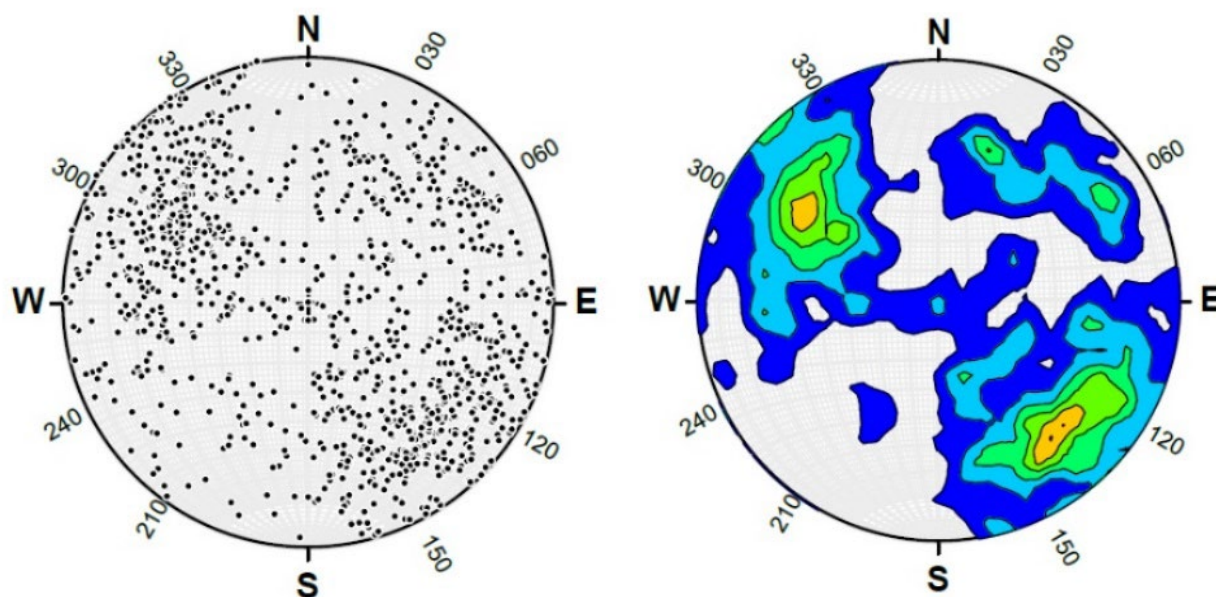


Figure 6. Lower hemisphere, equal-area stereographic projection of poles to 1,135 fault planes at Sterling Hill (left). Kamb point-density contours (right) are colored at intervals of one standard deviation.

Table 1 lists the fault sets recognized in their probable sequence of occurrence. Each set is detailed below, but given the preliminary nature of this interpretation, we don't entirely relate our fault chronology to the tectonic history of northern New Jersey.

Set 1 Faults

Faults of Set 1 generally strike N30-60E and have moderate to steep SE dips (fig. 7); their average orientation is N45E/62SE. They are the oldest and least common of the faults exposed in the Sterling mine and were measured at only 27 localities. All are ductile faults with mylonitic fabric in zones 8-70 cm thick. These faults are commonly sinuous along both strike and dip, in places markedly so, and some are corrugated parallel to the slip direction. Slickenlines — the axes of flattened, elongated mineral grains within the mylonitic foliation surfaces—all show steep pitches

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Table 1. Average orientation, slip sense, and ductile vs. brittle response of the rock for each of the five fault sets discussed in this paper.

Fault set	Average strike/dip	Material behavior	Comments
1	N45E/62SE	Highly ductile	Mylonitic shear zones with early normal movement. Multiply reactivated; at least four episodes of slip.
2	Subhorizontal	Ductile	Thrust faults with NW transport of upper plates; average slip direction N53W.
3	N41E/62NW	Ductile	Reverse faults
4	N48W/59SW	Brittle	Reverse faults transitioning to right-lateral
5	N31E/76SE	Brittle	Normal faults

(average = 88°) indicative of dip-slip movement. Intrafolial folds within the mylonites (fig. 8), S-C surfaces, and offsets of lithologic contacts show a normal sense of shear.

Wherever a Set 1 fault brings ore into contact with marble, the marble is highly sheared and the ore much less so because the mechanical strength of the ore is greater than marble. Accordingly, widths of mylonite zones along Set 1 faults in marble commonly exceed 20 cm, but those in ore are 3-10 cm thick or even less. In a few places, however, mylonite in ore is splendidly developed, with long streaks of brown (willemite), black (franklinite), and white (calcite), furnishing handsome specimens (fig. 9). Mylonites developed in marble, in contrast, are thinly streaked in tones of dark gray and white (fig. 8), where the darker streaks are highly flattened and elongated flakes of disseminated graphite, a widespread accessory component of the Franklin Marble.

The most prominent members of this fault set in the Sterling mine are the Zero and Nason faults. The Zero fault is exposed at the surface east of the Sterling mine property, in the town of Ogdensburg, but at depth it cuts off the Sterling mine orebody. Exposures of the Zero fault within the mine had long been flooded by the time our fault study began. The Nason fault, in contrast, was well exposed at multiple localities in the upper part of the mine and was measured in several places. Today it is visible only at the surface. Another fault of this same set is well exposed on the adit level of the mine beneath the timber sets southeast of the shaft station; attendees to this conference will view this fault during their mine tour.

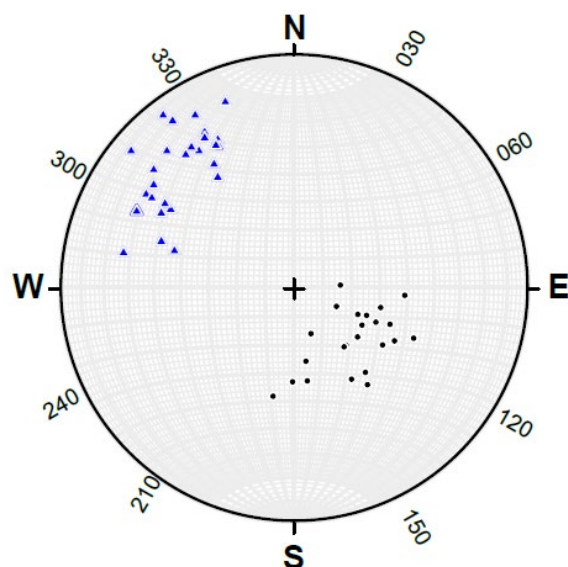


Figure 7. Lower hemisphere, equal-area stereographic projection of poles to 27 Set 1 faults at Sterling Hill (blue triangles) and their slip vectors (black dots).

Stephens and others (1988), in a study of the Zero fault, noted that pressure solution during faulting resulted in a marked increase in graphite content of the Franklin Marble within highly strained parts of the shear zone compared to that outside it. The presence within the Zero fault mylonite of abundant and well-oriented films of graphite made it, and other faults like it, especially prone to reactivation during later fault events. These faults have been repeatedly active, and some show evidence of three or even four episodes of movement. The latest episodes involved mostly brittle versus ductile deformation, commonly resulting in the formation of discrete slip surfaces (brittle faults) within the older mylonite zones, and with the development of subsidiary fault strands in adjacent rocks. These later faults increased the permeability of the mylonite zones by introducing fault-related openings that are orders of magnitude larger than the micropores of the original fine-grained mylonite. The original mylonites locally occluded subsurface fluid flow, but subsequent, brittle overprinting resulted in them locally channeling fluid movement. Parts of the mylonitic fault exposed on the adit level, for example, are thickly covered with flowstone precipitating from water descending into the mine through later breaks. The wall rock along similar openings deeper in the mine is highly weathered, and stalactites locally hang from the fault traces overhead. Still deeper in the mine, in the North Ore Body on the 2250 through 2550 levels, severe hydrothermal alteration and dolomitization of the ore have been ascribed to fluid flow along the Zero fault (Metsger, 1990).

Set 1 faults are similar to other, regional faults that constitute some of the most prominent tectonic boundaries in northern New Jersey. Examples include the Zero and East faults in the Sterling Hill - Franklin area, and the Reservoir and Ramapo faults to the east. The Proterozoic ancestry of various Set 1 faults in the region is discussed by Ratcliffe (1980), Volkert and Puffer (1995), Gates and Costa (1998), Metsger (2001), and Gates and Volkert (2004). The

tectonic significance of the Sterling Hill examples is uncertain, in part due to Alleghenian folding, which rotated them to new orientations. The nearest outcrops of basal Paleozoic sedimentary rocks overlying the Franklin Marble, about 2 km distant from Sterling Hill, dip 40°-50° northwest. Back-tilting the underlying Franklin Marble a similar amount would restore the Set 1 faults to steep northwest dips and a reverse sense of slip (see chapter 2, fig. 16 of Herman, 2025). Regardless of uncertainties about their original orientations, these faults experienced multiple episodes of slip at different times and under vastly different conditions, resulting in brittle overprinting of earlier ductile features.

Set 2 Faults

Set 2 faults have generally shallow to moderate dips ($\leq 40^\circ$; fig. 10) and are some of the largest and most abundant faults in the mine, with more than 200 examples in our dataset. Most have uneven, curved surfaces, the most irregular among them showing appreciable changes in orientation over only short distances. Numerous exposures show clearly that the upper plates of these faults moved to the northwest, with slip vectors commonly in the range N35°-75°W. The average slip vector, within the orange contoured area of figure 10, is 15/N53W.

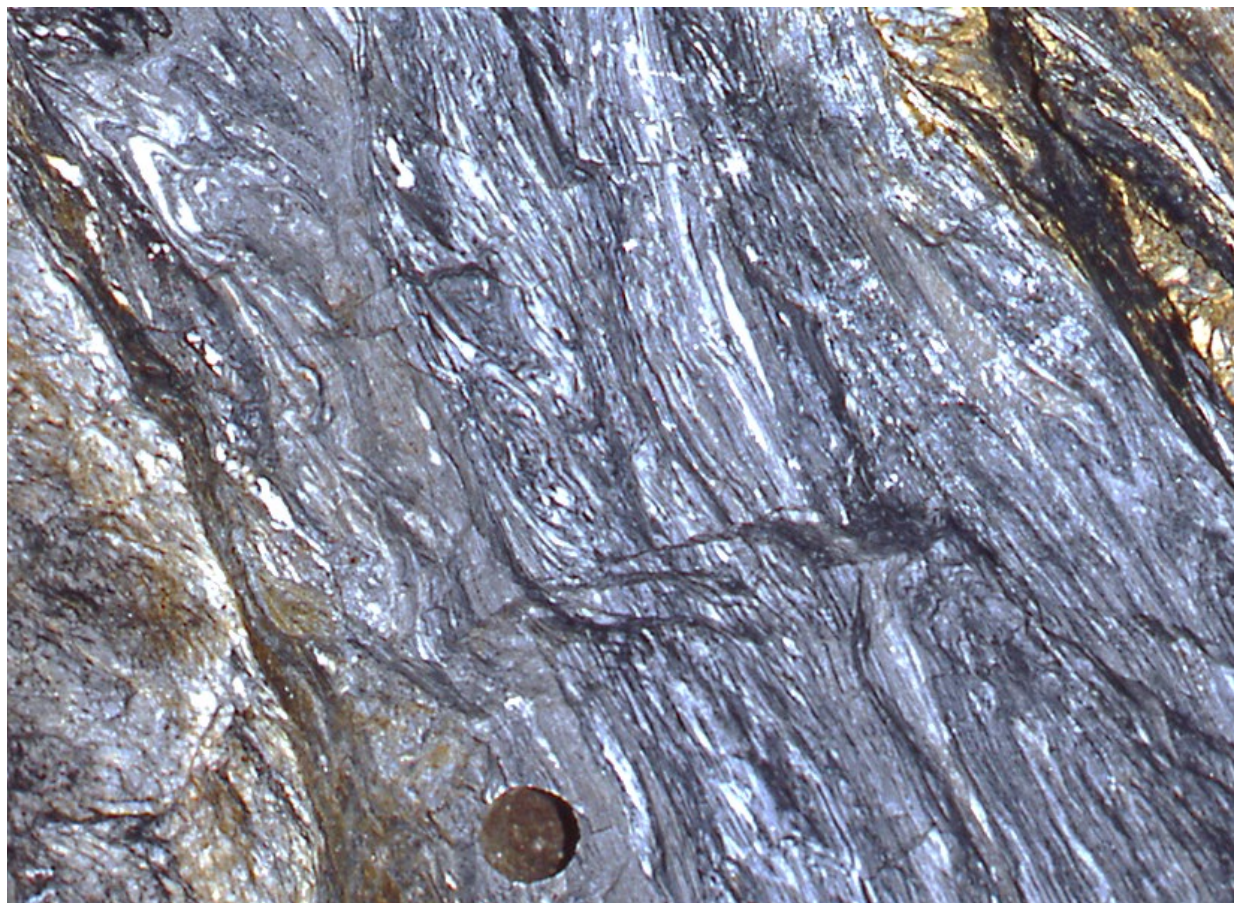


Figure 8. Intrafolial folds (upper left and center right) in marble mylonite of a Set 1 fault. Field of view is about 50 cm across.



Figure 9. Mylonitic fabric in willemite-franklinite-calcite zinc ore from the Nason fault, 1250 stope below 700 level, Sterling mine. Sterling Hill Mining Museum specimen SHMM-1367, 13 x 12 x 7 cm. The visible surface is sawn and polished. Hundreds of specimens of this material were produced from this stope and sold to collectors. The willemite fluoresces green and the calcite red under shortwave ultraviolet light.

Although slightly more than half of Set 2 faults currently have the geometry of low-angle normal faults, they too, like those of Set 1, were probably rotated to new orientations during subsequent tectonism. Restoration of the Set 2 faults based on the current tilt of the nearby Cambrian strata indicates they probably originated as northwest-directed thrust faults during Alleghenian orogenesis.

Individual strands of Set 2 faults commonly split and merge to form anastomosing, braided fault zones 20 cm to several meters thick (fig. 11). These fault zones are generally thinnest where they cut the Franklin Marble but broaden considerably as they pass into ore. Fault surfaces in ore commonly have a smooth and almost polished appearance, with delicate striations representing scratches by hard mineral grains (e.g., franklinite) as slip took place. The same is true in calc-silicate gneisses, where the faults are commonly lined with epidote (fig. 12). In marble, however, the fault surfaces lack a polished appearance and generally are darkly streaked or smeared by sheared-out graphite grains. Local concentrations of graphite on fault planes and adjacent to them suggest local dissolution of the calcite wall rock during or after faulting.

Although Set 2 faults generally lack mylonitic fabric, the adjacent wall rock commonly shows strong signs of ductile shear. Our notes make repeated mention of mineral grains flattened and reoriented by drag, including mechanically strong franklinite grains in ore and garnet grains in gneisses. In places these grains are highly flattened, with length:thickness ratios of 10 or more. However, along a few such faults, but always in mechanically strong, high-grade ore, we noted little evidence of wall-rock ductility and franklinite grains neatly cut off at the fault surface. Fault

breccias along Set 2 faults were noted in places but probably owe their formation mostly to later episodes of slip.

Many Set 2 faults show evidence of reactivation, with two and even three sets of striae indicating multiple episodes of slip. Numerous offsets of Set 2 faults by those of other sets suggest Set 2 faults are among the oldest in the Sterling Hill area, with the likely exception of the Set 1 faults previously described.

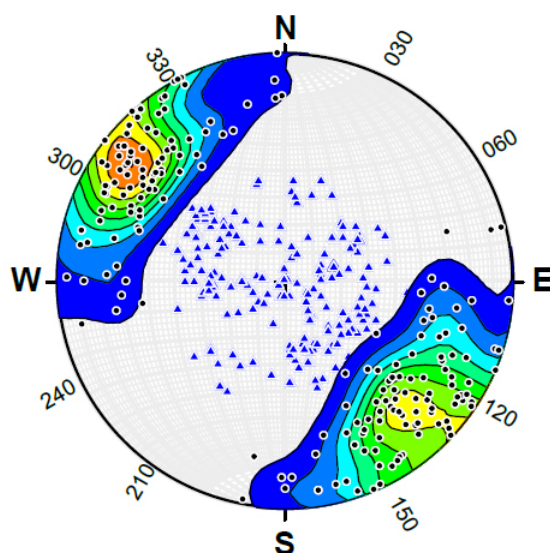


Figure 10. Lower hemisphere, equal-area stereographic projection of 203 Set 2 faults at Sterling Hill. Fault poles are plotted as blue triangles and slip vectors as black dots. Kamb point-density contours are colored at intervals of one standard deviation.

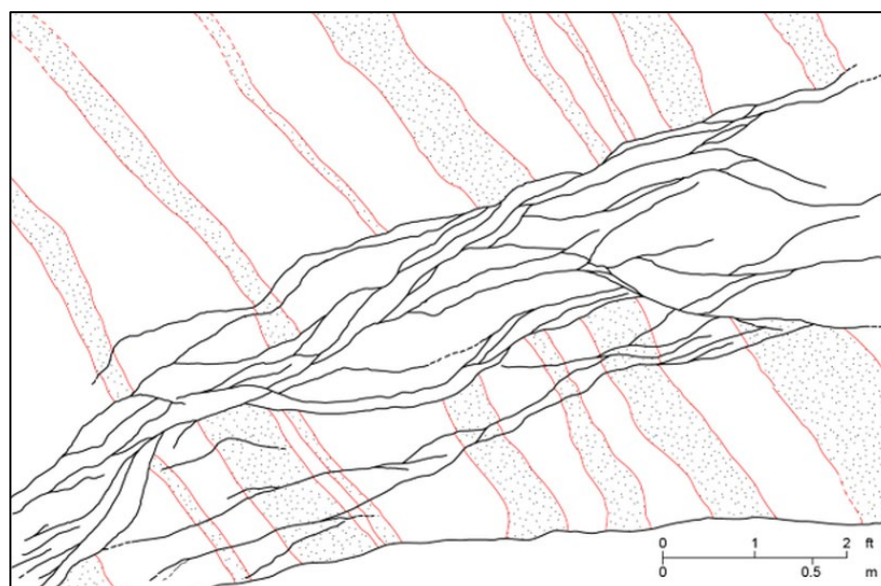


Figure 11. A braided Set 2 fault zone cutting high-grade zinc ore along a nearly vertical exposure in the 970 stope, 1000 level. Individual fault strands tend to be highly irregular and form a complexly anastomosing network. The plane of section extends from about S30W (left) to N30E (right); the view direction is roughly parallel to the transport direction of the upper plate. Stippled layers are zincite-rich; those between contain more calcite. Zincite is missing from most of the ore within the fault zone due to dissolution by hydrothermal fluids. This figure was prepared by establishing a control grid in the field, sketching the faults, and later using multiple overlapping photographs to map fault traces in more detail.

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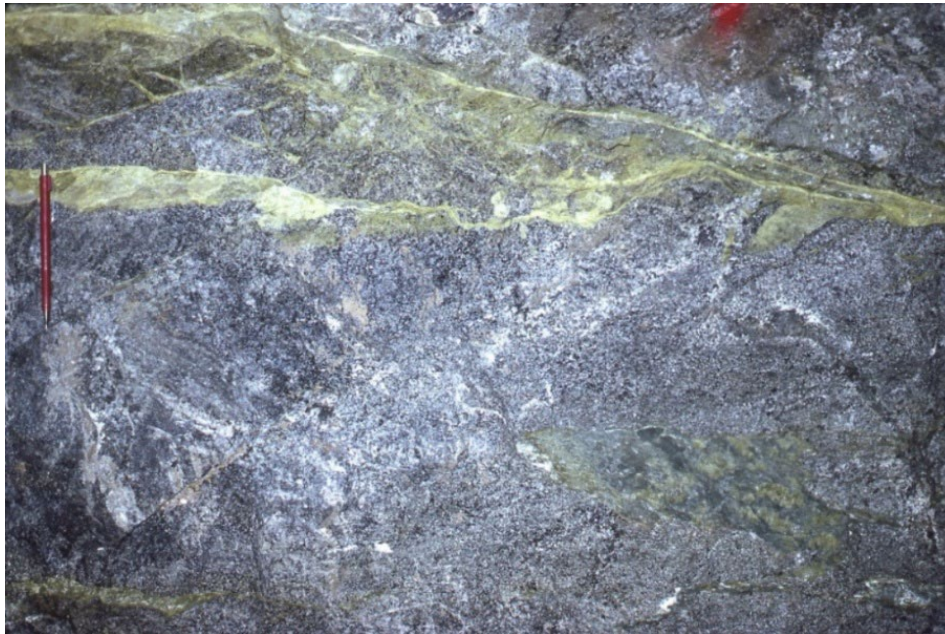


Figure 12. Irregular, gently dipping Set 2 faults cutting pyroxene-feldspar gneiss in the Sterling mine. Feldspar in the gneiss was altered to epidote by hydrothermal fluids flowing along the faults. Pencil at left is 14 cm long.

Set 3 Faults

Faults of Set 3 strike $N10^{\circ}-60^{\circ}E$ and dip moderately steeply ($45^{\circ}-75^{\circ}$) northwest (fig. 13). Their average orientation is $N41E/62NW$. Well-developed calcite accretionary fibers on more than 120 such faults in marble show unequivocally that they are reverse faults. As measured, these are the most common faults in the mine, with more than 230 examples in our dataset.

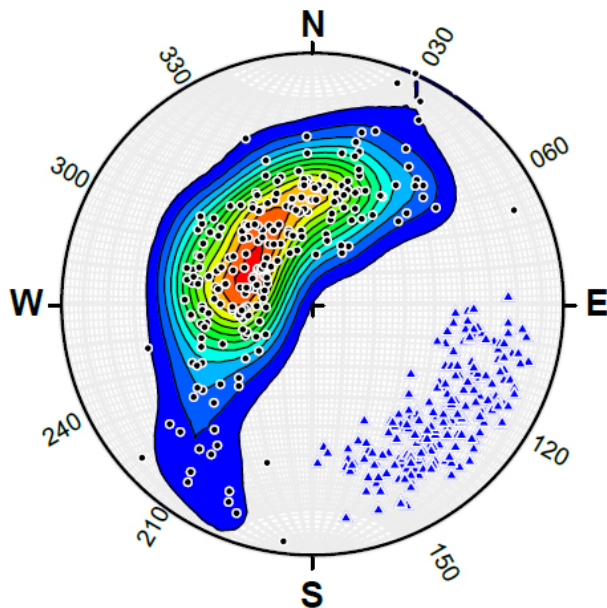


Figure 13. Lower hemisphere, equal-area stereographic projection of 232 Set 3 faults at Sterling Hill. Fault poles are plotted as blue triangles and slip vectors as black dots. Kamb point-density contours are colored at intervals of one standard deviation.

Slickenlines on Set 3 faults show a broad range of orientation (fig. 13), broader than the orientation range of the faults themselves. The slickenlines on individual faults, however, tend not to deviate markedly from the dip line, so reverse movement on most Set 3 faults was associated with only minor components of right- or left-lateral slip. The densest concentration of slickenlines is in the NW quadrant, many with bearings between N40W and N75W, and with a maximum about N55W. The latter is equivalent to a slip vector of S55E, only 6° off the dip line of the average Set 3 fault.

Set 3 faults commonly occur in zones of multiple, interconnected fault strands. These zones are much narrower than the braided fault zones of Set 2 and have typical widths of only 2-10 cm. Deformation of the wall rock adjacent to Set 3 faults, like those of Set 2, is overwhelmingly ductile. Numerous examples in the mine show franklinite and willemite grains strained to elongate shapes and sheared into near-parallelism with fault surfaces (fig. 14). Older faults offset by members of Set 3 often show curvature due to frictional drag adjacent to Set 3 faults as well.

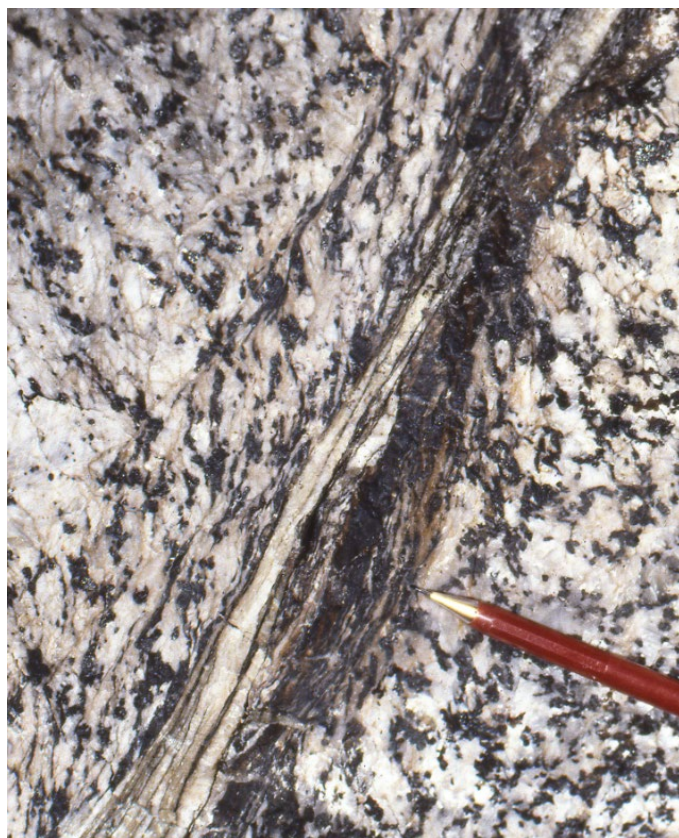


Figure 14. Detail of a Set 3 fault (no. 953 of dataset) in 780 pillar on 900 level of the Sterling mine. Deformation of the ore adjacent to the fault was dominantly ductile, as shown by the highly flattened and rotated franklinite grains. The white “ribbon” within the deformed zone is mostly accretionary calcite formed during a later episode of slip. The portion of the pencil shown is 7 cm long.

One Set 3 fault in marble, a mechanically weak rock, was expressed as a zone of ductile deformation 20-30 cm thick flanking a narrow mylonitic zone in the middle. The surfaces of Set 3 faults in ore and calc-silicate gneisses, like those of Set 2, often appear smooth and polished, with only shallow abrasion slickenlines producing a delicately streaked appearance. In marble, as previously noted, Set 3 fault surfaces are often obscured by a coating of calcite accretionary fibers.

As in faults of Sets 1 and 2, Set 3 faults showing more than one set of slickenlines are hardly rare, and some – but relatively few – show evidence of brittle behavior during reactivation. The rock along one such fault in ore was brecciated along and within the anastomosing strands of a narrow fault zone.

Set 4 Faults

Faults of Set 4 strike N20°-70°W and dip moderately steeply (typically about 60°) southwest (Fig. 15); their average orientation is N48W/59SW. They are moderately common in the mine, with more than 140 known examples represented in our dataset. A prominent feature of these faults is their nearly bimodal slip directions, as described below; many show clear evidence of a reverse sense of slip, and numerous others show equally clear evidence of right-lateral slip.

Set 4 faults are undulatory along both strike and dip. Locally, multiple fault strands that split and merge occur in zones about 15 cm wide. Unlike the faults of Sets 1-3, Set 4 faults show almost no evidence of ductile behavior along their traces. Minor brecciation of the wall rock has occurred along some of them, and along a few others, even in mechanically weak marble, the lenticular voids resulting from mismatch of nonplanar fault surfaces after slip have remained open, again attesting to the lack of ductile deformation of the rock to close them.

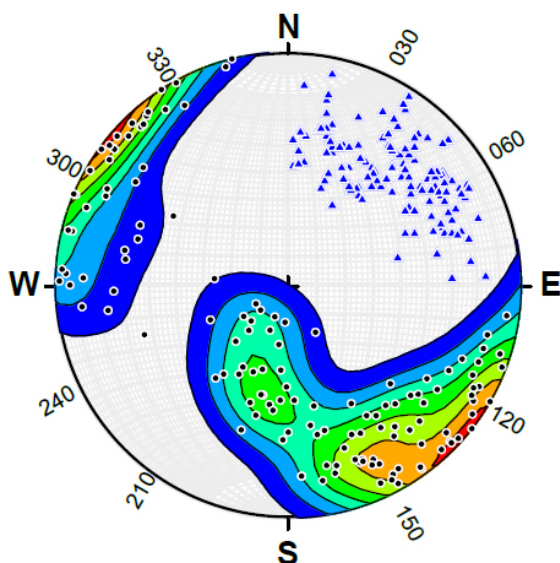


Figure 15. Lower hemisphere, equal-area stereographic projection of 140 Set 4 faults at Sterling Hill. Fault poles are plotted as blue triangles and slip vectors as black dots. Kamb point-density contours are colored at intervals of one standard deviation.

Slip vectors along Set 4 faults in marble commonly are revealed by fibrous calcite that grew within fault openings during slip. Along some of these faults, steeply pitching calcite fibers on the fault plane were plated over by younger, nearly horizontal ones, showing reverse movement on these faults predated right-lateral slip. Remarkably, however, some Set 4 faults preserve a transitional record between them. In seven places on a fault in the Fill quarry, for example, calcite fibers were observed to curve 90° from steep pitches to horizontal ones.

Observation of the polarity of the fibers – where they were rooted on the wall rock at one end and broken at the other – again revealed that reverse slip predated the right-lateral movement. Several other examples of strong fiber curvature in the same sense were noted elsewhere, including not only in marble, but in ore. The available data thus appear to indicate a complete and continuous transition from one stress regime to another.

Set 5 Faults

Faults of Set 5 have a rather broad range in orientation, with common strikes of N10°-60°E and dips ranging from about 50° SE through vertical to 80° NW (Fig. 16). They are the youngest of the five sets of faults recognized in the area and are fairly common, with more than 160 of them represented in our dataset. Most are broadly curved along both strike and dip. Their average orientation of N31E/76SE is roughly similar to that of Set 1 faults but with somewhat more northerly strikes (by 14°) and steeper average dips (also by 14°).

Set 5 faults, like those of Set 4, are brittle faults that show almost no sign of ductile behavior. Pyroxene grains in gneisses, for example, are neatly cut off by these faults. Calcite marble adjacent to them commonly shows no visible sign of deformation, and some of the faults retain open lenticular voids along their traces. The majority of Set 5 faults—85% of them—are dip-slip normal faults with slickenlines pitching 70° or more on their surfaces. The slickenlines cluster around an average bearing of S53E (Fig. 16), within 6° of the dip line of the average Set 5 fault.

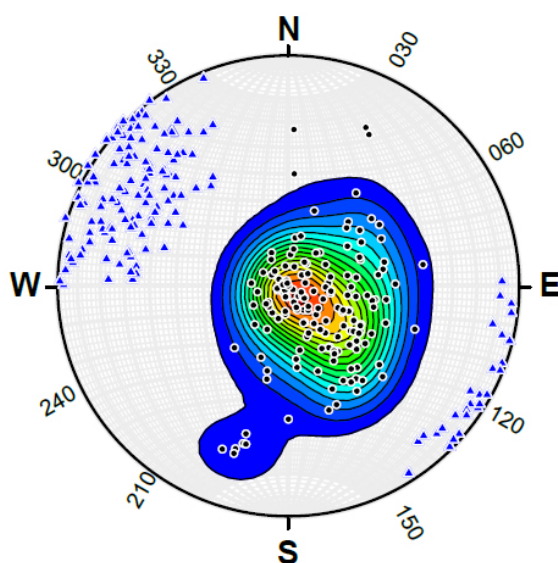


Figure 16. Lower hemisphere, equal-area stereographic projection of 163 Set 5 faults at Sterling Hill. Fault poles are plotted as blue triangles and slip vectors as black dots. Kamb point-density contours are colored at intervals of one standard deviation.

Some Set 5 faults have orientations inherited from the mylonitic fabric of much older Set 1 faults, and formed during reactivation of those faults in a brittle rather than ductile stress regime. As previously noted, films of graphite along the foliation planes of Set 1 mylonite made

them prone to renewed slip, especially during the favorably oriented stress regime of Set 5 faulting. Prolonged leakage of water into the Sterling mine along Set 5 brittle faults within reactivated mylonite has, in places, led to pronounced weathering of the wall rock (locally to limonitic mud) and to deposits of calcite flowstone where these faults intersect the mine workings.

Nearly all Set 5 faults show only a single set of slickenlines, consistent with their young age relative to other faults at Sterling Hill. About ten Set 5 faults, however, displayed two sets of slickenlines, one of them with abnormally shallow pitches on the fault surfaces. The downdip set proved to be the older in every case. Commonly its most visually obvious expression was as streaked-out graphite flakes on fault surfaces in marble. The younger, shallow-pitching slickenlines on several faults appeared as delicate, closely spaced, mutually parallel scratches oblique to the graphite streaks. Some of these scratches could be traced in continuity across one graphite streak into another. Most of these slickenlines pitch SW (e.g., the cluster of six points in the SW quadrant of Fig. 16), corresponding to late, oblique right-lateral slip.

OTHER FRACTURE SETS AT STERLING HILL

Although the focus of our study was on faults in the Proterozoic rocks of Sterling Hill, fractures of different origin exist there. Among them are joints, blast-induced fractures (not treated here), and, possibly, sets of ring fractures around solution-collapse breccia pipes.

Joints

We recognized three sets of extension joints in the Sterling mine, all of which appear younger than the faults and are unmineralized except for local coatings of calcite. One of the joint sets, with median orientation N60W/88NE, correlates well with joints measured at the surface by Volkert and Monteverde (2013) and earlier by Hague and others (1956). A second set, the most widespread set of joints in the mine with strikes of N76-86W and steep dips, also have probable correlatives in both Mesoproterozoic and Paleozoic rocks at the surface, again as measured by Volkert and Monteverde. Joints of a third set, documented at only two localities in the mine, have orientations similar to those of Set 3 faults (NE strikes, fairly steep NW dips) but probably are unrelated to them. Unlike the faults, these joints are unmineralized except for coatings of calcite, and they exhibit no sign of ductile behavior. Our observations and data on all three joint sets in the Sterling mine are given in Appendix D, which provides much more detail than summarized here.

Ring Fractures

Evidence for ring fractures peripheral to solution-collapse breccia pipes at Sterling Hill is tenuous at best. Such fractures form around the margins of breccia pipes as they stope upward through overlying rocks during successive episodes of collapse into an underlying cave system (Verbeek

and others, 1988). Metsger (1990, 2001) discussed the presence of multiple breccia pipes in the Sterling mine, one of which was intersected by mine workings over a vertical extent of more than 1,100 ft, but did not mention ring fractures associated with them. We had insufficient time to address this topic as well. However, during our study of faults in surface exposures at Sterling Hill, we noted the presence around the Noble pit of fractures concentric to the pit margin. The Noble pit is a probable smaller relative of the Passaic pit, which is underlain by a roughly cylindrical mass of highly altered breccia that probably originated as a solution-collapse breccia pipe. The rock peripheral to the Noble pit, however, is too weathered for surface features on the fractures to be preserved, and the collective evidence for ring fractures, though somewhat suggestive, is hardly convincing. Measurements of the orientations of these fractures and details of their appearance are on pages 46-48 of Appendix A.

FAULT-RELATED MINERALIZATION AT STERLING HILL

The Franklin and Sterling zinc mines constitute one of the most complex mineral localities on Earth. More than 1,100 scientific papers have been published on these deposits, the majority of them describing some aspect of the hundreds of secondary minerals that occur there. Many of these minerals were deposited along faults, either by hydrothermal fluids whose temperatures, pressures, and compositions changed markedly over time, or by meteoric water descending into the underlying rocks along some of the same faults. It is now possible to make some tentative correlations between the mineralization and fault histories of this area. A few general observations:

- Set 1 faults, with their mylonitic fabric, offered little opportunity for fault-related mineralization. The highly deformed mineral grains within Set 1 mylonite each recrystallized into much smaller, tightly interlocking, nearly strain-free grains (Stephens and others, 1988) resulting in a rock with almost no available space for mineral precipitation. It was not until much later, upon reactivation of parts of these faults, that sufficient open space developed for the formation within them of fault-lining hydrothermal minerals.
- Faults of Sets 2 and 3 produced some of the mineral species most coveted by collectors of Sterling Hill minerals. The main locality for mcgovernite, for example, was along a Set 2 fault on 900 level (fig. 17), and most of Sterling mine's specimens of magnussonite (a rare manganese arsenate, known from only four localities worldwide) were recovered from a Set 2 fault on 1200 level. The braided Set 2 fault zone shown in figure 11 produced numerous, highly fluorescent specimens of sphalerite and secondary willemite. Set 3 faults are best known for producing dozens of fine specimens of "dead zone" willemite (fig. 18) from a locality on 430 level, as well as additional nice specimens of mcgovernite from localities on both 800 and 900 levels. Pyrochroite was also found within a Set 3 fault on 1000 level.

- Minerals that formed along faults of Sets 2 and 3 are closely related to the lithology of the host rock in many places. So close is this relation that the assemblage of fault-lining minerals on some faults changes completely within distances of only 2-3 cm at lithologic contacts. This is evidence of a rock-dominated hydrothermal system, in which fluid flow is sluggish and most or all components of fault-lining minerals are available locally from the wall rock. Examples from the Sterling mine were documented in Verbeek and Grout (2018), and others from nearby areas by Jenkins and Misiur (1994) and Cummings (1988, 1997).
- Faults of Sets 4 and 5, despite their abundance in the mine, produced little in the way of collectible mineral specimens, save for one productive locality for sphalerite and other sulfides along Set 4 faults on 900 level. Secondary willemite (locally fibrous) and serpentine are known from faults of both sets in ore, and zincite where primary zincite is present in the wall rock, but these are uncommon. The most abundant mineral along faults of Sets 4 and 5 throughout the mine is calcite, in many places accompanied by small grains and patchy films of violet fluorite.



Figure 17. Flat rosettes of mcgovernite crystals encrusting a Set 2 fault surface in willemite-franklinite-calcite ore, 780 pillar, 900 level, Sterling mine. This specimen was collected by miner John Kolic on July 26, 1990 and was no. 529 in his collection; it is on public display in Zobel Hall of the Sterling Hill Mining Museum. Specimen size: 11 x 9 x 8 cm.

These are probably products of a low-temperature, hydrothermal mineralization event that affected the entire region (Cummings, 1993), when fluid flow through the pervasively fractured rocks could take place relatively unimpeded at shallow crustal levels. These late-stage minerals, then, signaled a change from minerals formed during rock-dominated hydrothermal mineralization (faults of Sets 2 and 3) to a more fluid-dominated system at lower temperatures (Sets 4 and 5).

- Many new minerals have formed at Sterling Hill in recent geologic times due to the combined effects of exposure to meteoric water, atmospheric gases, and biologic activity. The network of interconnected faults cutting the orebody has locally allowed oxygenated meteoric waters to freely penetrate hundreds of feet below the surface, resulting in locally severe alteration of the minerals originally present and the formation of new minerals in their place. This is an ongoing process.

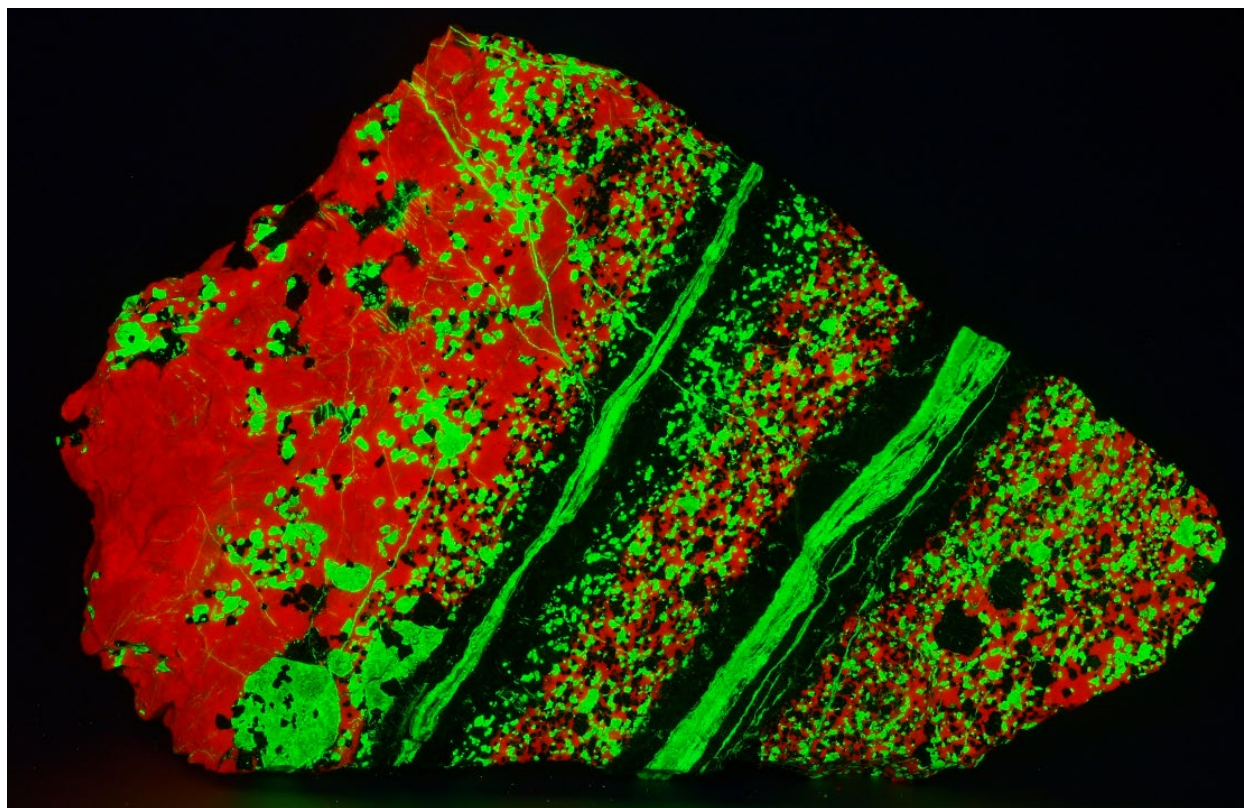


Figure 18. A large specimen of “dead zone” willemite, shown here under shortwave ultraviolet light, from a group of Set 3 faults on 430 level, high on the west rib of the East limb haulage drift, about 60-100 ft north of the safety exit. The two multistranded willemite veins are each flanked by zones of hydrothermally altered, nonfluorescent ore that constitute the “dead” zones. Example from Robert Hauck collection; now Franklin Mineral Museum specimen FMM-7303, 39 x 25 x 5 cm.

During our time at Sterling Hill, we largely confined our observations of minerals to those along faults and had little time to study other mineral occurrences. Our observations to date for fault-related minerals are given in Appendix B. For each species we provide summary comments and then list information for specific faults. Appendix C, in contrast, contains information on some noteworthy mineral localities in the mine, whether fault-related or not, with the localities listed in order of increasing depth in the mine.

ACKNOWLEDGEMENTS

In addition to the people mentioned on page 3 of Appendix A, we thank Pete Modreski, Steve Misiur, Bernie Kozykowski, and Jeff Glover for photographing key geologic features underground. We also thank Greg Herman and Mike Di Maio for encouraging us to publish these results, providing logistical support, and their review of this paper.

REFERENCES

- Allmendinger, R.W., Cardozo, N., and Fisher, D., 2011, Structural geology algorithms: Vectors and tensors in structural geology. Cambridge University Press, 289 p.
- Cummings, W., 1988, The Buckwheat Dolomite — Fissure mineralization of Paleozoic age. The Picking Table; Journal of the Franklin-Ogdensburg Mineralogical Society, vol. 29, no. 2, p. 4-6.
- Cummings, W., 1993, A Mississippi Valley Type lead-zinc vein of probable Paleozoic age at the Lime Crest quarry, Sparta, New Jersey. The Picking Table; Journal of the Franklin-Ogdensburg Mineralogical Society, vol. 34, no. 1, p. 14-16.
- Cummings, W., 1997, Ferroaxinite and heulandite from the Lime Crest Quarry: new minerals for the locality: The Picking Table; Journal of the Franklin-Ogdensburg Mineralogical Society, vol. 38, p. 30.
- Gates, A.E. and Costa, R.E., 1998. Multiple reactivations of rigid basement block margins: Examples in the northern Reading Prong, USA. In: Gilbert, M.C. and Hogan, J.P., eds., Basement Tectonics 12: Central North America and Other Regions. Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 123–153.
- Gates, A.E. and Volkert, R.A., 2004, Vestiges of an Iapetan rift basin in the New Jersey Highlands: Implications for the Neoproterozoic Laurentian margin. Journal of Geodynamics, vol. 37, p. 381-409.
- Hague, J.M., Baum, J.L., Herrmann, L.A., and Pickering, R.J., 1956, Geology and structure of the Franklin-Sterling area, New Jersey. Geological Society of America Bulletin, vol. 67, no. 4, p. 435-474, with map.

Chapter 3. Fault History of the Sterling Zinc Mine, Ogdensburg,
Sussex County, New Jersey, with Appendices

- Herman, G.C., 2025, Chapter 2. The Structural, Tectonic, and Geospatial Aspects of the Sterling and Franklin Zinc Mines, Sussex County, New Jersey., *in* Di Maio, M.P., Herman, G.C., and Verbeek, E.R., editors, *Revisiting the Sterling Hill Orebody: Challenges in Understanding this Magnificent Deposit: 41st Annual proceedings and field guide of the Geological Association of New Jersey*, The Sterling Hill Mining Museum, Ogdensburg, NJ, p. 59-115.
- Jenkins, R.E., II and Misiur, S.C., 1994, A complex base-metal assemblage from the Sterling Mine, New Jersey: *The Mineralogical Record*, vol. 25, no. 2, p. 95-104.
- Marrett, R. and Allmendinger, R.W., 1990, Kinematic analysis of fault-slip data: *Journal of Structural Geology*, vol. 12, no. 8, p. 973–986.
- Metsger, R.W., 2001, Evolution of the Sterling Hill zinc deposit, Ogdensburg, Sussex County, New Jersey, *in* Slack, J.F., ed., Part 1. Proterozoic iron and zinc deposits of the Adirondack Mountains of New York and the New Jersey Highlands: *Society of Economic Geologists Guidebook Series*, vol. 35, p. 75-87.
- Petit, J.P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks: *Journal of Structural Geology*, vol. 9, nos. 5-6, p. 597-608.
- Ratcliffe, N.M., 1980, Brittle faults (Ramapo Fault) and phyllonitic ductile shear zone in the basement rocks of the Ramapo Seismic Zone, New York and New Jersey, and their relationship to current seismicity, *in* Manspeizer, Warren, ed., *New Jersey Geology and Guide to Field Trips: 52nd annual meeting of the New York State Geological Association*, Rutgers University, Newark, p. 278-311.
- Stephens, G.C., Metsger, R.W., and Yang, Q., 1988, Shear zone development in marble: observations on the Zero fault at the Sterling Hill mine, Sussex County, New Jersey [abs.]: *Geological Society of America Abstracts with Programs*, vol. 20, no. 7, p. A180.
- Verbeek, E.R. and Grout, M.A., 2018, Hydrothermal mineral deposition in a rock-dominated fluid system at Sterling Hill, New Jersey: *The Picking Table; Journal of the Franklin-Ogdensburg Mineralogical Society*, vol. 59, no. 2, p. 15-22.
- Verbeek, E.R., Grout, M.A., and Van Gosen, B.S., 1988, Structural evolution of a Grand Canyon breccia pipe--the Ridenour copper-vanadium-uranium mine, Hualapai Indian Reservation, Coconino County, Arizona. U.S. Geological Survey Open-File Report 88-006, 75 p.
- Volkert, R.A. and Puffer, J.H., 1995. Late Proterozoic diabase dikes of the New Jersey Highlands—A remnant of Iapetan rifting in the north-central Appalachians, *in* Drake, A.A., Jr., ed., *Geologic studies in New Jersey and eastern Pennsylvania: U.S. Geological Survey Professional Paper 1565-A*, 22 p.

APPENDIX A. FAULT AND FAULT-SLIP DATA FOR 1158 MEASURED FAULTS AT STERLING HILL, OGDENSBURG, NJ

The following URL will access a PDF file containing all numerical data for fault orientations and slip vectors for the 1,158 faults measured at Sterling Hill, along with comments on the character of each fault, the minerals that formed along them, how their slip sense was determined, brittle vs. ductile response of the rock to faulting, and more:

<https://ganj.org/2025-auxiliary-data/GANJ41Verbeek&Grout2025AppendixA.pdf>

The original data, most of which were gathered between 1988 and 1992, were obtained by use of a bearing compass, which was in common use at the time. In our original field notes, the orientation of a fault might be given as N71W/50SW, and the orientation of slickenside striae on that surface as 46/S12E, where 46 is the plunge (inclination) of the striae and S12E is their bearing. However, the combination of numbers and letters to indicate orientations does not lend itself well to quantitative analysis via digital computers, where only numerical data are desired. For that reason, we converted all of the data to right-hand-rule (RHR) format for direct entry into software programs for analysis and plotting. In this example, the fault orientation is given as 109/50 and the orientation of the slickenlines, originally expressed as bearing and plunge, has been converted to a pitch (rake) of 69. Both our original data and their equivalents in RHR format are summarized in Table 1 for all 1,158 faults.

In Table 1, the letters n.d. stand for “not determinable” and the letters n.a. for “not applicable.” Data in RHR format are in orange-tinted columns.

APPENDICES B-D

The following URL will access a PDF file containing three appendices:

<https://ganj.org/2025-auxiliary-data/GANJ41Verbeek&Grout2025AppendicesB-D.pdf>

Appendix B. Minerals lining fault surfaces in various rock types and along individual faults.

Appendix C. Notes on selected mineral localities in the Sterling Mine.

Appendix D. Joints measured in the Sterling Mine.

Chapter 3. Fault History of the Sterling Zinc Mine, Ogdensburg, Sussex County, New Jersey, with Appendices



Photograph of a collection of New Jersey Zinc Co. thin sections from the
Metsger Estate donations to the New Jersey State Museum.



Photograph of sphalerite deposited along hydrothermal solution fronts in core DDH S-262 around the ~1883 ft section. Please see chapter 2, figure 12 for how this section correlates with the Sterling Hill ore body. The core is held in the Rutgers University core repository.

GANJ XLI (41) Field Guide

PART 1. FIELD TOUR OF THE STERLING HILL PASSAIC PIT, NOBLE PIT, AND FILL QUARRY

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The field tour through the open-surface cuts, or ‘pits’, and the fill quarry will take about 2.0 hours. We anticipate having two groups of 40, so we must exercise patience at each stop and make room for people to access each feature accordingly. The path we take and the field STOPS are highlighted in figures 1 and 2. We will first look at an east layer, depicted in figure 3 as an infiltrated top layer. We’ll use layer and vein rather than limb as it’s proven that the east and west veins are not part of a continuous, overturned, synclinal fold. The east layer is exposed in STOP 1 in the Passaic pit, followed by STOPS 2 and 3 in the fill quarry. We then proceed to STOP 4 after walking around the core structure to see the southern high wall of the Noble pit from a distance. This high wall is probably a Mesozoic normal fault that has dropped the ore body down into its current position to the north (STOP 4). It exposes probable, Alleghenian reverse-shear zones

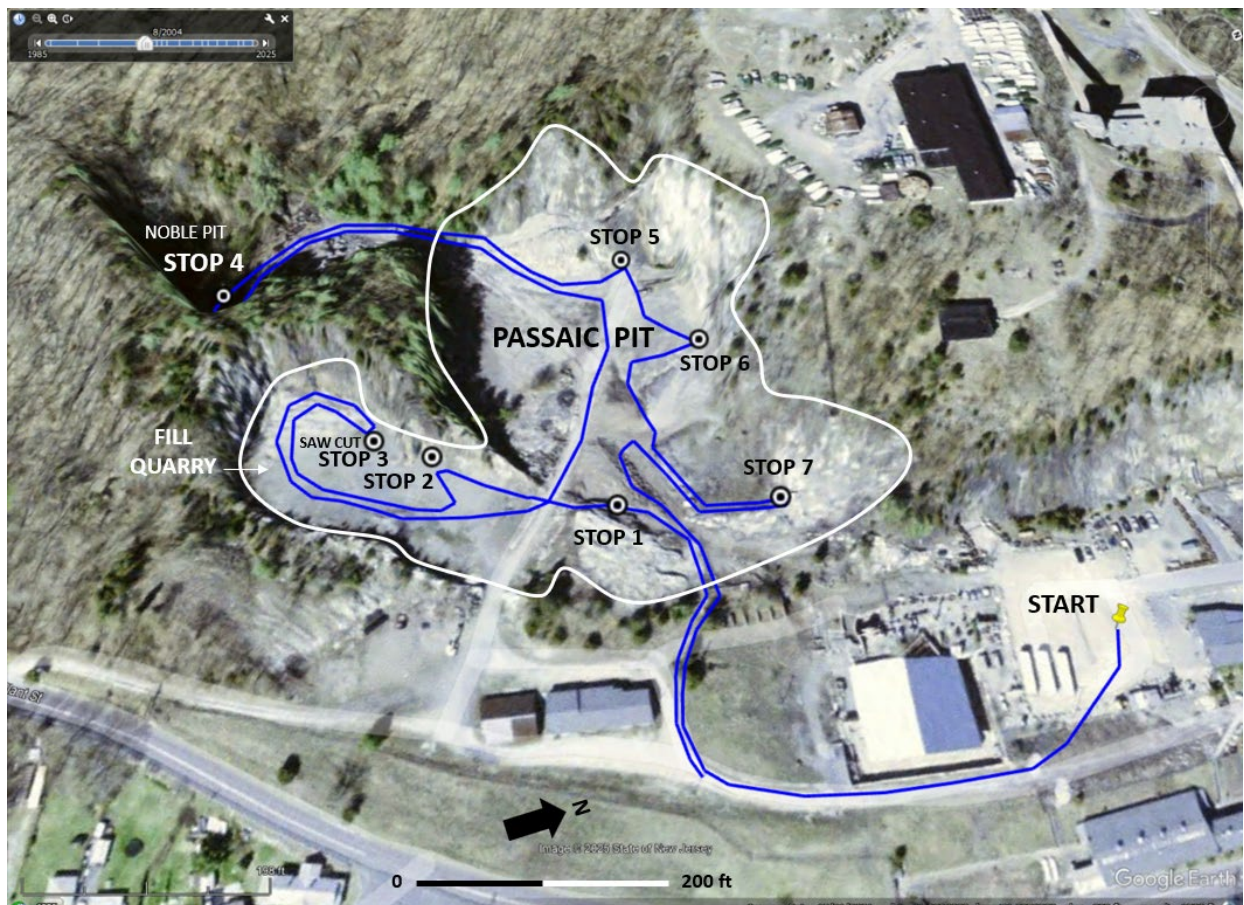


Figure 1. Google Earth Pro map 1 of the field stops. Overhead view

that are clearly visible in the cross-cutting fault surface. We then return to the Passaic pit to view the western high walls featuring a thick franklinite and black willemite layer at STOP 5 striking parallel to the core structure and an adjacent lower mineralized layer exposed in the northern highwall at STOP 6. STOP 7 includes a glacial valley-fill deposit sitting atop the edge of the structural core where partly melted, dark gneiss blocks are entrained within a marble showing ductile deformation.

Hemimorphite $\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$

Photo by Earl Verbeek



The Passaic pit dates to the late 19th century (circa 1870; Dunn, 1995) and was mined by the Passaic Zinc Co. Primary zinc ores were a suite of weathered, secondary, manganese and zinc minerals including hemimorphite with one crystalline form pictured to the left that led to the informal name of "maggot" ore.

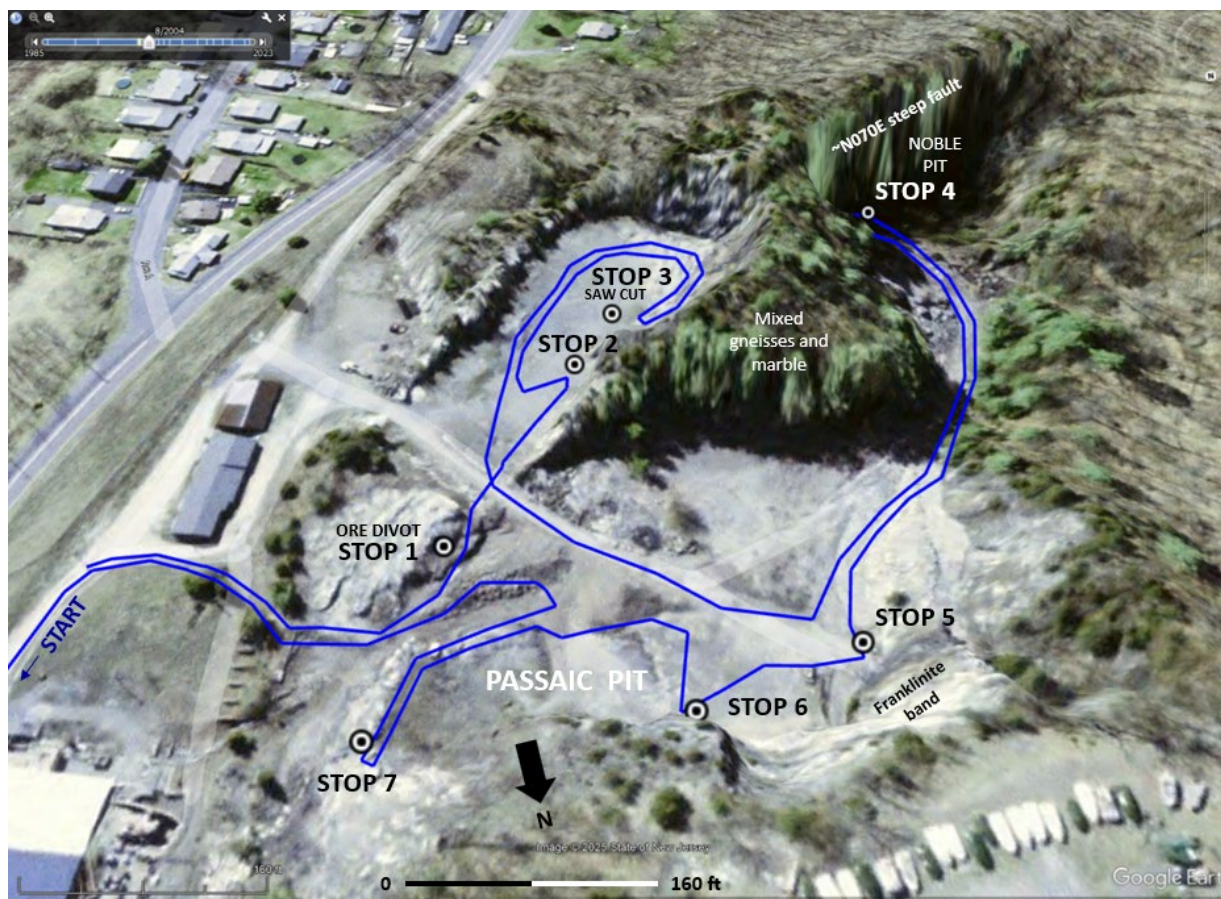


Figure 2. Oblique, overhead view of the pit tour looking southward.

The Noble mine covers parts of two lots of the Ogden Divisions (Dunn, 1995). It lies southwest of the Passaic pit and is the southern-most, major surface working on Sterling Hill. It holds the "keel" structure of the Sterling Hill ore body that is now covered by boulders and other fill material that litter the pit floor. Subsurface workings there were sealed by NJZC and later reopened by the SHMM. This area holds the Trotter tunnel and old haulage and steam-operated mining equipment that was added by the Hauck brothers when developing the mining museum.

An overhead view of the southern part of the site is shown using GE Pro in figure 4. The aerial photograph shows the nature of the ~N80E-directed shearing of the core structure. It also shows the locations of STOPS 2 to 4 and a photograph of a stratigraphic contact between a brecciated, brown dolomitic marble underlying a medium gray to black layer with abundant franklinite. This is the base of the mineralized sequence that's capped by the willemite- and zincite-rich layer seen in the vertical saw cuts (see chapter 2). This layer was mapped atop the ridge southward from STOP 3 to where it likely terminates against faults striking parallel to that forming the Noble Pit high wall. The bottom part of this ore layer is composed of highly magnetic franklinite that is a few meters thick overlying a sharp contact with highly strained, dolomitic marble (figure 5). The ore body continues on a fairly straight course from the ore pillar of STOP 3 to the corner of the fill quarry and is underlain by a thick magnetite and franklinite layer pictured in figs. 5 and 6. This layer is cut by some secondary faults, with one of similar composition to that mined for iron ore in the Noble pit where the keel of the ore deposit was stripped off along the

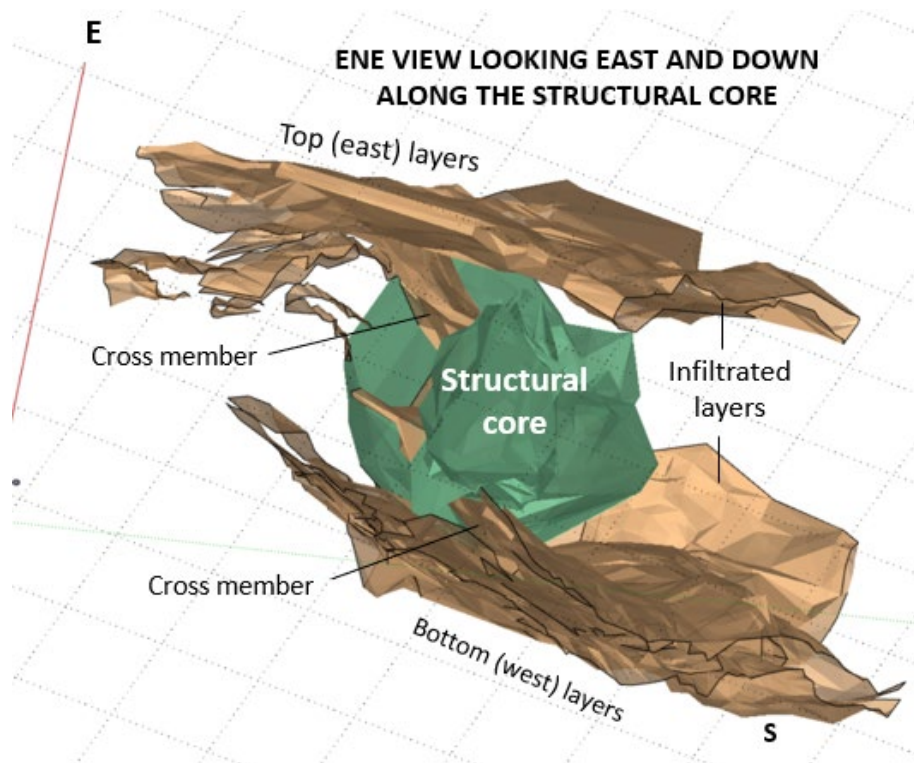


Figure 3. A 3D depiction of the structural core (green) and adjacent, infiltrated layers on the east and west sides. The core structure has offshoots called cross members that connect to the infiltrated layers. The grid has 100x100-ft. divisions. Modified from Herman, 2025; chapter 2, figure 14.

highwall. Continuing northward around the perimeter of the Noble pit, only a few outcrops of ore remain along the pit walls, but this was an area of much iron mining in the past. A franklinite-rich layer is exposed along the northwestern edge of the Passaic pit. A partly filled stope also occurs along the west layer that's located along the access road about 100 ft farther north. The N-trending part of the access road in this area lies along the approximate trace of the mined-out, bottom-most west layer. Dense vegetation masks outcrops along the trail which leads over the saddle area as we proceed to STOP 5 where a massive, black franklinite and black willemite layer is pocked with old, exploratory adits and stopes. This layer is enriched in magnetite, franklinite and black willemite and lies at the base of the mineralized sequence. If the surface expression conforms with the subsurface one, then the East and West layers don't directly

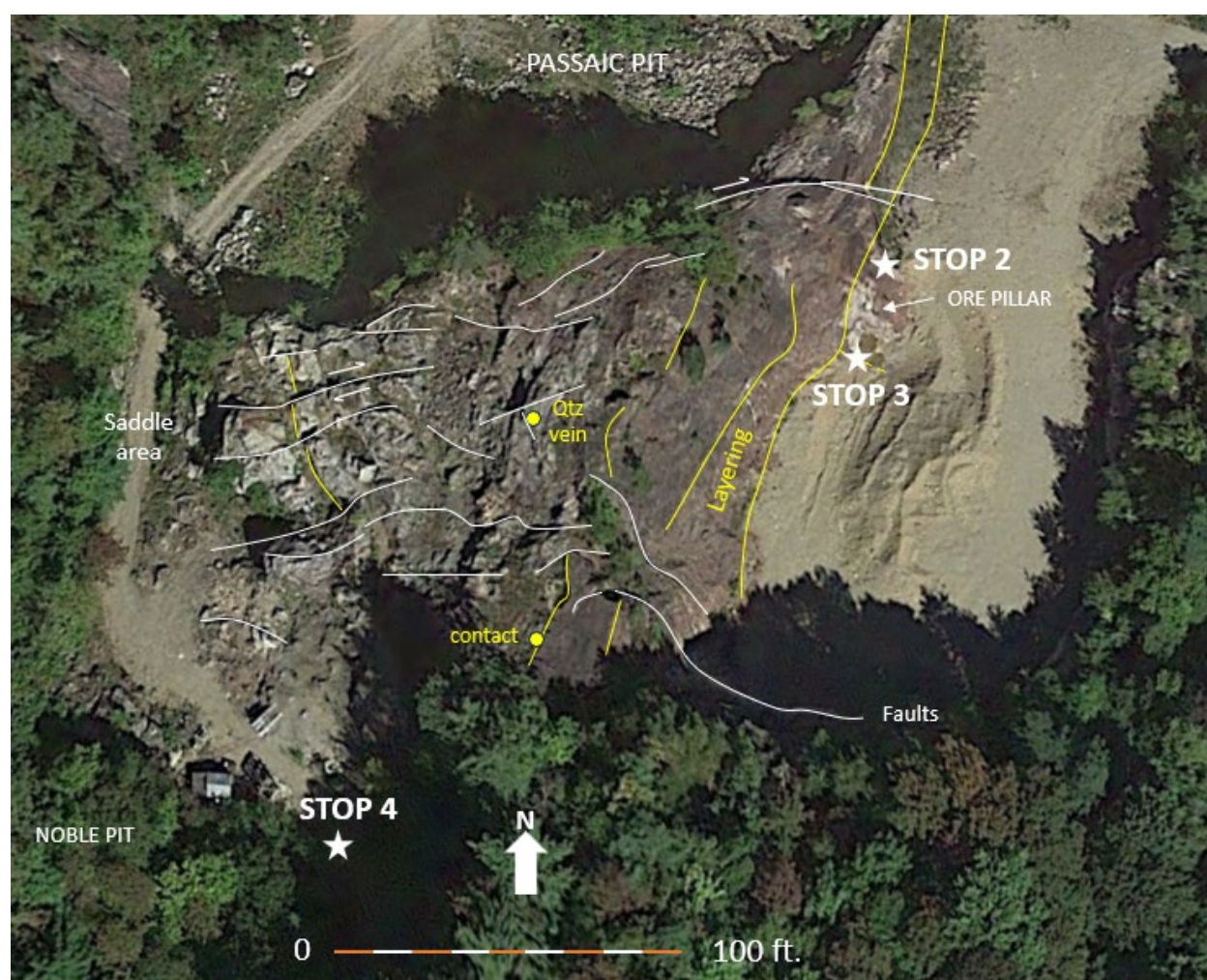


Figure 4. A September 2013 historical image of the Passaic and Noble pits from Google Earth Pro showing layering trending NNE cut by faults mostly trending ~N80E to E-W. This photo was taken before the east-layer ore pillar was sawed and slabbed (see figs. 11 -13 below). Locations for STOPS 2 through 4 are noted.

connect but are offset along faults. As demonstrated in chapter 2, the keel structure is downwarped along normal faults in addition to inheriting its synclinal form from early Mesoproterozoic fault-propagation folding.



Figure 5. The contact between dolomitized, broken marble below and the base of the first top layer is exposed high on the ridge south of STOP 3. The location of this contact is noted in figure 4, strikes SW-NE and dips moderately east. The marble layer is pervasively sheared and recrystallized. A thick basal layer of the mineralized layer is laced with coarse franklinite.



Figure 6. Left to right are Mike Di Maio, Mark Zdepski, and Earl Verbeek standing atop a very thick layer enriched in magnetic franklinite that's been glaciated and weathered to show internal layering dipping about 60° to the right (fig. 7). View looking northeast.



Figure 7. A set of thick, iron-mineralized quartz veins filling tension gashes strike NW-SE along azimuth $\sim 125\text{-}155^\circ$ and dip steeply NE through gneiss layers within the structural core that are part of the early ductile-brittle shear zone cutting bedrock. Their location is noted in figure 4. The incorporated gneissic lithons are stretched, segmented and engulfed by iron-rich cements that have yet to be studied in detail.

**STOP 1. Excavated ore from the East (first top) layer in the Passaic Pit
41.082329, -74.605298°**

~20 minutes. This stop features an excavation in the first top layer of the ore body. The drift is about 5 meters long and parallels metamorphic layering. Ore was removed from about a two-meter-thick section of the layer that is bounded to the southeast by two faults; an older (Alleghenian?) one showing a slickensided surface having oblique-reverse slip. That fault is offset along a younger normal fault (Newark?) with a steep northwest dip that cuts and offsets the reverse fault (fig. 8). The kinematics conform with the nested, asymmetric folding seen in the rock bridge above the drift.



Figure 8. A short (~5 meter) drift in the east layer removed about a 2-meter ore section. The thick, basal franklinite-rich layer was not mined. A red box in the left middle highlights the underside of an infiltrated layer shown in figure 9. White annotation on the hanging-wall fault planes denotes their structural orientation. Small folds can be seen high on the rock bridge above the drift.



Figure 9. Two views of STOP 1. The excavated drift is pictured to the left and the wooden ladder rests against a footwall face of an ore layer. A thin cataclastic breccia or more recent glacial gravel clings onto the surface just above the ladder. The bottom photo shows a webwork of franklinite running through the dolomitized Franklin Marble on the underside of the layer to the left. The mineral veins permeate the layer and demonstrate the fluid or highly ductile nature of the mineralization event. The carbonate lithons have an elongate, elliptical symmetry that may reflect the direction of compressive paleostress oriented normal to the long axis of the ellipses within a layer.



Franklinite webwork in
Franklin Marble

STOP 2. An old near-surface drift in the first top ore layer of the Passaic Pit
 41.081927°, -74.605697°

~15 minutes. This stop features an old near-surface mine drift that provides an opportunity to inspect the inside of an ore layer! It was driven into a layer that now forms an ore pillar on the eastern limb that was the focus of extracting rock slabs for museum displays in New York City and elsewhere (figs. 11 and 12). The ore layer is about 20 ft (6 m) thick here. Slickensided shear planes penetrate the rock around the entrance and curvilinear fractures span the ore layer and dip gently northwest that are filled with a secondary willemite (fig. 11). At least some of these fractures are Set 2 thrust faults with NW transport of the upper plates (Verbeek and Grout, 2025; chapter 3). In this area, some of these structures were reactivated and have north-trending slickenlines. Some of the ore in the interior of the drift, plus some of the footwall rock extending northward, was excavated by SHMM personnel in the early 1990s that explains the fairly fresh appearance of some of the rock faces. Note the “new” drill holes near the base of the entrance to this drift and the nearly white rather than brown (weathered) color of the ore.



Figure 10. An old exploratory drift within the east layer forming the rock pillar in figure 10. The drift sits above the saw cuts in the layer on the other side of the ore pillar. The ore layer dips 56° to the southeast and is about 20' thick. Curvilinear fractures that span the layer are cemented with secondary willemite.

STOP 3. The saw cuts in the East-layer pillar within the fill quarry

41.081799°, -74.605827°

~30 minutes. This stop features cable-saw cuts across the first east layer where 1-2" thick slabs of ore were cut out at the base of a remnant ore pillar in the fill quarry (fig. 4). This site was cleared and excavated by the SHMM to facilitate removal of thin rock slabs of zinc ore for display in the American Museum of Natural History, NYC. Those depicted in figure 11 were acquired at the same time and are also now displayed in an underground chamber that's part of the SHMM mine tour. This layer lies just above the structural core and may locally exceed 30 percent zinc in bulk concentration (Baum and Williams, 1947; also see chapter 2). It hasn't been brecciated or plasticized like subjacent core segments. So, the question is, do the willemite-rich siliceous seams represent cross beds, and if so, were these seams zinc-enriched silts and sands expressed as SEDEX beds, or an intercalated carbonate and clastic assemblage that was subsequently infiltrated by zinc-and-iron-rich fluids?

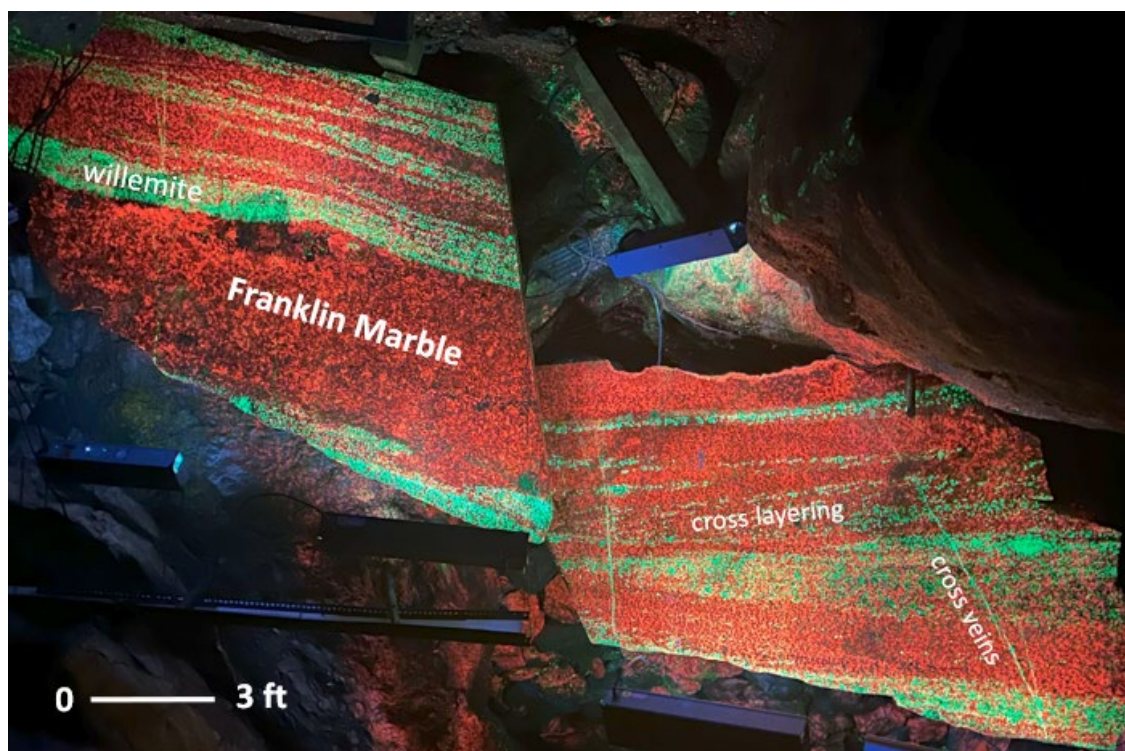


Figure 11. Ultraviolet lights in the slab room of the SHMM mine tour are used to highlight the mineral layering in the ore slabs removed from the saw cuts (fig. 8). This photo is shown upside down to highlight the geometry of cross layering seen in the lower right slab in right-side up alignment. Willemite fluoresces green and highlights the siliceous seams within the calcareous layering (fluorescing red). Second-generation willemite fills the curved fractures and shear planes that cut layering at high angles (also see fig. 10). The upper left slab is upside down with respect to the lower right one. The willemite seems to highlight siliceous cross beds preserved in the metamorphic layering that's not apparent under white light.

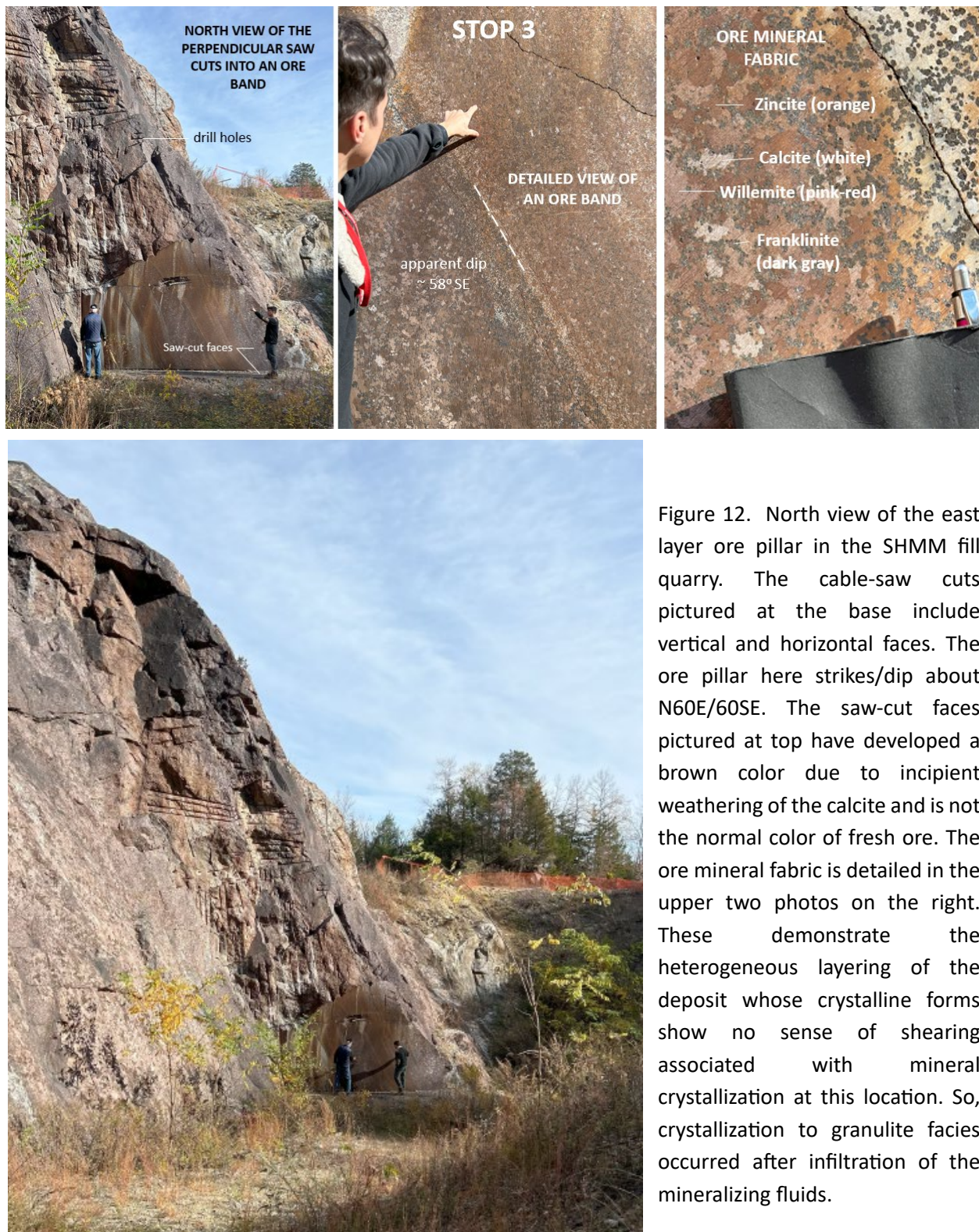


Figure 12. North view of the east layer ore pillar in the SHMM fill quarry. The cable-saw cuts pictured at the base include vertical and horizontal faces. The ore pillar here strikes/dip about N60E/60SE. The saw-cut faces pictured at top have developed a brown color due to incipient weathering of the calcite and is not the normal color of fresh ore. The ore mineral fabric is detailed in the upper two photos on the right. These demonstrate the heterogeneous layering of the deposit whose crystalline forms show no sense of shearing associated with mineral crystallization at this location. So, crystallization to granulite facies occurred after infiltration of the mineralizing fluids.

More recent saw cuts to extract more slabs are shown below (fig. 13).



Figure 13. The most recent saw cuts in the east vein ore pillar show mineral layering dipping 60° SE (top) and a Set 2, top-to-the-northwest small fault of Verbeek and Grout (2025) that offsets layering and layer-parallel thin, dark veins with metasomatic margins. The relay zone between overlapping shear planes is highlighted using shear-sense arrows and filled with secondary brown-weathering calcite. The small black box in the top photo outlines the area covered by the bottom photo.

*STOP 4. The southwestern highwall of the Noble Pit**41.081799°, -74.605827°*

~20 minutes. The highwall in the Noble pit marks the southern terminus of the ore body (figs. 14 and 15). It's accessed by a dead-end trail that funnels through some saplings and ends near the base of the wall. The trail leads to an old adit into the Trotter Tunnel that exits on Plant Street; beneath surface cuts into the ore body. We will explore the area around the base wall, but be careful because space is limited and we must accommodate a rotation of 40 people in the group through this area. So again, be patient and courteous in your approach. The short hike from STOP 3 circumvents part of the median gneiss lying just south of the mud zone and adjacent to the upward projection of the core structure. The southwestern highwall of the Noble pit is seen in the distance and marks the termination of the ore body (fig. 14). Relict mining machinery and other mining props were staged here by Tom Hauck when starting the mining museum.



Figure 14. Distant view of the Noble pit highwall.



Figure 15. The southwest highwall of the Noble pit strikes about $\sim N067^{\circ}E$ and cuts across earlier cataclastic shear zones of probable Paleozoic (Alleghenian) age, now exposed and showing dolomitization (cream-colored minerals) of the cataclastic zones. The shear zones have top-to-the-northwest kinematics and likely correlate to the 10-20' offsets mapped throughout the Sterling Hill mine stope sections (see chapter 1, figure 25). These Set 2 thrust faults are further described in chapter 3. The 067° faults are mapped on the lower left of figure 14, Chapter 2. The top photo shows the narrow path leading through saplings to the highwall viewing area.

STOP 5. The bottom ore layer in the western highwall with the 'Old Dutch' adit
 41.082642°, -74.606298°

~10 minutes. A thick franklinite and black willemite layer crops out in the southernmost part of the western highwall of the Passaic pit (fig. 16). An old adit and stope developed in the layer was probably driven by 19-century miners. The adit leads to a bedrock stope behind the face that Mike Di Maio and I scrambled up past on our free ascent of the wall immediately to the left of the picture. We didn't inspect these excavations more closely because they were partly filled with fallen boulders and rubble that we avoided. We followed a run of two-inch galvanized pipe resting in bedrock creases that leads from the mine floor up past the break in the face slope at the top. The pipe was probably used for dewatering and helped in our ascent where it crossed sections lacking good handholds. The stope behind the adit gutted the interior of the ore layer leaving a shell of franklinite and black willemite in place. Note the meter-sized, leucocratic block floating in the dark mass above the gate to the left. Franklin Marble dips moderately northeast above it.



Figure 16. A basal, very-thick layer of franklinite and black willemite crops out in the western high wall of the Passaic Pit. Its apparent thickness is ~32 ft. but its true thickness is half that as it strikes and dips ~080/55 SE, about parallel to the structural core and toward the viewer.

STOP 6. A second bottom layer in the Passaic Pit Western highwall

41.082781°, -74.605823°

~10 minutes. This stop features an ore band exposed high on the north wall of the Passaic Pit. Just a few-dozen meters above ore layer with the thick, black willemite layer (STOP 6). The spatial relationship between the two is discordant and complicated by intervening faults. The sub-horizontal aluminum bars tacked onto the high wall were placed there by the SHMM to facilitate rock climbing and rappelling.



Figure 17. A second mineralized layer seen in the north face of the western highwall in the Passaic Pit. It sits structurally above the last one with a strike/dip of ~020/55 SE. This same layer is cut by one of the tunnels in the mine tour.



Figure 18. Far view (top) and close-up (below) of a second mineralized layer exposed in the north face of the western highwall in the Passaic pit that sits just below the structural core. Weathering of the face accentuates the mineralized laminae. A crosscut in the modern mine tour runs about parallel to this face and is not far from it. The ore layer underground contains mostly franklinite with subordinate willemite. This wall corresponds roughly to the exposed northern margin of the mud zone, which truncates this N-S striking unit.



STOP 7. Floating gneiss blocks in the Franklin Marble capped by Pleistocene, cemented valley-fill alluvium 41.082717°, -74.605098°

~20 minutes. This stop features an interesting assemblage of some of the oldest and youngest geological features in New Jersey. Complex Mesoproterozoic structures about 1.1 billion years old are partly capped by carbonate-cemented Pleistocene alluvium (figs. 19 and 20). To explain everything one sees here is impossible, and we haven't seen everything here ourselves. Vegetation and alluvium mask covered intervals and more detailed, systematic mapping of the respective rock units is required. But we'll attempt to summarize key aspects that are visible. Please take your time inspecting the sequence here, but be cautious when venturing up to the valley-fill alluvium, as it's draped across bedrock down over a steep wall (fig. 19 upper right photo). Please be conscious of crowding and exercise patience in taking turns to see the various highlights. We will spend about 20 minutes here before heading back out to the parking lot.

We're on the northeastern side of Metsger and others (1958) core of white crystalline limestone (see John Puffer's chapter 1, figure 4) amid a layered section of partially mixed white marble and dark-gray gneiss (black rock). Immediately downslope to the south is a discordant thick black, biotite gneiss layer that could be metamorphosed paleokarst muds that were washed into pre-Ottawan caves while the Franklin Marble was still a limestone (Verbeek, 2015). These bodies near ore contain gahnite (ZnAl_2O_4) and appear to be high-grade metamorphic rocks. A similar body in one of the local marble quarries lacked gahnite because the mud lacked zinc. The mineralized ore layer seen at STOP 6 sits stratigraphically below us, and here we see fragmented, angular blocks of dark-gray gneiss frozen in the course of being assimilated into the plasticized white marble (figs. 19 and 20). The disrupted siliceous interlayers were clastic beds and/or volcanic beds deposited in a back-arc basin before initial tectonism. Some of these dark, siliceous seams situated around the core structure elsewhere show the telltale, yellow weathering of sulfides accumulated along secondary fractures.

Where entrained in marble, the boulders of black rock are angular with ragged edges from limited, anatectic assimilation. Thin cm-thick iron-rich selvages rim the boulders that appear to have been rapidly plasticized, heated and cooled before deep burial and subsequent granulite-facies metamorphism. Black-rock gneiss beds were disaggregated and incorporated in the flowing carbonate rocks during a compressional tectonic event that broke the gneiss into fragments that became locally entrained in adjacent, plasticized carbonate rocks. The angularity of the fragments and thin reaction rims testify to either a relatively short event, or one of more protracted length but with low volatile content and slow chemical reactions. The Ottawan is known to be a protracted one where these rocks were deeply buried and subject to regional dynamothermal metamorphism before periodic, Paleozoic uplift and renewed exhumation.

The Pleistocene alluvium isn't currently mapped here at the 1:24,000 scale by Stanford and Witte (1995), but Stanford told us (personal communication, 3/30/2025) that it was the sand to pebbly gravel that is one of the deltaic units deposited into glacial Lake Sparta as mapped nearby. These gravels contain heterolith cobbles and pebbles that are cemented together with calcium carbonate, likely sourced from the subjacent, weathered Franklin Marble (fig. 21).

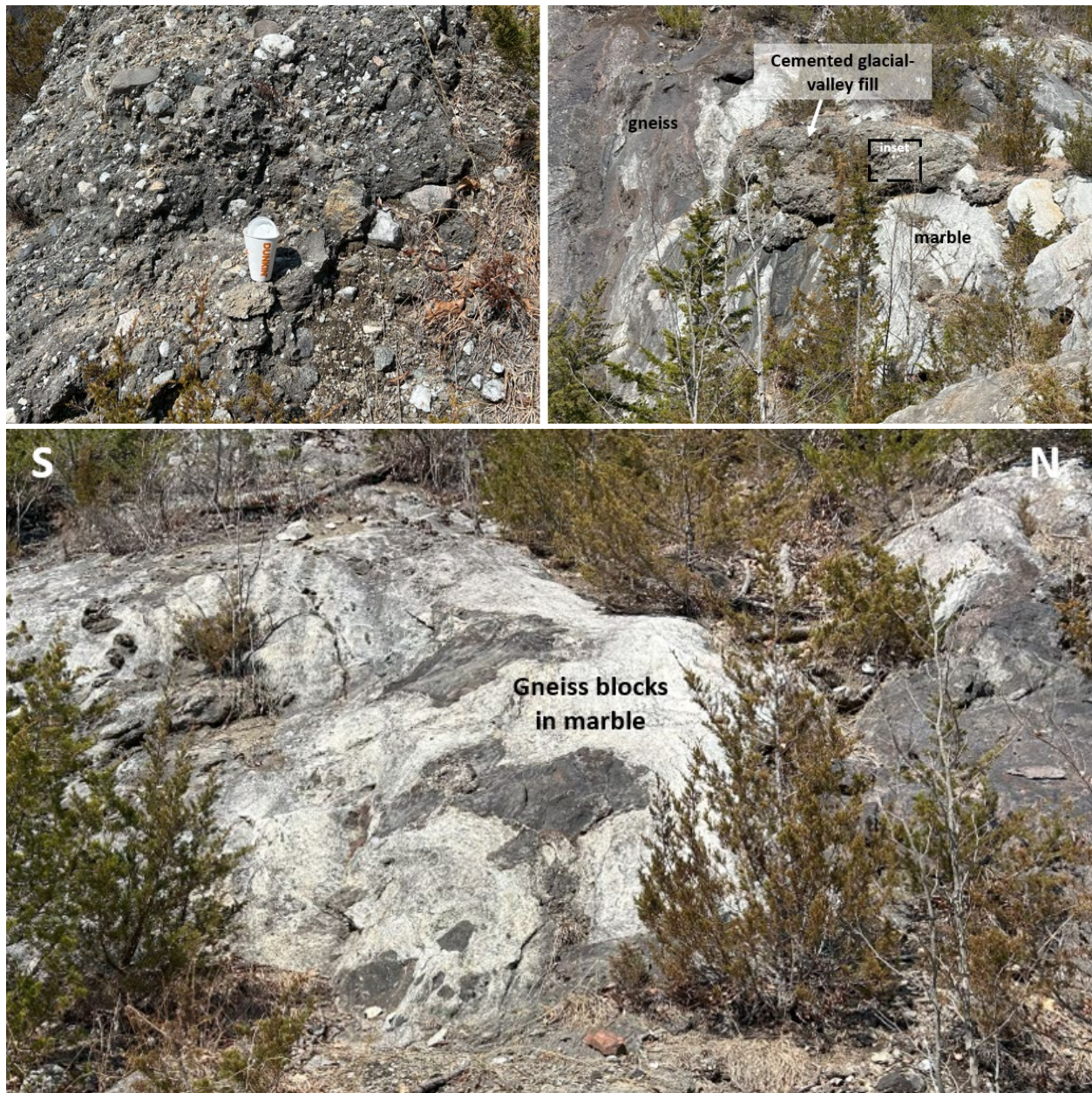


Figure 19. Photographic montage of features to see at STOP 7. The marble here entrains boulder to cobble-sized fragments of dark gray gneiss. We're on the north edge of the core structure where the marble shows evidence of ductility. The carbonate-cemented alluvium (top left) is seen plastered to the outcrop in the upper right photo.



Figure 20. The dark gray gneiss blocks floating in Franklin Marble at STOP 7 show ragged edges with iron-rich rims. The gneiss blocks were broken apart under pressure and were partially melted and assimilated into the carbonate. This demonstrates the highly plastic nature of the carbonate protolith during the mineralization event in the core structure.



Figure 21. Photograph of the Pleistocene gravel sitting atop gneiss and marble bedrock at STOP 7. The subangular clasts are mixed lithologies in a carbonate-cemented, coarse-grained matrix.

PART 2: AN UNDERGROUND GEOLOGICAL TOUR OF STERLING HILL

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Introduction

While the formation of the Sterling Hill and Franklin orebodies within the Franklin Marble is dated between 1294 ± 8 Ga and 1254 ± 5 Ga (Volkert and others, 2010), the mine you are about to step into incorporates a rich geologic history beyond the bounds of those dates. Geologic processes can be felt as water containing dissolved carbonate drips on your head; the carbonate precipitated from this same water forms the speleothems and flowstone that you will see as you walk through the drifts. Careful observation will reveal evidence of the multiple tectonic events that are recorded in these rocks through the structures they leave behind. There are even microbiological processes taking place in the water and on the walls. Most visitors to this mine are enamored by the bright fluorescing minerals of the deposit, but the authors of this tour intend to emphasize the mine's diverse geological and historical aspects as well.

The Sterling Hill property was believed to have first been worked by Dutch settlers in search of copper in the 1600's. It is likely they mistook the red zincite for cuprite, Cu_2O . Starting in the 1700's until the early 1900's, iron mines had been the largest metal producers of the New Jersey Highlands, with the most common ore being magnetite. Magnetite and franklinite are similar mineralogically, both being spinel-group minerals; however, franklinite has Zn^{2+} in the divalent position instead of Fe^{2+} for magnetite. This chemical difference has important implications for processing these minerals, as franklinite requires higher temperatures to be reduced, allowing for the removal of metals. This caused problems for New Jersey's iron furnaces, as any attempt to process franklinite would result in poor metal yields and necessitated pausing furnace operations for cleaning. For this reason, franklinite ores were not much worked until the 1850's (Dunn, 2002).

STOP 1 Parking Lot

The parking lot of the current museum used to be the site of a railroad spur that transported processed ore to a smelter for production of zinc metal. Just south of the parking lot stands the foundation for the mineral processing plant that once operated here. Adjacent to this plant was the East shaft, whose entrance lies behind various historical mining artifacts and pieces of equipment. Along the west side of the parking lot is the largest exposure of the Franklin Marble outside of the Passaic or Noble Pits. It also hosts the mine portal.

STOP 2 Mine Portal

This exposure is attributed to mining operations along the East vein (which is visible at Stop 1 and on the way to Stop 7 of the Field Guide section in this guidebook) and gangue marble for

backfilling stopes (personal communication with Doug Francisco, 2024). Also visible at this stop is a hopper for the fill slurry between the rock discovery area and the base of the exposure north of the mine portal. Two pipes are visible to the left of the mine portal: one for pumping out water and another for compressed air. To the right of the mine portal is a man car similar to the ones that formerly transported the miners from level to level in the mine. The brownish-purple patina visible on the marble is a result of photo-oxidation of the manganese-rich ore body.

STOP 3 Inside Portal Doors

The change in temperature can immediately be felt as the mine's atmosphere sits around 55°F all year. A mannequin of a miner can be seen on the ladder in the safety exit, which serves as an escape route in case of an emergency. If there was an emergency, a packet of 'stench gas' could be dropped into the compressors that blow air into the ventilation pipe, the same one as seen at STOP 2 and is now visible overhead. The sulfur-smelling gas would quickly reach miners and serve as an alarm to initiate an evacuation.

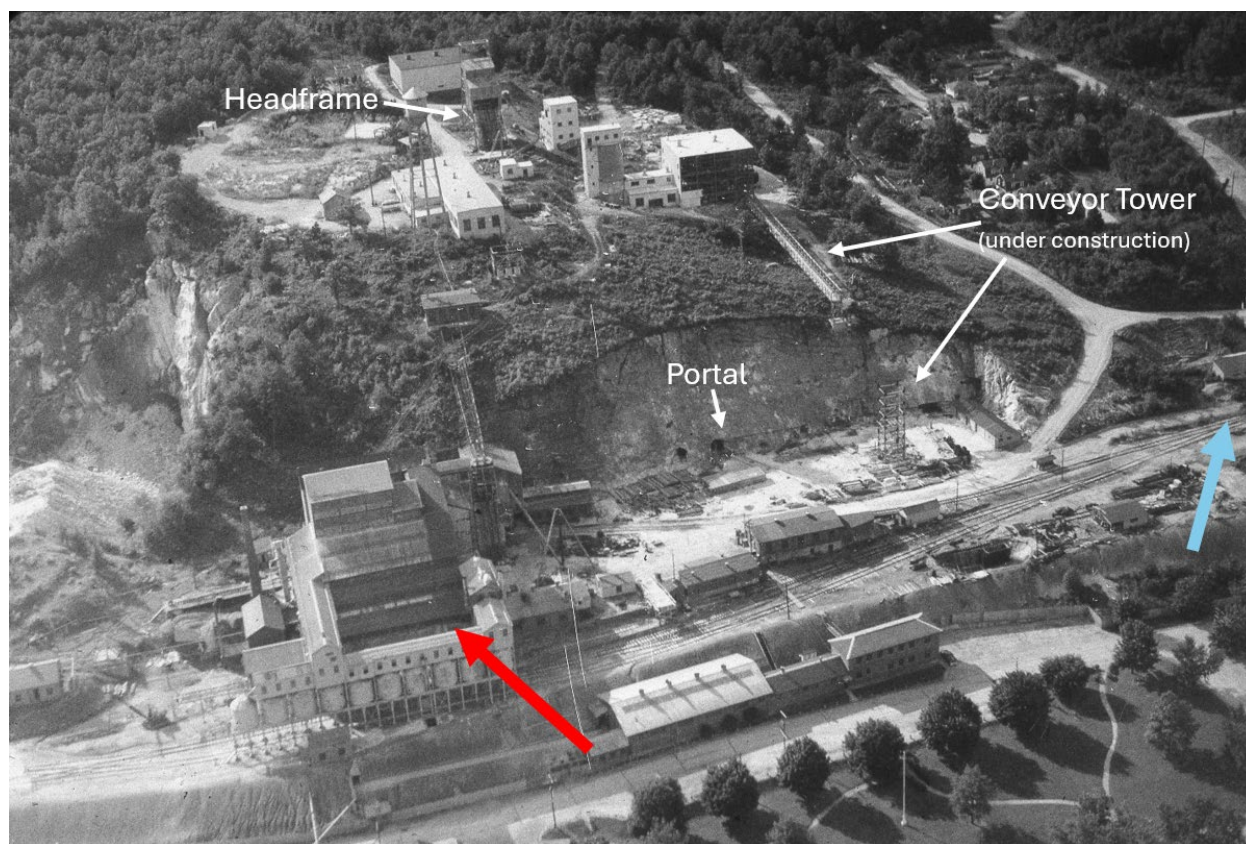


Figure 2. An aerial photograph of Sterling Hill's mining operation in the mid-1900's. The original ore processing plant (red arrow) sits adjacent to the East shaft. The blue arrow points to the entrance of the current museum. The second generation ore processing plant which still stands at the top of the SHMM property) was under construction at the time of this photo.

Foliation can also be observed best on the rib of the adit. The foliation of the deposit dips at approximately 50° which is similar to the dip of the entire deposit, as seen in the models included in chapter 2 of these proceedings (Herman, 2025).

STOP 4 Inside Ventilation Doors

The large wooden doors served to seal the mine off from the outside atmosphere to facilitate efficient ventilation within the mine. These doors were opened and closed automatically via a spring system that lies on the floor next to the tram rails. The ceiling of this area has many small but well-developed stalactites. Reprecipitated calcite (flowstone) can also be seen on the walls of this area. The slightly acidic rainwater descending into the mine dissolves the marble while it flows through the many fractures of this area. A flowstone-laden fault can be seen on the



Figure 3. The green doors cover the mine portal. Water and compressed air pipes can be seen on the left. A yellow man car that used to shuttle miners to their workstation sits at right

northern wall of the adit. Another fault in this area is covered by steel I-beams and reinforced concrete because the rock along and near it is highly fractured and prone to collapse. Features like these can be very dangerous during mining operations and are referred to as 'bad ground' by miners.

STOP 5 Lamp Room

Miners would collect important safety devices in this room. The eastern wall hosts charging stations for battery packs that powered the miners' cap lamps, as seen on the image over the shaft station at STOP 6. Various lighting methods used throughout the history of mining are on display in the front of the room. A mannequin stands behind a workbench with parts of cap lamps and various breathing appliances that call attention to the craftsmanship, ingenuity, and resourcefulness of the miners who walked these very same passages.



Figure 4. Stalactites are visible throughout the mine. Here, along the ceiling, they connect to form ridges, known as 'dragon's teeth.'

Miners would also get self-rescue devices at this location. In case of a fire or other IDLH (immediately dangerous to life and health) atmosphere, miners would use the rescuer by inhaling through the mouthpiece. This device would convert carbon monoxide (a product of combustion, and lethal even at low concentrations) to carbon dioxide to give the miner time to evacuate the mine or escape a dangerous environment.

A large board in this room holds the numbered brass tags that each miner would use for personnel accountability. A miner would take their brass tag before going to their workstation. At the end of the shift, they would return the tag to the board. Subsequently, the shift supervisor would be able to tell if anyone had not returned from their workstation at the end of the shift. This would serve to notify the supervisor if someone was missing or injured, and they would initiate an attempt to locate that individual.

STOP 6 Shaft Station

Plunging east at 52° is the 1920 ft deep (measured vertically) West shaft, which is separated into five compartments. The leftmost compartment contains a ladderway similar to that at STOP 3, which allowed miners to climb down and up without using the 'cage' or 'man car'. Of the four large compartments, the two on the left were occupied by 'cages' to bring miners to the nearest location they could access their work area. Ore crushed deeper in the mine was carried up in bins to the headframe. After arriving at the headframe, the ore would be dumped into a hopper, called a "day bin," from which it would be conveyed to a crusher to begin processing the ore for shipment.

STOP 7 Ore Pass, Grizzly, and Drills

This is an ore pass, which conveys broken ore to a rock crusher 1100 feet below. The purpose of the rectangular grid of steel beams was to ensure that rocks dumped into this pass were not so large that they would jam the crusher. Once the ore was crushed to manageable size, it was conveyed underground to a loading pocket, where it was dumped into skips (large containers on inclined rails) and then hoisted to the surface.

Beyond the ore pass is an array of different drills that were operated at this mine throughout history. The first two drills (one on a tripod and one on an extendable strut/column) were sometimes referred to as widow-makers. These drills did not use water-lubricated bits and generated much rock dust as they were used. Miners breathing that dust often developed lung conditions that shortened their lives.

The western wall of this drift exposes multiple faults. Streaks of graphite are visible with a hand lens on some of them and in places indicate approximately a centimeter of movement.



Figure 5. Behind the galvanized I-beam the flowstone varies in color. The green color is due to algae, which can grow here because the tour lights provide enough energy for photosynthesis to occur. Note the white vertical stripe in the photo; no algae grow in this area because it lies in the shadow of the I-beam.

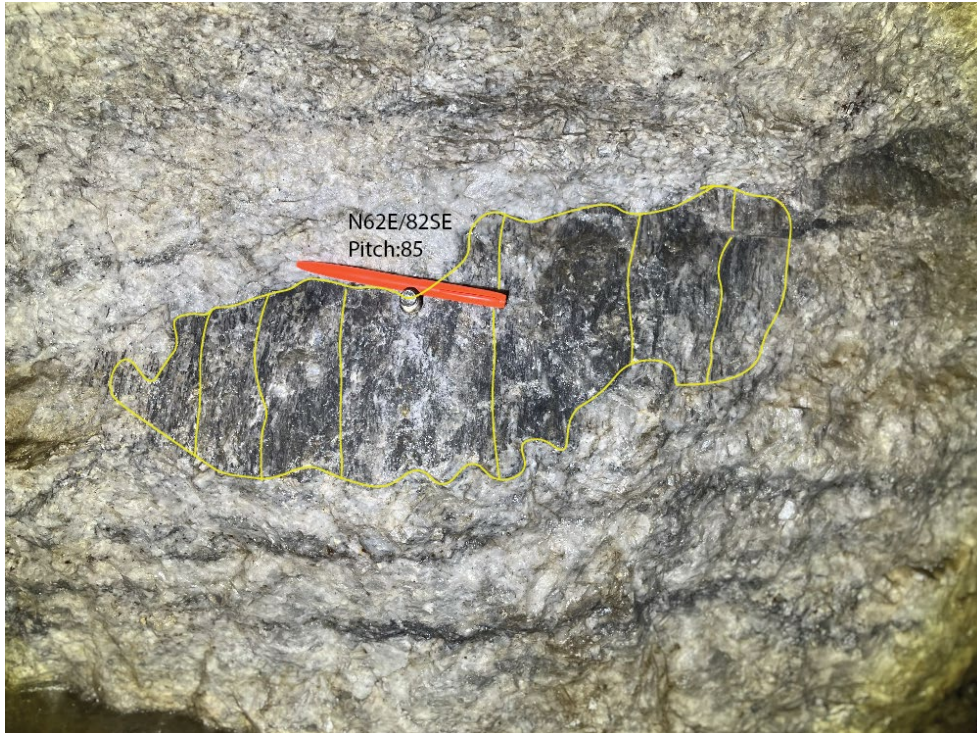


Figure 6. Yellow lines trace the plane and outline of a fault surface exposed on the drift wall. This is an inset of figure 6 (denoted in that figure by dashed lines).

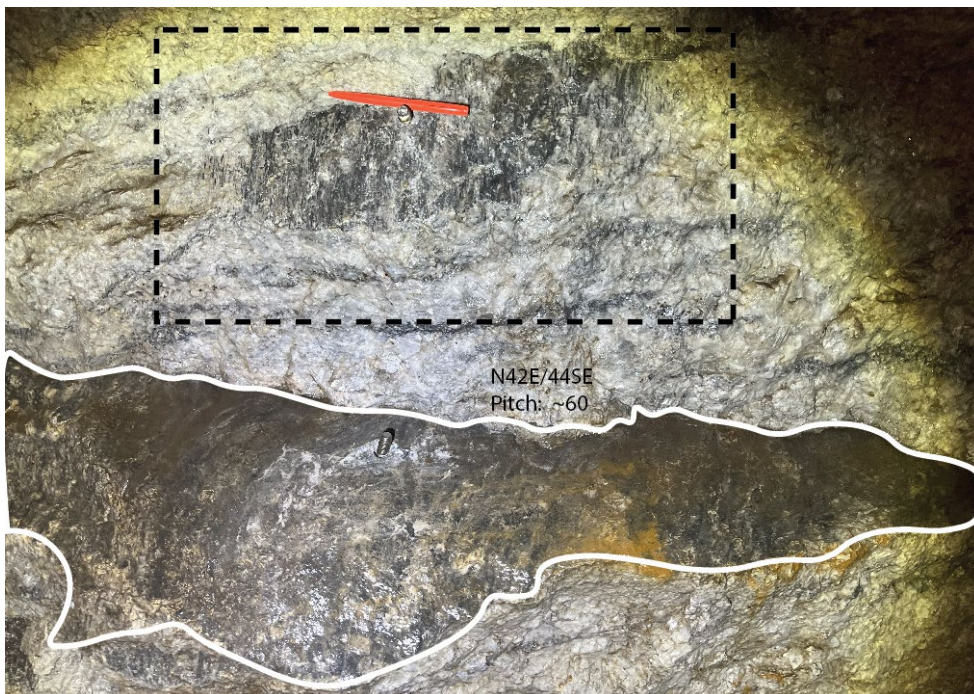


Figure 7. The upper fault is the same graphite-streaked fault shown in Figure 5 and the lower one, outlined in white, is another fault that experienced a greater amount of slip. The individual graphite streaks overlap to form a graphite-smeared surface.

STOP 8 Powder Magazine and Diamond Drill

The machine on the right is a diamond drill which was used to sample rock beyond the walls of the stopes and drifts to help mine geologists guide the mining operations and planning. The symbol DDH (Diamond Drill Hole) occurs on many mine maps, and machines like this were the workhorses for those operations. A digitized cross section of the mine with, possibly, the deepest drill in the state of New Jersey is shown in figure 12 of chapter 2 of this guidebook. In addition to the core-drill bit is a wider, 2.5-inch-diameter tungsten carbide bit for drilling larger holes with a separate machine. Rock core from such operations would then be put into core boxes like those seen below, logged for mineralogy and sampled for chemical assay or thin section analysis. Numerous thin sections and rock chips from these operations are housed at the New Jersey State Museum, following a donation by Robert Metsger, former mine geologist at Sterling Hill, who is recognized in the dedication of Chapter 1 (Puffer, 2025). Researchers interested in

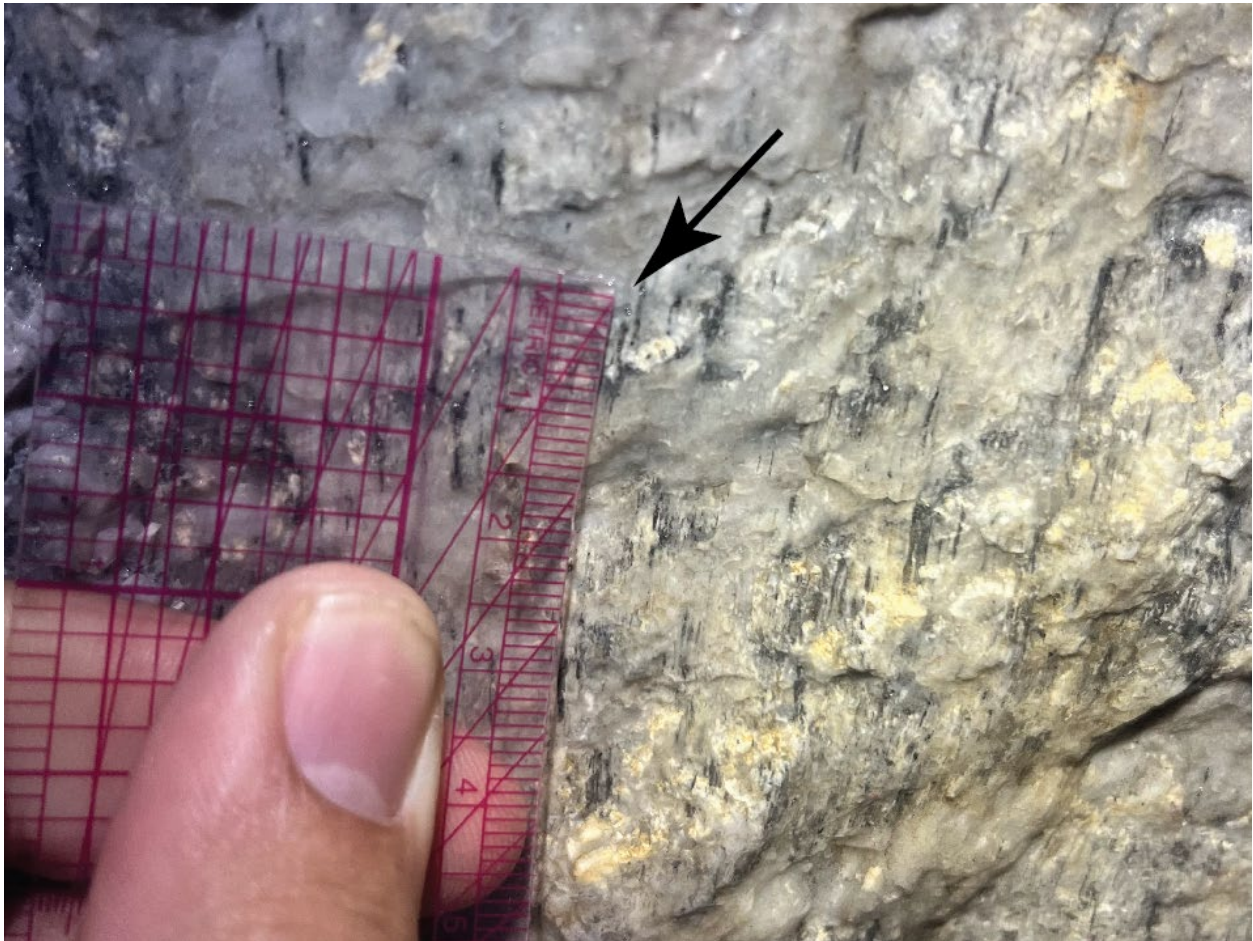


Figure 8. A close-up view of a graphite-streaked fault surface where one can trace back the streak to its parent graphite grain, revealing the slip direction of the fault (see Chapter 3 (Verbeek and Grout, 2025) of this guidebook)

utilizing these samples for research are directed to the abstract earlier in this edition by R. Pellegrini.

The small room across from the coring drill and its mannequin operator is the powder magazine. This room was used to store the blasting caps for the blasting operations. Another room like this is situated on a lower level and housed the explosives for blasting. Keeping these rooms separate from where most people were working was critical to minimize the impacts of an explosion if these were to ignite. As you move out of this area to continue the tour, the yellow sign hanging on the east wall indicates this is where the mine ended when the mine was in operation. The passages for the remainder of the tour were developed later, when converting the mine to the museum we see today.

STOP 9 Mylonite, Timber Sets, Rock Bolts, and Faults

Beyond the timbers in this area are various faults that belong to different fault sets described in chapter 3 by E. Verbeek and M. Grout. The most prominent of these is the mylonite zone visible on the east wall adjacent to the timber sets. The upper plane of the mylonite at chest height is oriented at N45E and dips 62° SE while the lower plane is oriented at N49E and dips 60° SE. The nonuniform thickness of this mylonite is visible as you trace it to the roof of the drift. This mylonite belongs to the earliest set of faults described in chapter 3.

Beyond the timbers, flowstone is being deposited by water flowing from a different, lower angle, fault. A nice specimen of marble exhibiting slickensides from movement of a fault is sitting on the sill. The original orientation and location of this rock are unknown.

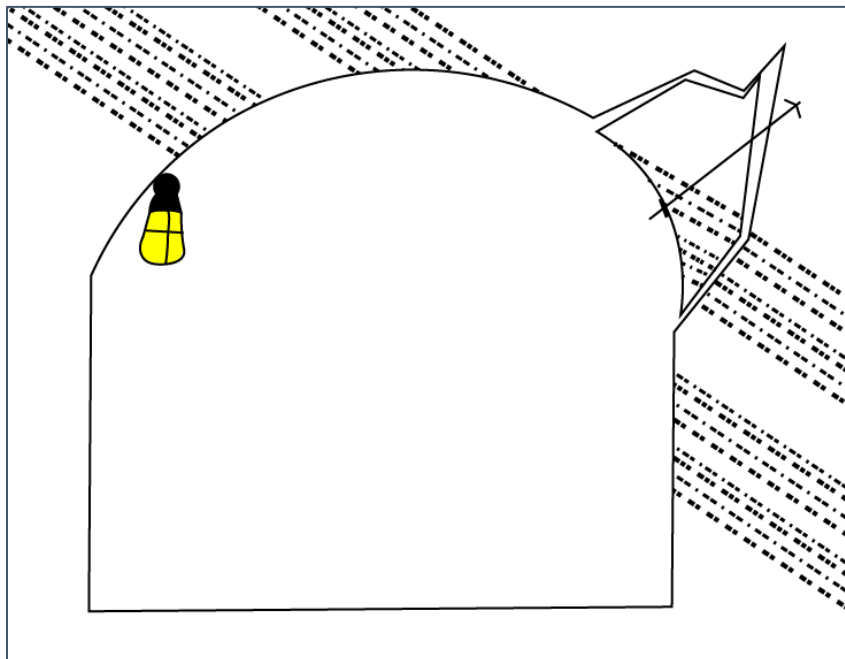


Figure 9 A simplified cross section of a drift where a rock bolt holds fractured rock from falling into the open space created after blasting.

To a geologist, faults are among the most fascinating aspects of field relationships, but for miners these fault zones can be very dangerous. These create 'bad ground,' or areas where the rock is loose, prone to collapse, and can easily injure or kill a worker. To mitigate this issue, rock bolts are used to hold back loose rock while miners work underneath. Many modern hard-rock mines also use wire mesh similar to chain link fences held in place with similar bolts seen here. Figure 8 shows the fundamentals of how rock bolts secure large, potentially deadly rocks to the roof of a working space underground.



Figure 10. Mylonitized marble in front of the timber sets, which belongs to the set 1 group of faults described in chapter 3 of this volume.

STOP 10 Rainbow Room

Perhaps the most striking aspect of these ores is the fluorescence of willemite (green) and various other minerals in the deposit. The red-fluorescing feature visible under shortwave UV is an inclined band of marble. The red fluorescence of the marble is attributed to the Mn^{2+} substitution for Ca^{2+} in the calcite.

The rocks seen here were hoisted from lower levels of the mine, after the property was purchased by the Hauck brothers in 1989. The large rock numbered 1 in the center of figure 10 contains yellow-fluorescent wollastonite from the 1270 sub drift at the 340 level. An up-close image of this rock can be seen in figure 7 of chapter 1 as evidence for partial melting of the Franklin Marble. The rock numbered 2 in figure 10 is an excellent example of a fold in willemite and zincite, likely from the 820 ore pillar at the 900 level. The rock numbered 3 is from the ore pillar in the fill quarry. Rock 4 is adorned with a 'chandelier' or a rock bolt that was deformed by blasting. Figure 11 is an example of 'Dead Zone' willemite where bands of willemite are flanked by nonfluorescent sections; this specimen was found about 100 feet north of the safety exit on the 430 level. This zone is associated with Set 4 faults (see chapter 3). Secondary willemite veins are visible in the photo of figure 12, taken on the southern wall (behind the rocks pictured in figs. 11 and 13) of the Rainbow Room, composed of high-grade ore dominated by green-fluorescing willemite. Mylonitized ore from 20 feet below the 700 level is visible in figure 13.

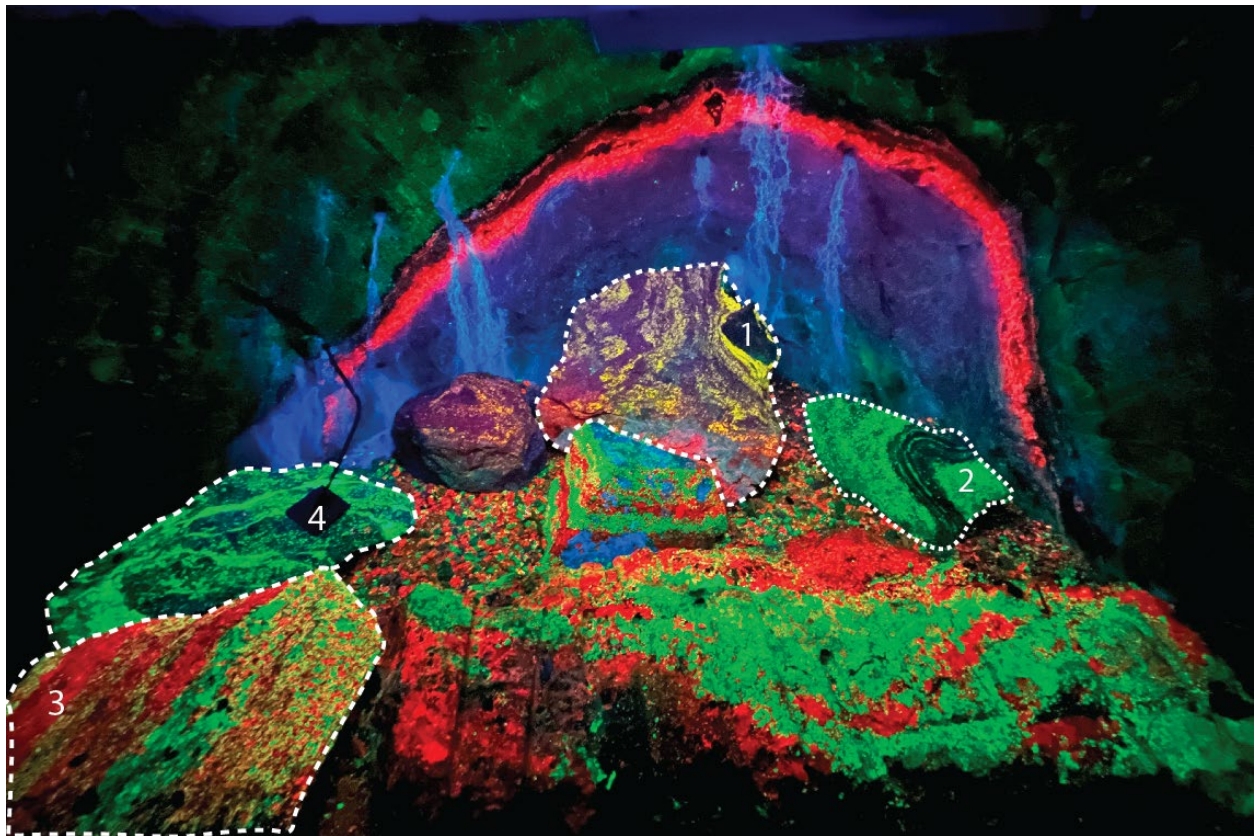


Figure 11. The west end of the Rainbow Room exhibits magnificent textures and fluorescence from various parts of the mine (see text for information). This area exposes a portion of the west limb of the ore body.

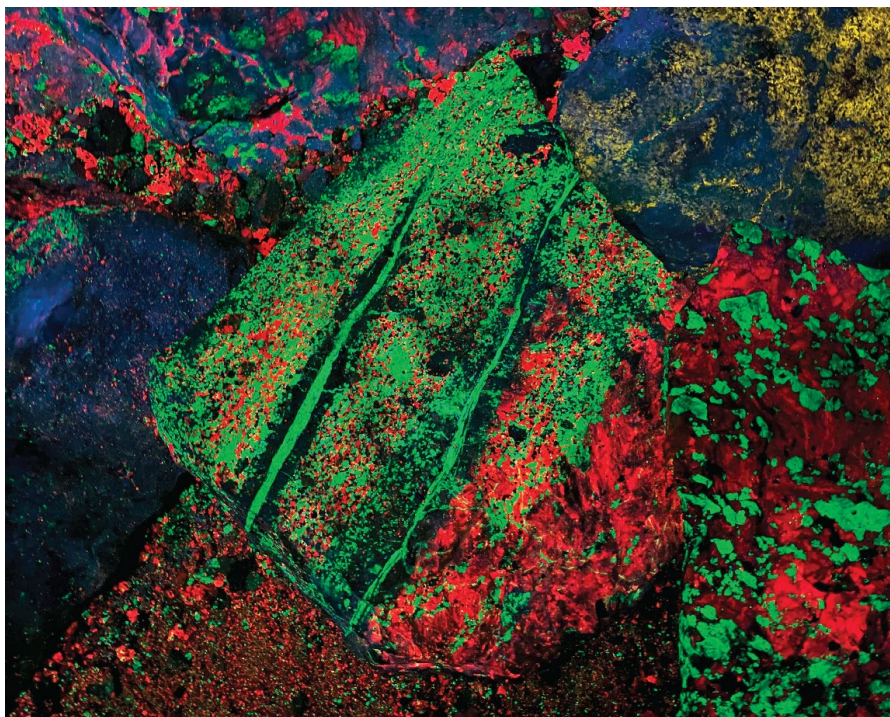


Figure 12. Willemite veins formed by infilling set 4 faults; see chapter 3 of this guidebook (Verbeek and Grout, 2025). Hydrothermal fluids circulating through the faults altered the adjacent wall rock to leave zones lacking fluorescence. Such specimens are known as ‘dead-zone willemite’ and were taken from 100 feet north of the safety exit on the 430 level.

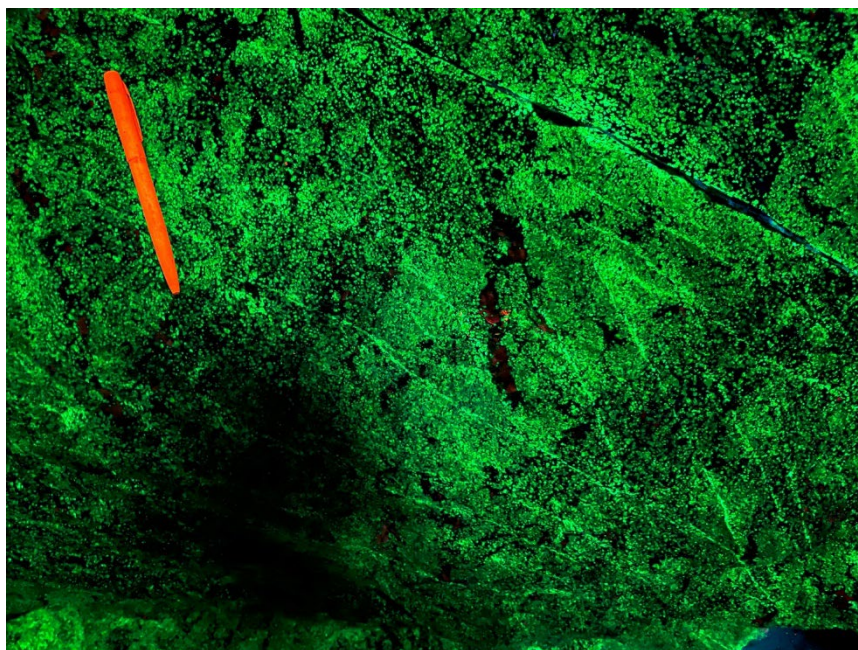


Figure 13. Willemite-rich ore on the south side of the Rainbow Room with secondary willemite filling fractures that intersect each other at $\sim 45^\circ$.

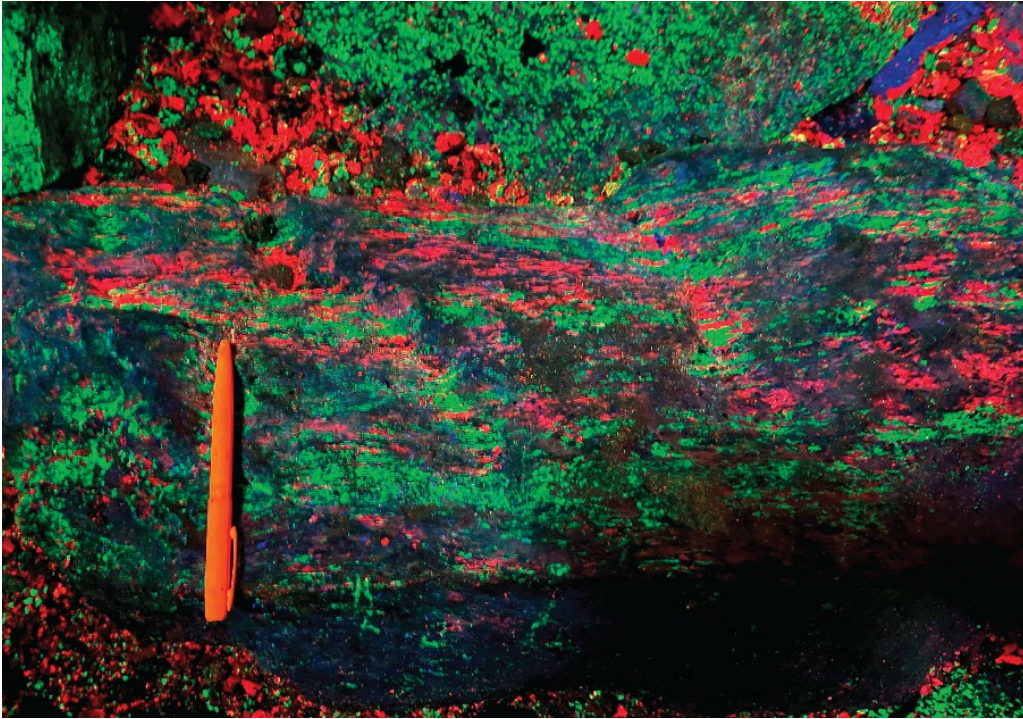


Figure 14. Mylonitized willemite-calcite ore from the Nason fault, 20 ft below the 700 level

As you leave the Rainbow Room and cross the hall to the blasting station there is a clear example of crosscutting faults. A N49E fault dipping 51° SE crosscuts an older N51W fault dipping at 49° SW. The older, brittle fault outlined in red in figure 15 likely belongs to the Set 4 faults (see chapter 3; Verbeek and Grout, 2025). It is crosscut by a brittle fault with a normal sense of displacement likely belonging to Set 5 of the aforementioned chapter. The foliation on the opposite wall for the next 30 feet is of uniform orientation, but notice how that changes as you walk farther along this drift.

STOP 11 Blasting Station

Creating the drifts we walk through during our tour necessitates precision drilling and blasting. Figures 16 and 17, drafted by Bill Kroth, President of the Sterling Hill Mining Museum, show the details of blasting a drift in cross section and longitudinal section, respectively.

STOP 12 Loading Bin

Before reaching the crushers below the surface, the ore gets placed in a loading bin. This allows the miners to control exactly how much ore goes into the ore cars positioned below that are used to convey the ore to the crushers.

Behind this display sits a seismometer maintained by researchers at the Lamont-Doherty Earth Observatory.

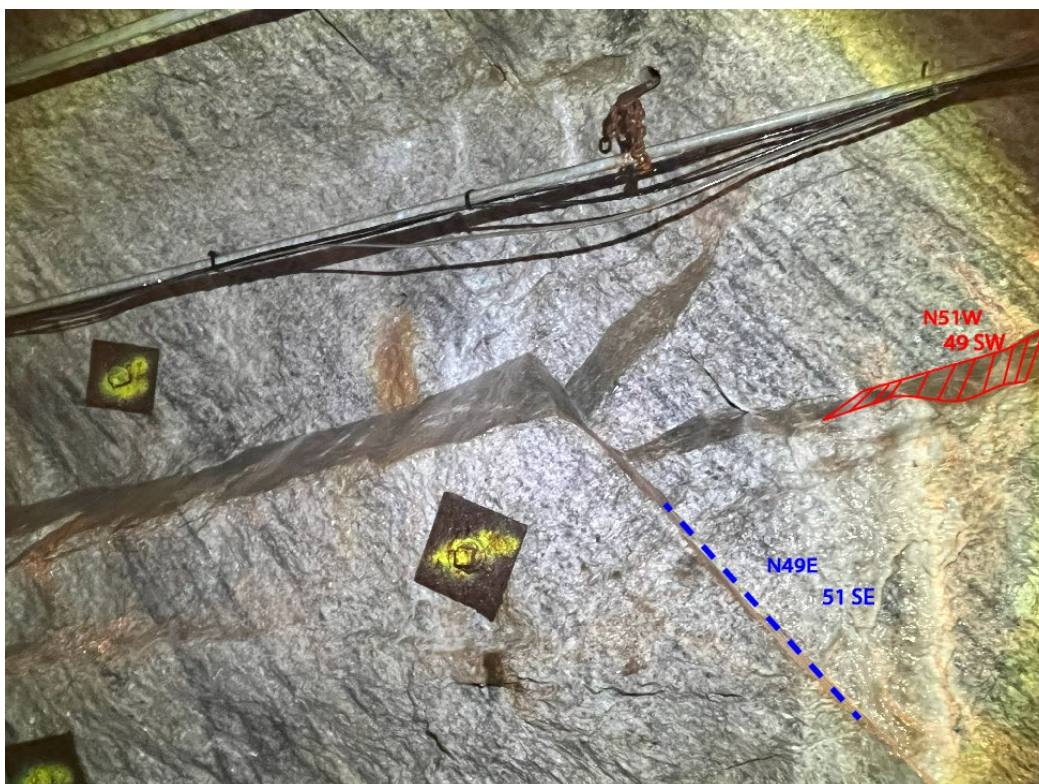


Figure 15. A set 5 fault in marble crosscuts a set 4 fault on the north side of the crosscut between the Rainbow Room and blasting station. See chapter 3 of this guidebook for more information.

STOP 13 Stope

This stop shows what a working stope might look like. You'll notice the ceiling has rock bolts about every 4 feet to protect the miners. There is a machine—a double-boom jumbo—that has two hammer drills with the ability to extend those drills far out and above miners to keep them safe from dangerous, hard-to-reach areas. You will also notice a scraper bucket attached to a cable that runs from a winch through a snatch block to scrape the ground. This makes it easy for miners to drag the blasted rock into the small 'ore chute' in front of the winch. The ore would then fall down the chute and eventually land in a loading bin, from which it would be loaded into ore cars for transport.

As you head past the sign that reads "Landmesser Tunnel," you'll notice that a miner is working above you. This miner is creating a 'manway' or a small raise to connect to the level of the mine above you. There are two different kinds of raises. One is a rock raise, the beginnings of which you see here as the inclined opening into the rock above your head. The other is a fill raise, the beginnings of which you see in the corrugated pipe at ground level. If it is desired to keep the passage from one level of the mine to another open through an intervening stope which is going to be backfilled, a corrugated pipe with an internal ladderway is installed so the fill can be added around it. This is critical as the fill component of cut and fill procedure used at this mine would

block the area you walked in after a filling operation (using gangue minerals from the processing plant to make a cement that will raise the floor allowing miners to work the roof of the stope).

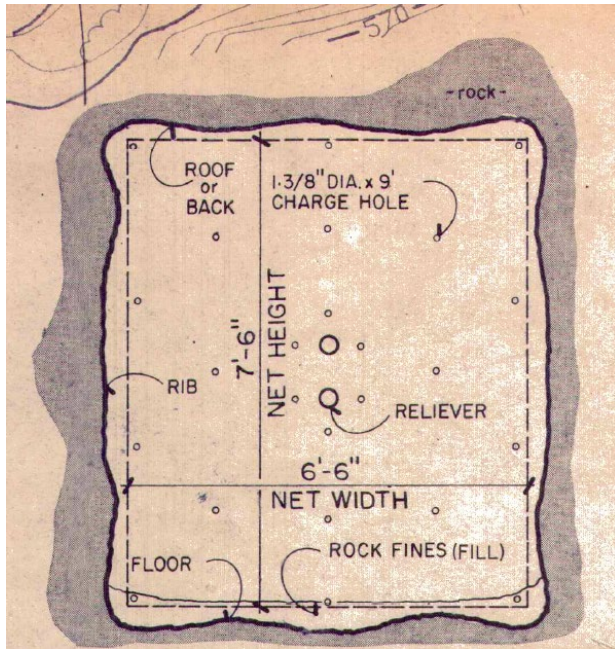


Figure 16. A diagram from Kroth (1993) demonstrating the dimensions of the face and locations of blasting charges and relief holes of a blast for extending the drift.

STOP 14 Landmesser Tunnel Structures

The Landmesser Tunnel offers a variety of unique textures that are discussed by John Puffer in Chapter 1 of this volume. There are also textures showing evidence of ductile displacement that intersect the decline you are walking through.

STOP 15 Old Stope and Water Table

This stope was not documented in the mine maps of the New Jersey Zinc Company. However, this area exhibits a shaft with heavy grade chains hanging in a vertical shaft to assist in breaking the ore that was thrown down it. A small pond is on the other end of the stope. The level of water reflects the amount of rain in previous months. This stope can flood every so often when rainfall is persistent.

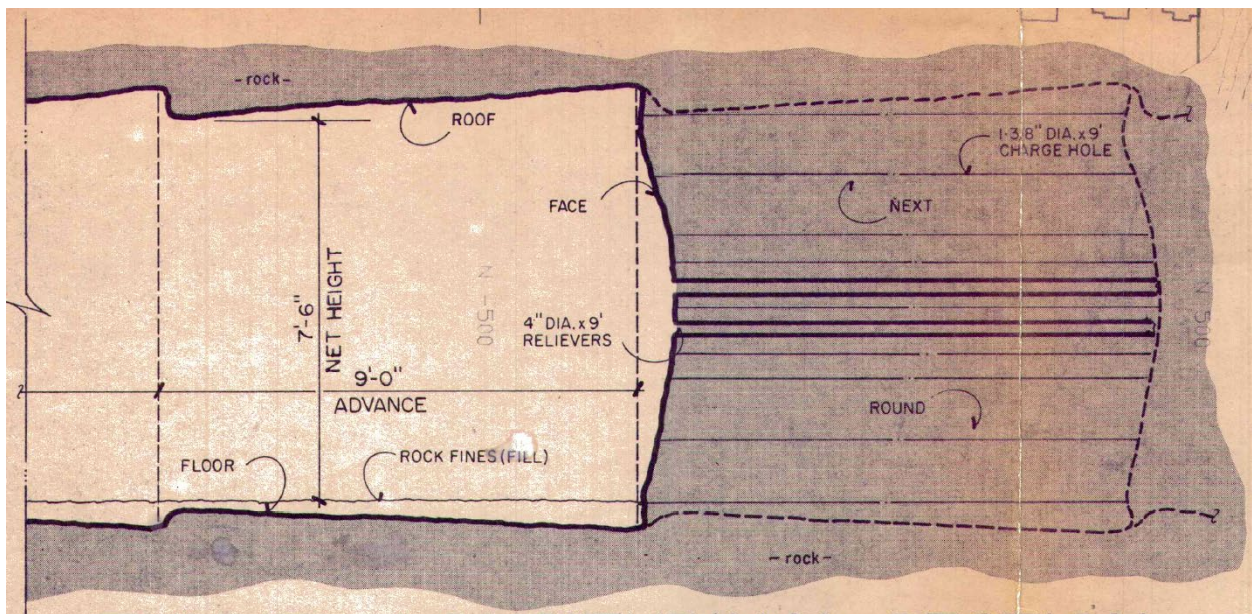


Figure 17. A longitudinal section showing the traces of holes drilled into the working face (Kroth, 1993).

STOP 16 Edison Tunnel Siliceous Horizon and Mineralogy

The Edison Tunnel crosses over the Landmesser Tunnel (See Chapter 2, fig. 23; Herman, 2025) thus many of the characteristics, mineralogy, and textures are visible once again. On the northern wall (the left side as you are walking out) there are multiple occurrences of sphalerite at different points along the drift. Sphalerite, being a zinc sulfide, is the most common zinc ore found in operating mines throughout the world. However, it was not an ore mineral here. The sphalerite fluoresces a range of colors in this area, in some cases it is blue and orange in others. It can also



Figure 18. Marble exhibiting fluidized flow patterns hosting blocks of gneiss are visible in certain sections of the Landmesser tunnel.

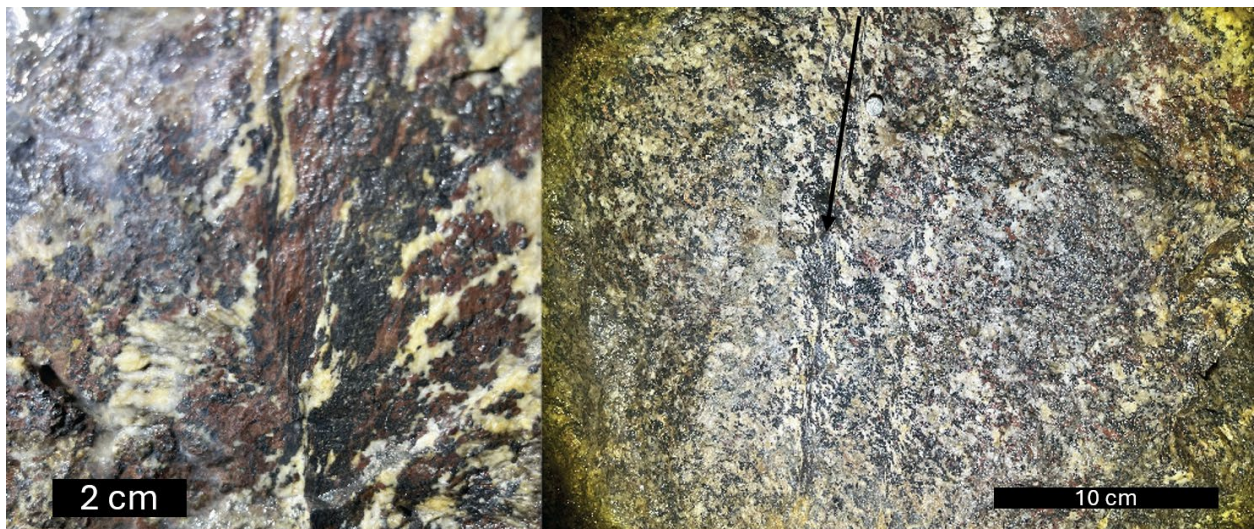


Figure 19. The left image shows the ductile movement on a fault. The image on the right shows another ductile fault extending from the tip of the downward facing arrow where mylonitized marble and ore occur with franklinite (black) and willemite (red).

be a mix of the two creating a pinkish color under longwave UV. Sphalerite often forms disseminated foliations that intersect the tunnel, except in a few instances where it forms larger masses on the edge of or within block of gneiss.

Approximately seven feet from the exit, a mass of apatite can be observed at chest height on the southern wall. Large anhedral franklinite crystals can also be observed in this area. Willemite also occurs here in large quantities.

STOP 17 Exit to Parking Lot

As you exit the mine, a nice reminder of where you were underground comes in the form of the doghouse-style structure that covers the skylight in the old stope. Surrounding that area are different tools used in mining, various ore specimens and local rocks, and a twisted beam of steel from the World Trade Center attacks on September 11th, 2001.

REFERENCES

- Adsit, A.J., 2022, Interdiffusion of Zn-Fe-Mn in Clinopyroxene and Gahnite During Grenville Granulite Facies Metamorphism at Sterling Hill Mine, Ogdensburg, NJ: Senior Comprehensive Project; Allegheny College, Department of Geology, 42 p.
- Dunn, P. J., 2002, Mine Hill in Franklin and Sterling Hill in Ogdensburg, Sussex County, New Jersey: Mining History, vol. 1, p. 1765-1900.
- Herman, G.C., 2025, Chapter 2. The Structural, Tectonic, and Geospatial Aspects of the Sterling and Franklin Zinc Mines, Sussex County, New Jersey., *in* Di Maio, M.P., Herman, G.C., and Verbeek, E.R., editors, Revisiting the Sterling Hill Orebody: Challenges in Understanding this Magnificent Deposit: 41st Annual proceedings and field guide of the Geological Association of New Jersey, The Sterling Hill Mining Museum, Ogdensburg, NJ, p. 59-115.
- Kroth, W., 1993, Composite site plan; Surface and sub-surface features: Sterling Hill Mining Museum, Inc., Ogdensburg, New Jersey. Scale 1":100'. Inset diagrams of the mud zone at 1":150'.
- Palache, C., 1937; 1935, The minerals of Franklin and Sterling Hill, Sussex County, New Jersey: U.S. Geological Survey Professional Paper 180, 135 p.
- Puffer, J., 2025, Chapter 1. The Sterling and Franklin Zinc Mines: The Case for Partial Melting, and the Legacy of Robert Metsger, *in* Di Maio, M.P., Herman, G.C., and Verbeek, E.R., editors, Revisiting the Sterling Hill Orebody: Challenges in Understanding this Magnificent Deposit: 41st Annual proceedings and field guide of the Geological Association of New Jersey, The Sterling Hill Mining Museum, Ogdensburg, NJ, p. 23-57.

- Verbeek, E.R., 2015, Fluid flow in metamorphic rocks, part 3: The Picking Table, vol. 56, no. 2, p. 9-19.
- Verbeek, E.R. and Grout, M.A., 2025, Chapter 3. Fault History of the Sterling Zinc Mine, Ogdensburg, Sussex County, New Jersey, with Appendices, *in* Di Maio, M.P., Herman, G.C., and Verbeek, E.R., editors, Revisiting the Sterling Hill Orebody: Challenges in Understanding this Magnificent Deposit: 41st Annual proceedings and field guide of the Geological Association of New Jersey, The Sterling Hill Mining Museum, Ogdensburg, NJ, p. 117-140.
- Volkert, R.A., Aleinikoff, J.N. and Fanning, C.M., 2010, Tectonic, magmatic, and metamorphic history of the New Jersey Highlands: New insights from SHRIMP U-Pb geochronology, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., from Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Memoir 206, p. 307-34.

ZOBEL EXHIBIT HALL

Earl R. Verbeek, Franklin Mineral Museum, Franklin, New Jersey (U.S. Geological Survey, Denver, retired)

Introduction

You are visiting a zinc mine today. This mine was operated by the New Jersey Zinc Company and was in nearly continuous production for 136 years. It closed in 1986 due to depressed zinc prices and a dispute with the Borough of Ogdensburg over property tax values.

This is one of the most famous zinc mines in the world. More than 11 million tons of zinc ore, averaging more than 20% zinc content, was taken from here. The ore from most other zinc mines, in contrast, averages only 4-6% zinc. The Sterling Hill zinc deposit was both large and fabulously rich.

This mine, and its sister mine two miles to the north in Franklin, are famous for two other reasons as well – the number of mineral species found here, and the number of those that fluoresce. At last count, more than 400 different minerals have been recovered from these deposits, and nearly two dozen of these are found nowhere else on Earth. Only two other localities in the world (Mont Saint-Hilaire, Québec, and the Clara mine in Germany) surpass the Franklin-Sterling Hill area for number of mineral species found in one small area. Of our 400+ mineral species, about 100 are fluorescent, a world record.

About one million tons of ore remain in the mine, enough for ten more years of production. However, the ore will never be extracted – it would cost too much to rehabilitate the mine and build another mill and smelter to process the ore. Instead, it will remain what it is now, an educational museum open to the public.

The Building

This building, the old change house, was built in 1937-1938 and is where miners at Sterling Hill would begin and end their day. Originally it contained many dozens of lockers, but most were removed to make room for the exhibits. Look above you: each locker had a steel chain that extended to the roof, over a pulley, and then down to a basket with a hanger beneath. At the end of the day a miner would take off his wet and dirty clothes, hang the clothes from the hanger, place his boots in the basket, and pull the basket up to the ceiling so the clothes would dry overnight. Why hoist the clothes up to the ceiling? Because that's where the warm air was – warm air is lighter than cold air.

After removing his dirty clothes, a miner would go to the east side of this room to the gang shower. There are 20 shower heads along the length of this building (they're still there), so 40 miners could shower down at once. Later, upon drying off, the miner would put on a set of clean

clothes from his locker and go home. Most miners took their work clothes home for washing on Fridays. Some washed them only once every two weeks, and some never.

Exhibits

There is much to see in Zobel Hall, and many visitors could happily spend hours viewing the exhibits. Here are a few of the highlights:

Oreck Mineral Gallery: Hundreds of world-class mineral specimens are displayed in 15 large display cases in the shower run along the east side of this building. Most of the specimens were donated by the Oreck family, the same people who make the vacuum cleaners you see advertised on TV. For sheer beauty this is one of the most popular exhibits in Zobel Hall.

Fluorescent mineral exhibit: In one corner, behind a black curtain, is a fine display of the local fluorescent minerals, all of which came from either the Sterling mine or the Franklin mine two miles to the north. These two mines are unsurpassed in the world for the brilliance and variety of their fluorescent minerals. Currently, more than 100 different mineral species from this area are known to fluoresce.

Periodic Table exhibit: The large, three-dimensional periodic table of the elements at the end of the room is one of only a few such exhibits in the world. Samples of nearly all the naturally occurring elements are on view, as are the ores that are mined to obtain them, plus manufactured items made from those elements. (While there, ponder the relation between titanium and Oreos cookies.) A push button enables visitors to view the glow of the noble gases (Remember neon signs?) when an electric current is passed through them.

Mine lighting exhibits: A portable means of producing light is an obvious necessity for miners working underground. Multiple display cases in Zobel Hall explore the evolution of mine lighting over thousands of years:

- Oil lamps were among the earliest lighting devices and were first used more than 12,000 years ago. Various fuels were used, depending mostly on availability; these included olive oil, whale oil, fish oil, beeswax, nut oil, animal fats, seed oils, naphtha, and even clarified butter. Around the mid-1800s, kerosene supplanted whale oil and naphtha as the most prevalent fuel used in mine lamps.

- Candles have been in use as a lighting source for more than 5,000 years. In addition to the paraffin and beeswax candles familiar to us today, a variety of other waxy substances were used at various times and places: tallow (rendered animal fat); waxes from various plants, nuts, fruits, and insects; spermaceti (solidified whale oil), and stearin.

- Carbide lamps burn acetylene gas through a reaction between calcium carbide and water. Carbide as a fuel was discovered in 1892, and a lamp designed for mining soon followed,

in 1897. Carbide lamps burn with a bright, pure white flame and quickly became the lamp of choice among miners. Their prime disadvantage was that the light source was an open flame.

- Rechargeable electric cap lamps were developed about the same time as carbide lamps but were slow to catch on because of the heavy weight and poor light output of early models. By the 1930s, however, they were in general use. Until recently, the electric cap lamps used in mines employed lead-acid batteries (smaller versions of automobile batteries) as the power source, but these are now rapidly being supplanted by more efficient LED mine lights that require only small, lightweight batteries to work.

Mining and processing equipment: Look around Zobel Hall for rock drills, ore cars, an arrastra, generators, dynamite boxes, detonators, sinking buckets, a jaw crusher, a slusher motor, various hand tools, magnetic separation equipment, assay balances, a mine hoist, and even a mine toilet on rails.

Works of art: The arts have not been forgotten in Zobel Hall. Various bronze and brass statues depicting miners and mine scenes are scattered about, and full-size statues are in several places outdoors. Sand jars fashioned by local miners are also on view, as are paintings on the walls overhead. Look also for a “spar box,” which in bygone days was fashionable in England.

Uses of Zinc

The Sterling mine contained high-grade zinc ore and ultimately produced more than 2.2 million tons (not pounds!) of zinc metal over more than a century of mining. The mine would not have had such a long and successful history if zinc were not in constant demand. But what is zinc used for? Here is a brief list:

Die castings- Several parts of most cars, including carburetors, door handles, and fuel pumps, are die-cast parts made of zinc. Zinc is ideal for this purpose because it doesn’t shrink upon solidification from the liquid state, so a true-dimension casting can be made.

Tires- About 20% zinc oxide is added to automobile tires to strengthen the rubber and help in heat dissipation.

Pharmaceutical products- Zinc is used in diaper-rash medicine, zit medicine, anti-itch creams and lotions (e.g., calamine lotion), and dandruff shampoo.

Vitamin pills- Zinc is a necessary trace element in the human body. Your immune system requires it for proper operation, and without it you would quickly die of disease. Most vitamin pills contain zinc as a mineral supplement. Zinc is also found in many foods, particularly red meats and dairy products. Though you can live a long and healthy life without gold, you cannot live without zinc.

Galvanized metal- Iron or steel is commonly coated (galvanized) with zinc to prevent it from rusting. Trash cans, nails intended for outdoor use, guard rails along highways, chain-link fences, metal roofs, and gutters and downspouts are commonly made of galvanized steel.

Paint - Zinc oxide, a pure white powder, is the opacifier in much paint. Without it the coverage would be poor because older coats of paint would show through the new one. The zinc oxide renders the paint almost completely opaque, even in thin films.

Sunblock- Zinc oxide is opaque not only to visible light but to ultraviolet light as well, and so makes an excellent sunblock. If you see someone on the beach with a white nose, that's zinc oxide.

Pennies- Since 1982 pennies have been made not of copper as before, but of 98% zinc with a thin coating of copper. The reason is economic: zinc is by far the cheaper metal. The thin coating of copper is necessary so we don't confuse pennies with dimes, which are about the same size. Zinc was also used in pennies during the Second World War when copper was needed for the war effort. Those pennies were made of steel, with a zinc coating as a rust preventative.

Brass- Brass, an alloy of copper and zinc, is stronger than both metals alone. Brass is commonly used where strength is a factor, as in the casings for bullets, brass handrails in theaters and restaurants, brass valves in bathroom faucets, gears in clocks and watches, etc. The attractive gold color of brass also lends it to many decorative uses in the home, such as lamps, door handles and locks, curtain rods, and lighting fixtures. Any of you who play trumpet, trombone, or any other brass instrument in your school band or orchestra are using zinc as well.

Batteries- Nearly all dry cells, such as the batteries used in flashlights, used to have zinc casings, and the zinc was necessary to the energy production. Nowadays we have more powerful batteries, but inexpensive zinc batteries are still on the market.

The Necessity of Mining

Many people do not like mines and rank them somewhere between toxic waste sites and junkyards for things they'd rather not see in their own neighborhoods. In fact, however, we cannot get along without mining. To illustrate this, visitors to this museum are often presented with a challenge: Name any manmade product from their daily lives that did not involve mining in its production or transport. There is no such product. Some common answers and rebuttals are listed here.

Pencils- The "lead" in pencils is a mixture of graphite and clay, both products of mining.

Clothing- If made from synthetic fiber, these materials are made from coal or oil. If made from a natural fiber such as cotton, bear in mind that the farmer had to apply fertilizer to the field (phosphate mines) and use a metal tractor (iron mines) that burns fossil fuel (oil wells) to plow

that field. The clothing manufacturer used metal sewing machines to make the clothes, and the clothes were transported to the store where you bought them by truck (metals and oil again) or train (ditto). You probably drove to that store in your car, which is a product of at least a dozen different kinds of mines.

Tires- Automobile tires are not just rubber, but contain about 20% zinc oxide. The zinc is there to strengthen the tire and to help dissipate heat so the tires don't overheat and melt when driving.

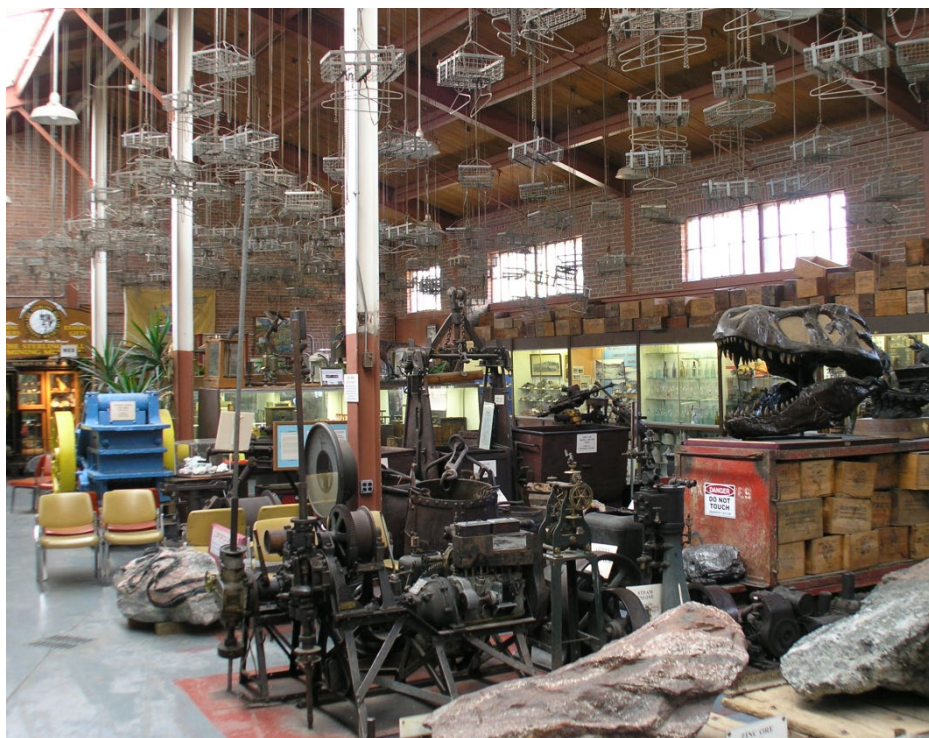
Water- Water is a natural product of our environment (not manmade). However, mining is involved in several stages of bringing that water to your faucet. The pumps used to convey water from one place to another, the pipes the water runs through, the filters and chemicals that are used in water treatment plants, the faucet your water pours from, and the glass you drink it from are all products of mining. Unless you went out to a stream this morning and drank water out of your hand, the water (or coffee or tea or soda) you already drank today was brought to you by mining.

Candles- Made from paraffin, which in turn is made from oil.

Wood (as chairs, tables, studs, golf tees, on and on)- Like water, wood is a natural product of our environment—we grow trees, not mine them. But you don't chop that tree down with your teeth, right? You use an axe or a saw, both products of mining. The saws that are used to cut the wood into boards are products of mining, as are the lathes, sandpapers, polishing compounds, paints, and lacquers that are used to create a piece of furniture.

Summary

Mining is necessary to our daily lives, and every manufactured product that you use involves mining in one way or another. Despite this, most people don't want a mine anywhere near them (as illustrated by repeated efforts to shut down the Lime Crest quarry in Sparta). However, you have to mine where nature put the ore deposits—we don't mine where we want to; we mine where we have to.



A view of some of the displays in Zobel Hall. Note the baskets hanging overhead, with hangers beneath. These were used for drying miners' clothes overnight.



The three-dimensional Periodic Table of the Elements at the far end of Zobel Hall. The noble gases at right – helium, neon, argon, krypton, and radon – glow different colors when an electric current of the proper voltage is passed through them. You can see why neon was widely used in advertising signs.



Displays of mine lamps in Zobel Hall. Carbide lamps at right, oil lamps of various designs to left. The large canisters atop the cases held calcium carbide, a dark-colored granular material that when wet releases acetylene gas, the fuel used in carbide lamps to produce light in the mine.



One of several cases illustrating various uses of zinc, both old (washboard against left wall, zinc-coated caps for canning jars near center) and new. Zinc ingots at bottom.



Fifteen cases of fine mineral specimens, attractively displayed under fiber-optic lighting. Note the shower heads on right. This is the area where miners cleaned up at the end of a workday before returning home.



Miners' sand jars – local works of art. Crushed and screened minerals from the Sterling and Franklin zinc mines were used in these jars, including franklinite (black), calcite (white), willemite (green), andradite (ochre-brown), rhodonite (pink), zincite (dark red), etc.