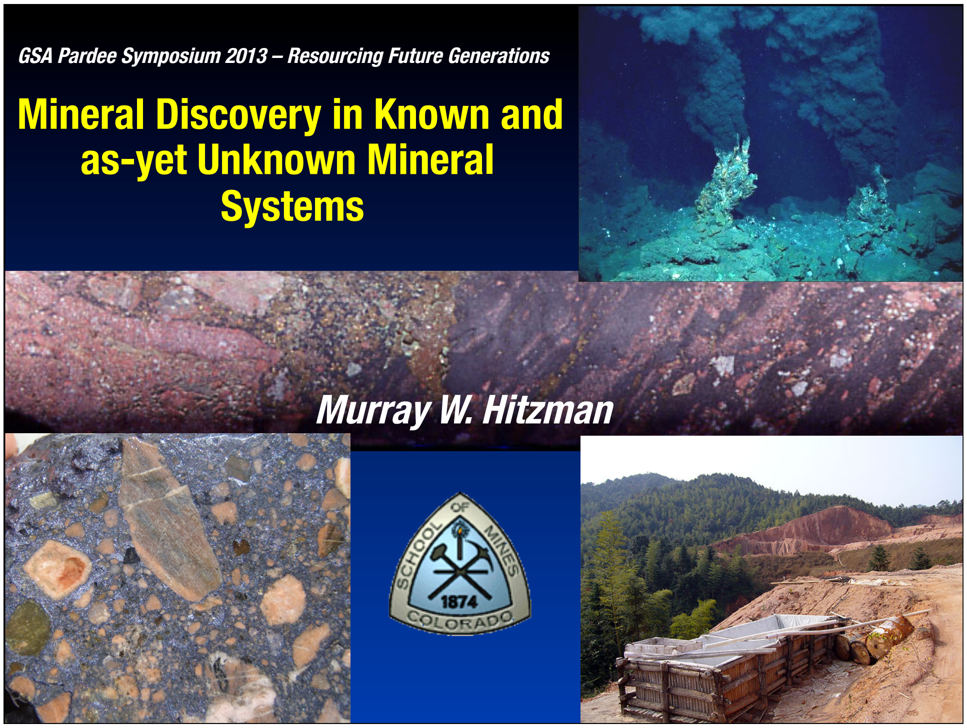
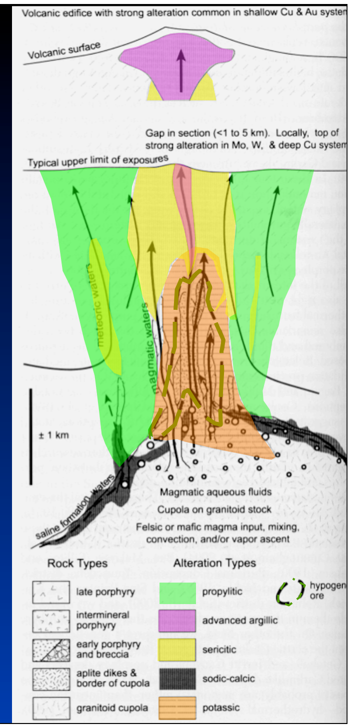

GSA Pardee Symposium 2013 – Resourcing Future Generations
Mineral Discovery in Known and as-yet Unknown Mineral Systems
Murray W. Hitzman
SCHOOL OF MINES
1874
COLORADO


Economic geologists have been quite successful in finding more known types of ore deposits during the past 50 years
2007
The Round Mountain gold mine in Nevada (volcanic-rock-hosted deposit) discovered in 1904, has yielded 13 million ounces of gold from 1977 to 2012 – continuous record of discovery around the initial deposit.

Mineral Exploration Success

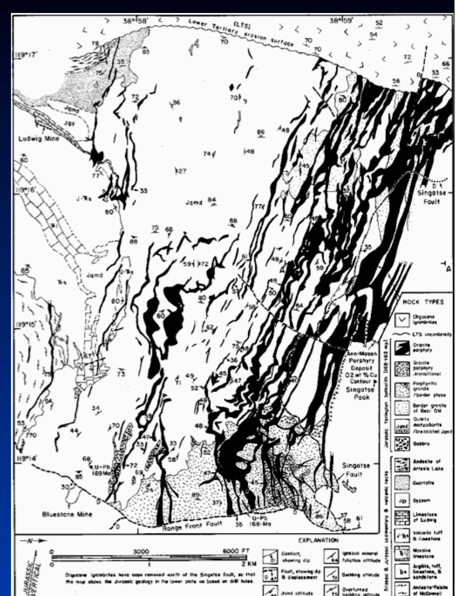
- Due in large part to the development of successful predictive models of mineral deposit formation that allow for focused exploration.
- A good example is the porphyry copper model that provides understanding of the 4-D development of these mineral systems and the physical and chemical properties of rocks within and around the deposit allowing for targeted exploration — geologic, geophysical, and geochemical.



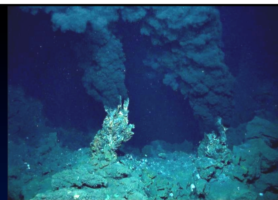
From Seedorf et al., 2005, SEG 100th Anniv. Vol.

Porphyry Copper Model

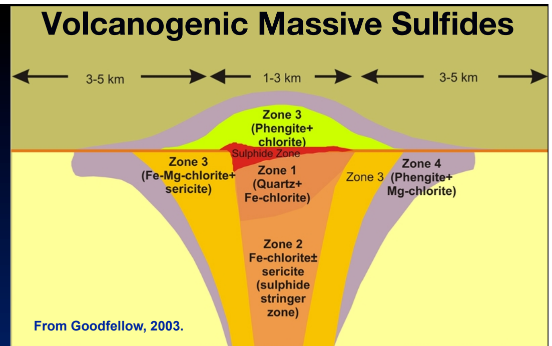
- Developed through literally thousands of person-years of applied and fundamental geological-geochemical-geophysical research.
- Work in many localities, including unique locations like Yerington, NV where a 5km thick section through a porphyry system is exposed at the earth's surface, that allowed a 3-D model to be developed.
- Careful fieldwork and geochemical and geochronological work allowed for a 4-D (time) understanding.



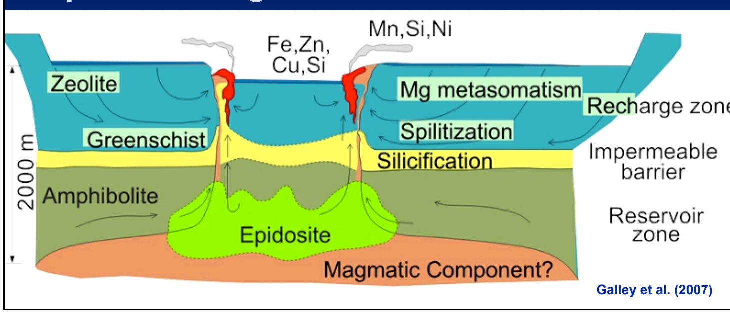
from Dilles and Einaudi, 1992, Econ Geol., p. 1967



Mineral Exploration Success

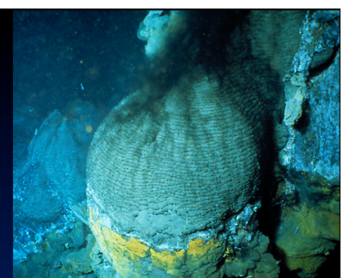


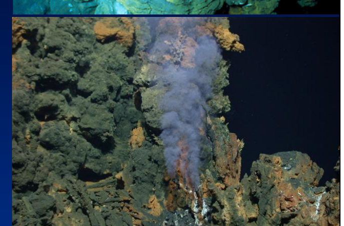
The most successful mineral system models operate at both deposit and regional scales.

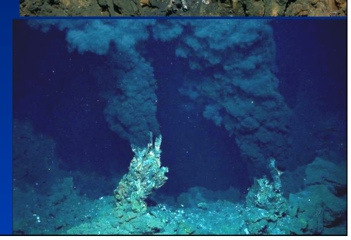


Volcanogenic Massive Sulfide Model

- **Developed independently in several places – Japan (early-20th century); Canada (1950-60's).**
- **Work on deposits in many localities.**
- **Culminated with discovery of active sea-floor systems:**
  - **Red Sea brine pools 1966**
  - **Mid-ocean ridge black smokers 1979**
- **Aided by geological-geochemical research on ophiolites and sea floor geology (regional framework).**







We have also discovered new ore deposit types in the past half century

Deposit type	Type locality (year discovered) and new features
Carlin Au	Carlin, Nevada (1961): disseminated gold in sedimentary rocks
Roll-front U	Wyoming, Kazakhstan (1960s): redox boundaries in sandstones
Granite-hosted U	Rössing, Namibia (1960s): U-rich granite
Unconformity U	Rabbit Lake, Saskatchewan (1968): high-grade U near unconformities
Disseminated Ni	Mt. Keith, W. Australia (1969): disseminated Ni sulfides in major komatiitic lava tubes
Iron oxide Cu-Au	Olympic Dam, S. Australia (1975): iron-oxide-rich ores in huge regional hydrothermal systems
Intrusion-related Au	Fort Knox, Alaska (1980s): Au in granitic rocks, without Cu
Ion absorption REE	South China (1980s): low-grade REEs with kaolinite in weathered granites

Some discoveries were technology driven

Carlin Au	Carlin, Nevada (1961): disseminated gold in sedimentary rocks
Ion absorption REE	South China (1980s): low-grade REEs with kaolinite in weathered granites

Some discoveries were geologically driven

Roll-front U	Wyoming, Kazakhstan (1960s): redox boundaries in sandstones
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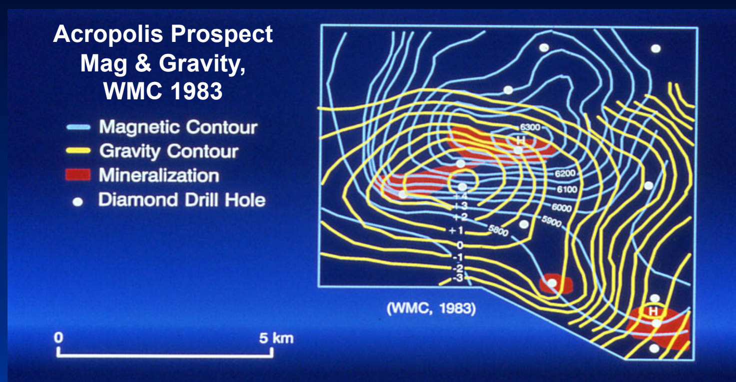
Some were lucky

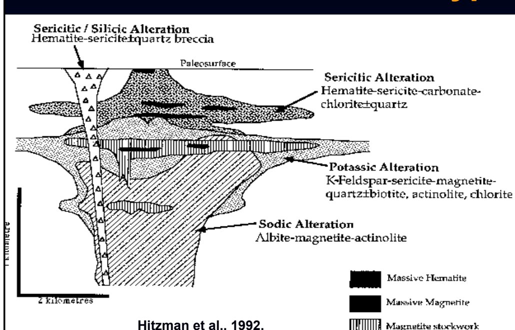
Iron oxide Cu-Au

Olympic Dam, S. Australia (1975): iron-oxide-rich ores in huge regional hydrothermal systems



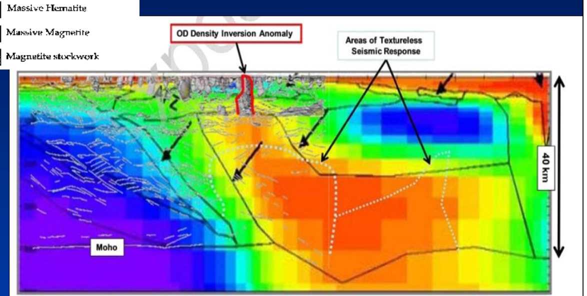
Though to be fair, WMC was following a model (sedimentary rock-hosted copper) and utilizing regional geophysics to target what they thought were source rocks (basalts).

We have developed models for most of these deposit types



Hitzman et al., 1992.

Iron Oxide-copper-gold (IOCG) [Olympic Dam-type] Model

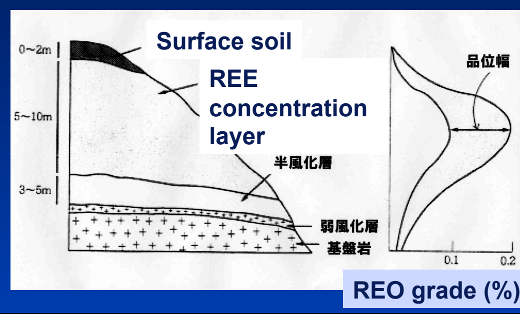


Olympic Dam regional magnetotelluric survey

We are developing models for others

Ion Absorption REE deposits

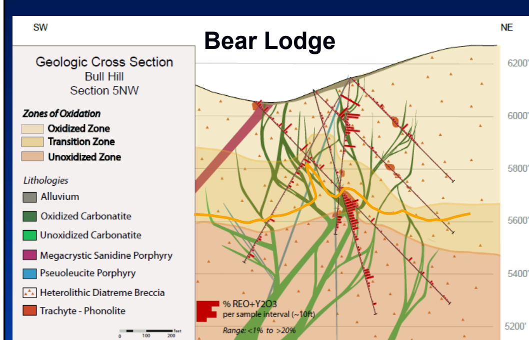
- Supergene clay deposits, China (major source of HREE) – develop over granites; over 100 low-tonnage, low-grade (0.03-0.35% REO) deposits.
- Poor data on these deposits hampers model development



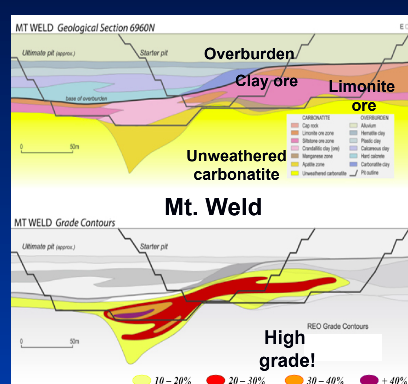
We are developing models for others

Ion Absorption REE deposits

- We are utilizing other supergene-enriched deposits to develop models:
  - Bear Lodge, WY (2^{nd} largest REE deposit in US).
  - Mt. Weld, Australia.



Mandi Reinshagen, CSM MS candidate



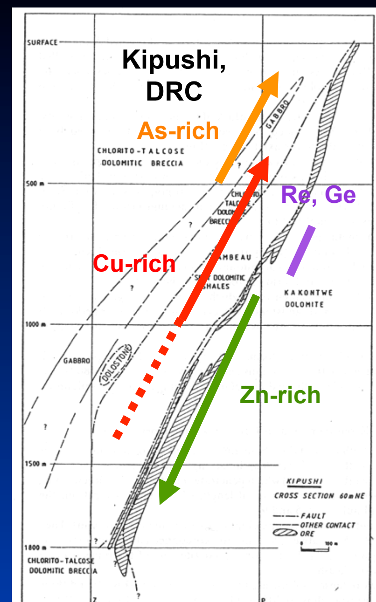
There are other known deposits for which we do not have good models

This is usually because there are few examples of the deposit type.

Some of these include deposits containing elements that are currently in demand.

Examples:

- Ge-rich Tsumeb-type Cu-Zn deposits (Tsumeb, Kipushi, Kombat, Apex)
- Ga, Ge, and In-rich carbonate-hosted zinc deposits



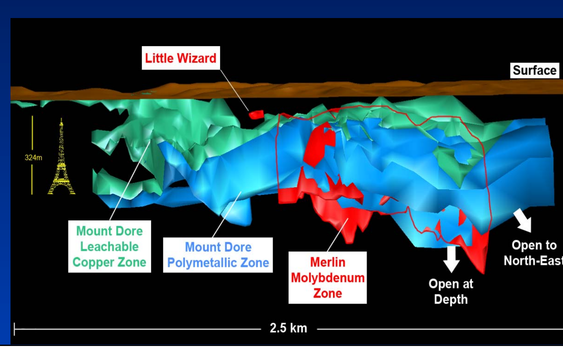
(from deMagnee and Francois, 1988)

Fig. 7. Vertical profile perpendicular to the Kipushi ore bodies. (M. Intiomale)

We have found new deposit types in the past five years — we do not understand these yet

Merlin-type Mo

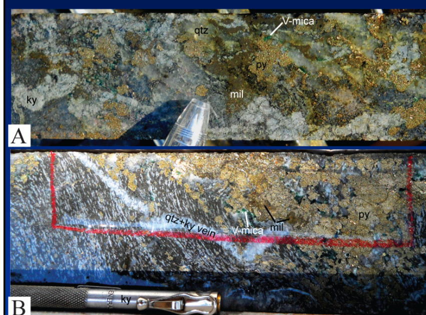
Merlin, Queensland (2008): High grade moly vein in IOCG district – no obvious connection to typical moly-causative intrusions.

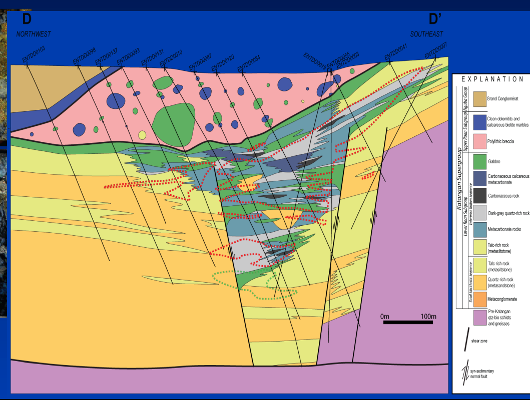


We have found new deposit types in the past five years — we do not understand these yet

Sedimentary Ni

Enterprise, Zambia (**2010**): High-grade hydrothermal nickel deposit in metasedimentary rocks with no mafic ultramafic rocks. Another similar deposit discovered (by accident) last year in the district.





Patricia Capistrant, CSM MS 2013

We have found new deposit types in the past five years — we don not understand these yet

<u>Deposit type</u>	<u>Type locality (year discovered) and new features</u>
Merlin-type Mo	Merlin, Queensland (**2008**): High grade moly vein in IOCG district – no obvious connection to typical moly-causitive intrusions.
Sedimentary Ni	Enterprise, Zambia (**2010**): High-grade hydrothermal nickel deposit in metasedimentary rocks with no directly associated mafic/ultramafic rocks. At least one other similar deposit discovered (by accident) since then in district.

We can expect additional new types of ore deposits to be discovered in the future by serendipity and through development of new models …

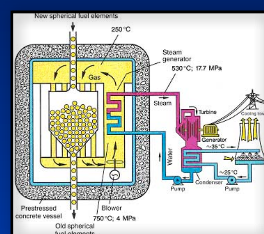
We need to develop deposit models for a variety of "new" elements

- **Important for renewable and CO_2 neutral energy technologies**

Tellurium Gallium
Indium Germanium

Neodymium Dysprosium
Praseodymium Samarium

Terbium
Europium



Helium

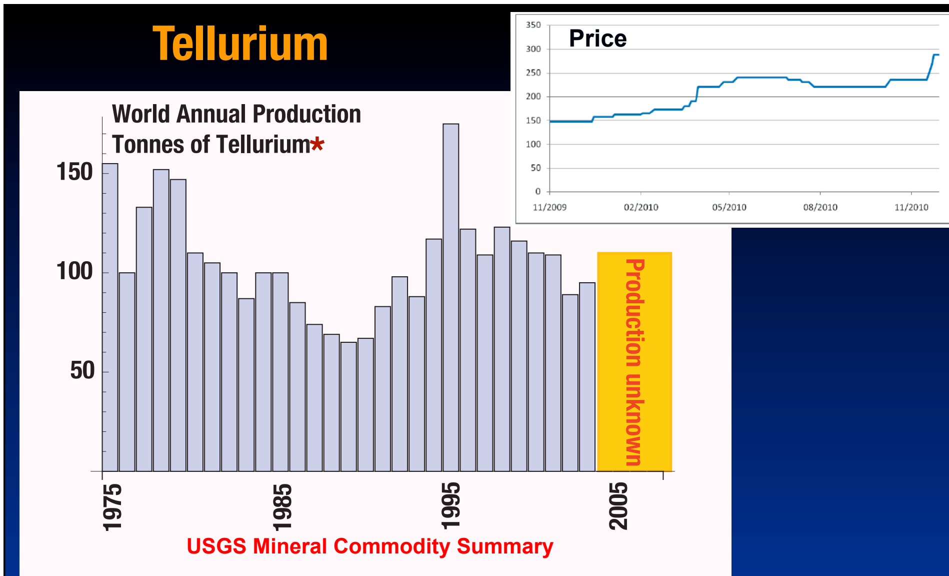
Lithium
Lanthanum

Geological Models for Energy Critical Element (ECE) Deposits

We have good geological models for:

- Mafic intrusion-hosted **PGE** deposits
- **Lithium** deposits (lacustrine brines and pegmatites)
- Some **REE** deposits
- Many deposits that have **ECEs** as by-products:
  - Porphyry copper deposits (Te)
  - Porphyry moly deposits (Re)
  - Sedimentary rock-hosted copper deposits (Co)
  - Epithermal precious-base metal deposits (Ag, In)
  - *We do not, however, understand why some deposits have higher concentrations of ECEs*

Tellurium



- 0.0000001% of earth's crust (compare to gold — 0.0000004%)
- Almost all comes from by-product of copper smelting
- Key ingredient in Cd-Te thin-film solar photovoltaics

Tellurium in Photovoltaics

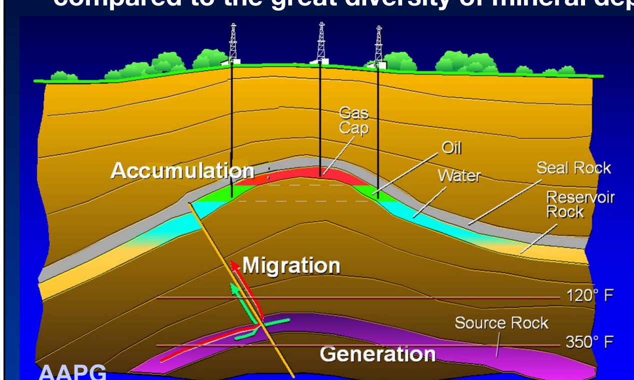
- It takes between 100-400 tonnes of Te per GW of solar. World electric consumption is 2000 GW/yr. The reserve base of known Te is approximately 48,000 tonnes = 120 GW.
- Will constraints on availability of tellurium obstruct the large scale deployment of CdTe thin film photovoltaics?
- Studies ask "is there enough Te to build … over… years?"
  - Zweibel → "yes"
  - Ojebouboh → "probably"
  - Fthenakis → "maybe"
  - Green → "maybe not"
  - Feltrin & Freundlich → "no"

Tellurium in Photovoltaics

- Tellurium is produced as a by-product of copper smelting (and often unwanted due to toxicity!)
- Tellurium production has gone down as more copper is produced from solvent extraction (SXEW) treatment of copper oxides rather than smelting of copper sulfides.
- There are undoubtedly high grade tellurium deposits out there – several known (Colorado, Mexico, Fiji).
- We have not developed geological models of how they form and how to find them.

Systems Approach

- The petroleum industry has been extremely successful in defining economic energy resources through exploration.
- This is because of the superb tools and technologies available to them (seismic) and the relatively simple geology of petroleum systems compared to the great diversity of mineral deposit systems.



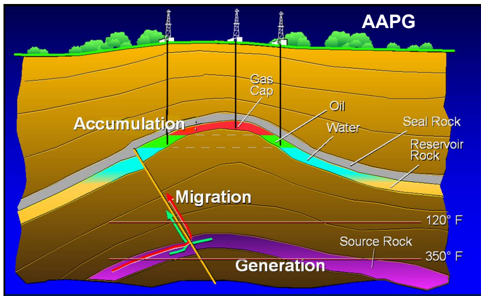
BURIAL ENERGY

TRAP

TRANSPORT PATH

SOURCE

Adopting a systems approach from the petroleum industry would be beneficial to mineral exploration.



Minerals Systems Approach

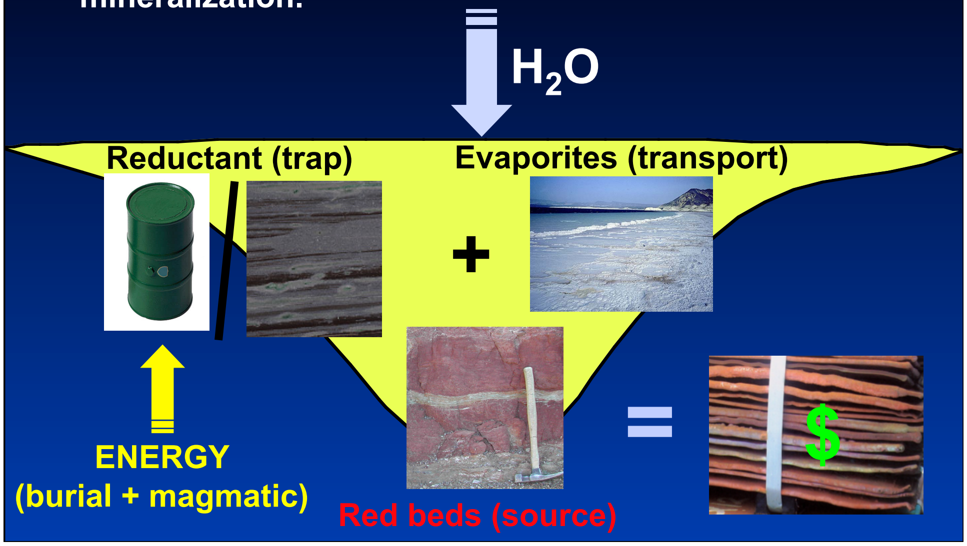
- Individual sulfide ore deposits require:
  - *Metals and sulfur source*
  - *Means of element transport*
  - *Chemical and/or (more rarely) physical trap*
  - *Energy to drive the system*

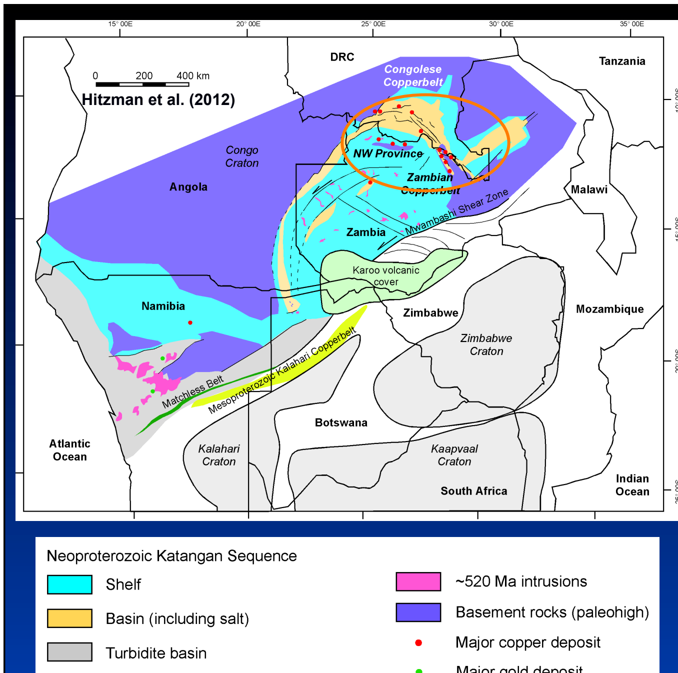
Mineral Systems Approach Requires a Regional View

•The Porphyry Copper and VMS models are powerful because they describe the deposit at multiple scales (space and time) and allow prediction of physical properties of the rock mass enclosing the deposits.

•As we develop new models that include source, migration/transport, trap, and energy, we need to appreciate sense of scale.

Sedimentary rock-hosted stratiform copper systems are relatively simple geochemically. But world-class deposits form in special situations — closed basins that allowed for a long period of fluid interaction and mineralization.

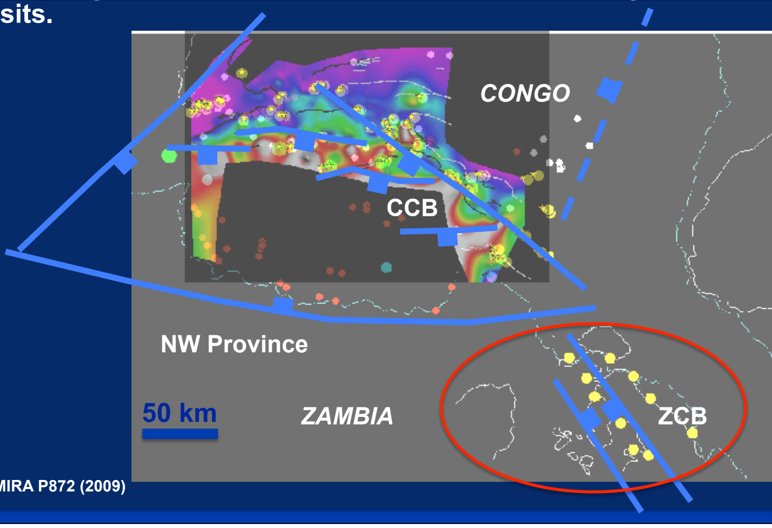




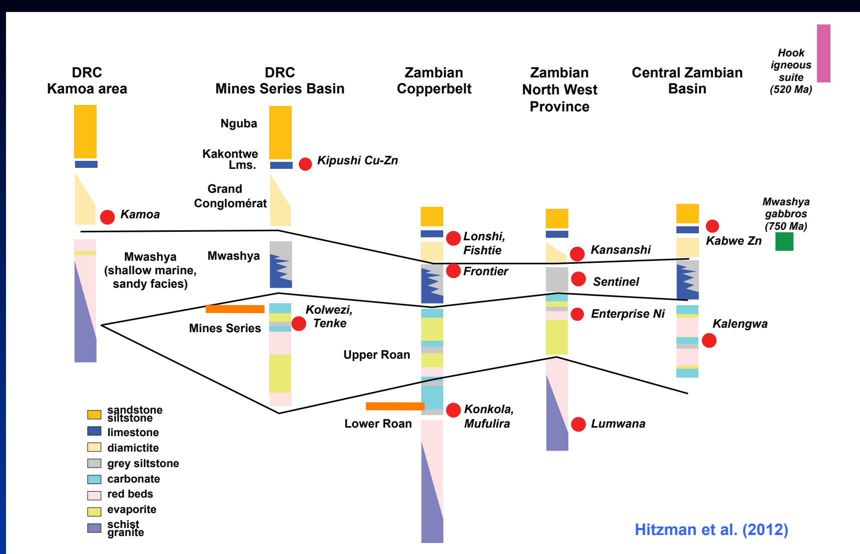
Central African Copperbelt – Taking a Regional View of Mineral Exploration

Central African Copperbelt Basin

African Copperbelt (Katangan) basin is a trap-door basin, hinged to the south. The CCB is in the main basin. The ZCB is a sub-basin on the southeast shoulder of the main basin. The NW Province is southern edge of basin. All the sub-districts contain significant deposits.



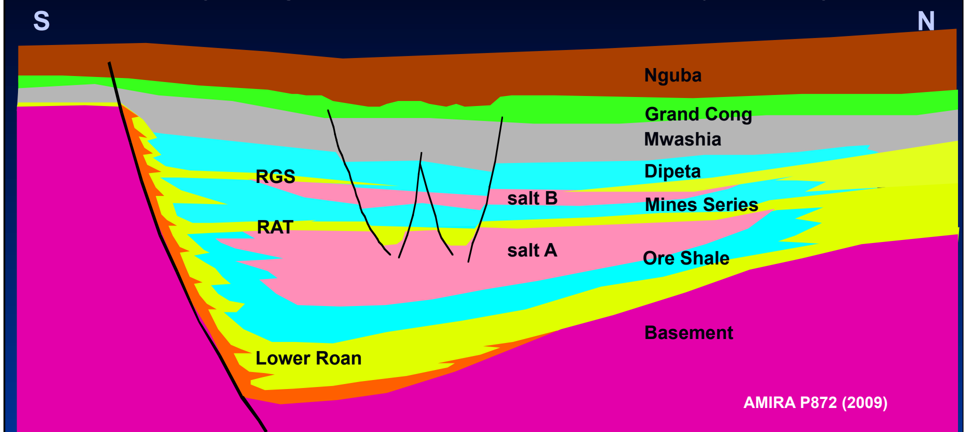
Central African Copperbelt Basin



Recent discoveries indicate mineralization at multiple stratigraphic locations.

Central African Copperbelt Basin— Model

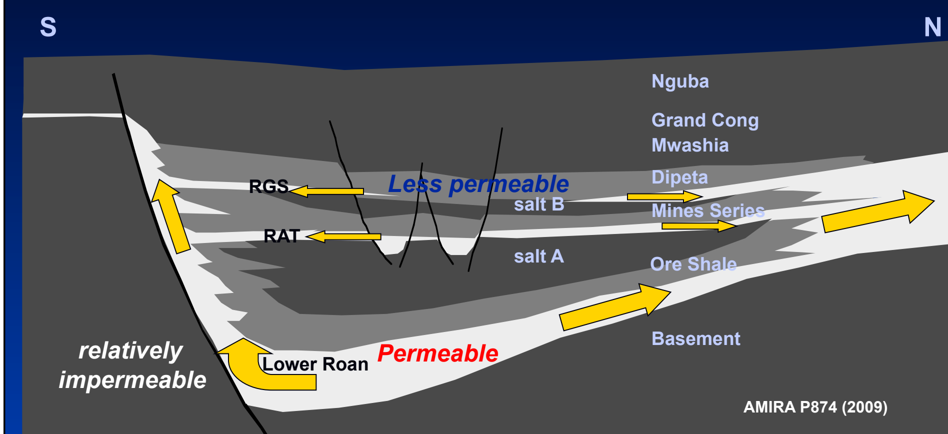
Relatively straightforward basin with several major salt layers.



New exploration models utilize the stratigraphy to determine the physical and chemical architecture of the basin both of which are critical for mineralization.

Central African Copperbelt Basin

Understanding the architecture of paleo-permeability within the basin that provided fairways for migrartion - fluid flow (now displaying basin-scale hydrothermal alteration) is critical for exploration and discovery.



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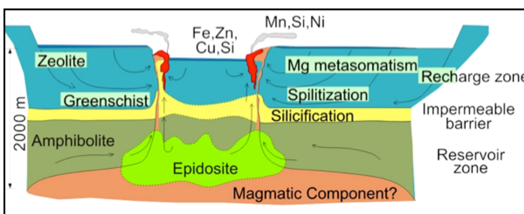
Economic Geology, v. 108, pp. 000–000

The Kamoa Copper Deposit, Democratic Republic of Congo: Stratigraphy, Diagenetic and Hydrothermal Alteration, and Mineralization

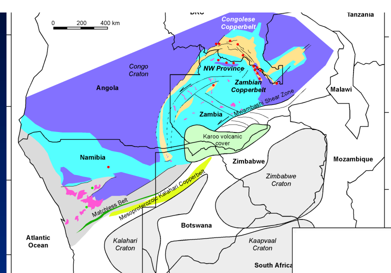
DANIELLE SCHMANDT,[1] DAVID BROUGHTON,[2] MURRAY W. HITZMAN,[1,†] PIRET PLINK-BJORKLUND,[1] DAVID EDWARDS,[2] AND JOHN HUMPHREY[1]
[1] *Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401 USA*
[2] *Ivanplats Ltd., 82 Maude St., Sandton 2146, South Africa*

Central African Copperbelt — Kamoa Discovery (2006-08)

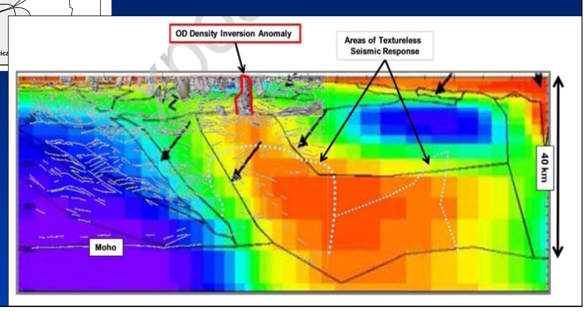
Utilization of Copperbelt model allowed recognition of typical sedimentary rock-hosted Cu style mineralization in a (then) atypical setting — regional thinking.



Scale is Important



We need to think beyond the deposit itself.



Important scales for mineral systems are 100's to 1000's km^2.

Technological Tools are also Critical for Discovery of Known and as-yet Unknown Systems

- Development of new geophysical tools in particular will be critical for new discoveries.
  - Adaption and adoption of seismic technologies
  - Improved inversion processing of traditional electrical and magnetic data
- These tools should be utilized at the appropriate scales.

Santa Cruz (AZ) in-situ copper mining test project - US government funded (1986-1998)

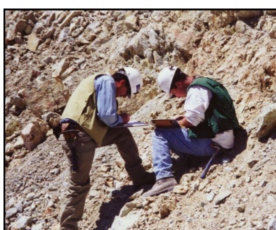
Could more research projects like this stimulate a new industry – as DOE research did with shale gas/fracking?

Technological Tools are also Critical as they may give us "New" Deposits to Find

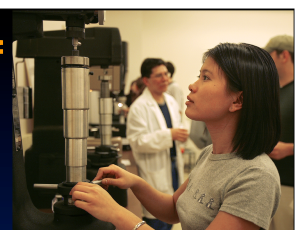
Discovery of Known and as-yet Unknown Mineral Systems

"Where oil is first found is in the *minds of men.*"

Wallace Pratt (1885-1981)



Mineral Discovery of Known and as-yet Unknown Mineral Systems



Like those in the petroleum industry we need to realize that imagination is ultimately the most powerful exploration tool.

Developing new ore deposit models and technological tools to better understand the physical properties of the Earth – including the location of ore deposits – requires utilizing our imaginations.

We will find the as-yet unknown mineral resources the world needs by careful observation *AND* dreaming.

PEOPLE ARE THE BEST EXPLORATION TOOLS