Volcanic-associated Massive Sulfide Deposits

Lecture 17&18

Fundamentals of Earth Resources

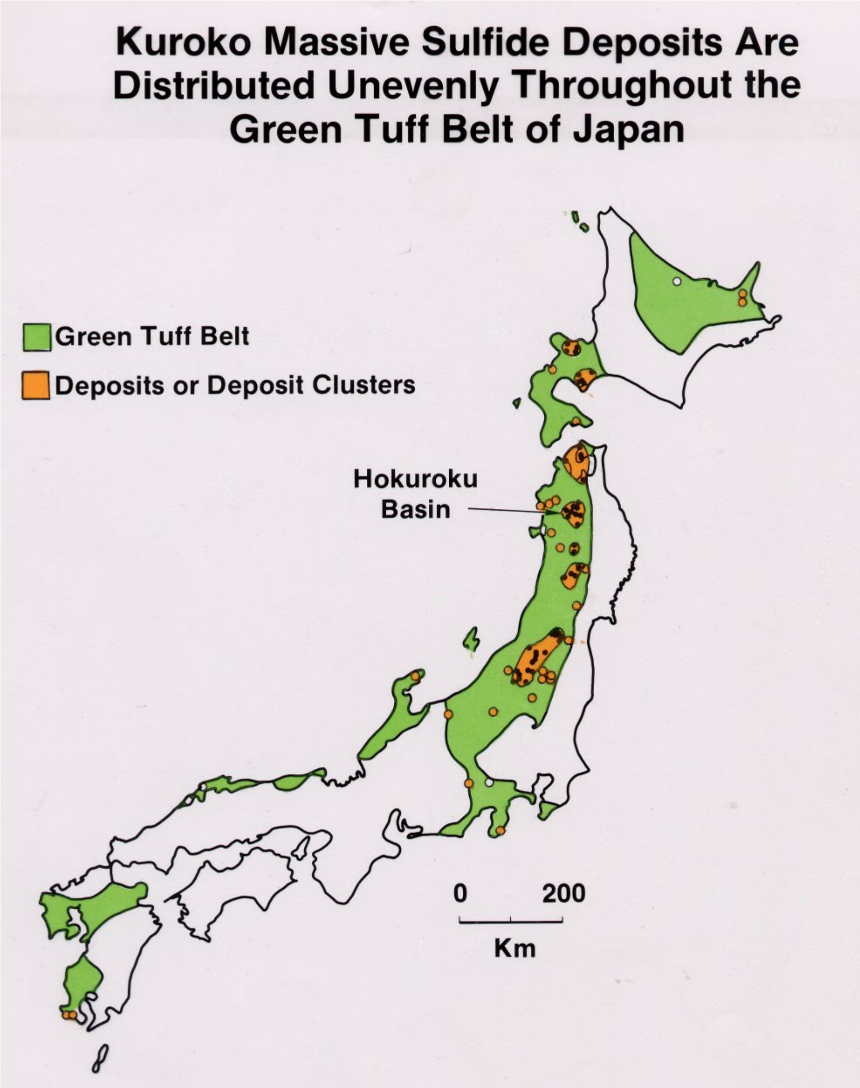
Resources from Earth's Internal Energy

L. M. Cathles

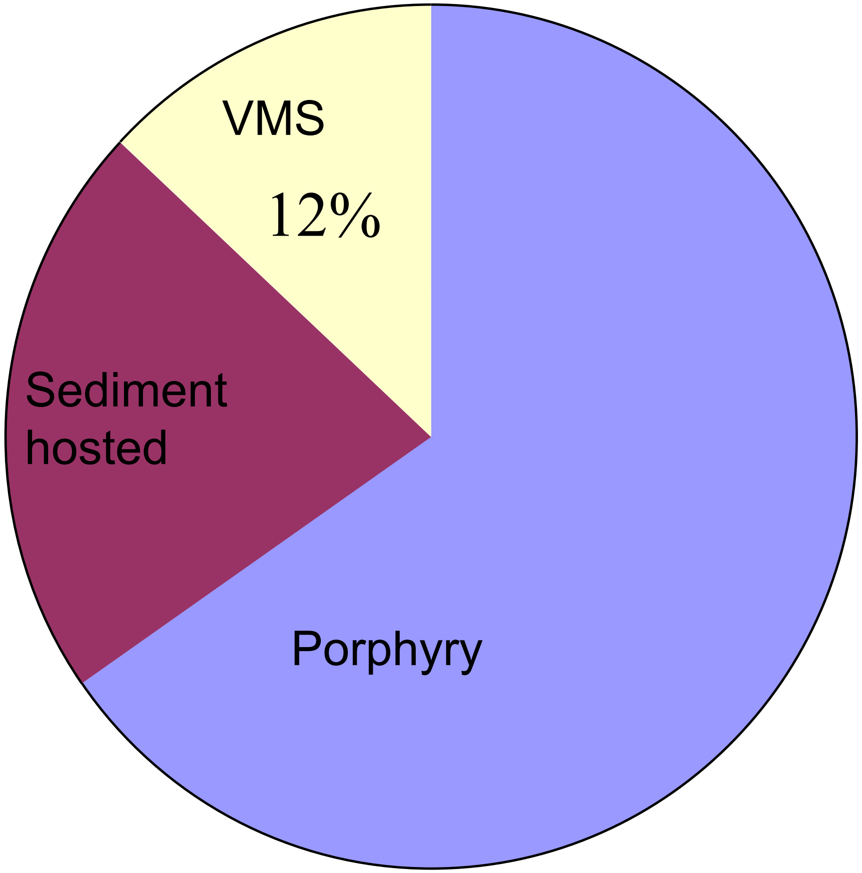
2008

Consider the VMS* deposits in Japan

*Volcanic-associated **M**assive **s**ulfide



Cathles, Economic Geology Monogr 5 (1983)



Current Copper Production

Craig et al., 2001, p306

A basin developed across Japan in Mid-Miocene

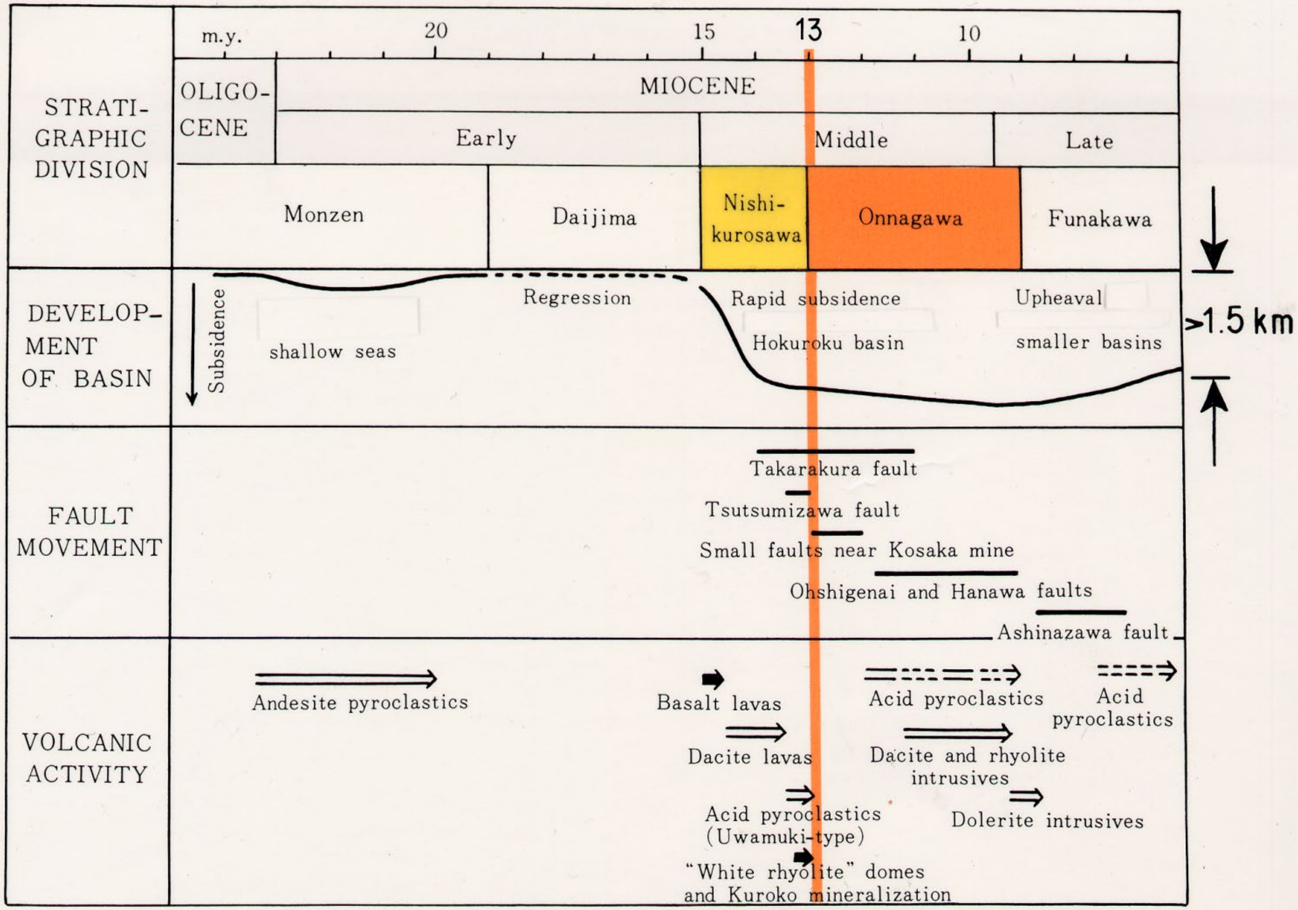


Fig. 5. Tectonic evolution of the Hokuroku basin.

From T. Sato et al., in Geology of Kuroko Deposits, Mining Geology Special Issue #6, 1974

EARLY MIOCENE PALEOGEOGRAPHY
(Kitamura, 1959)

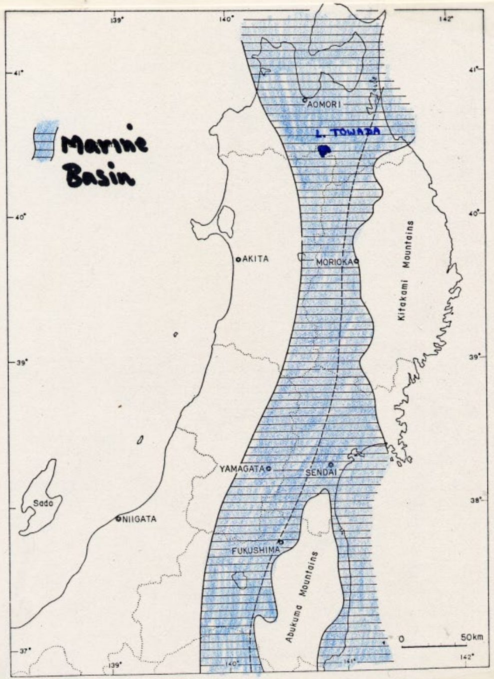
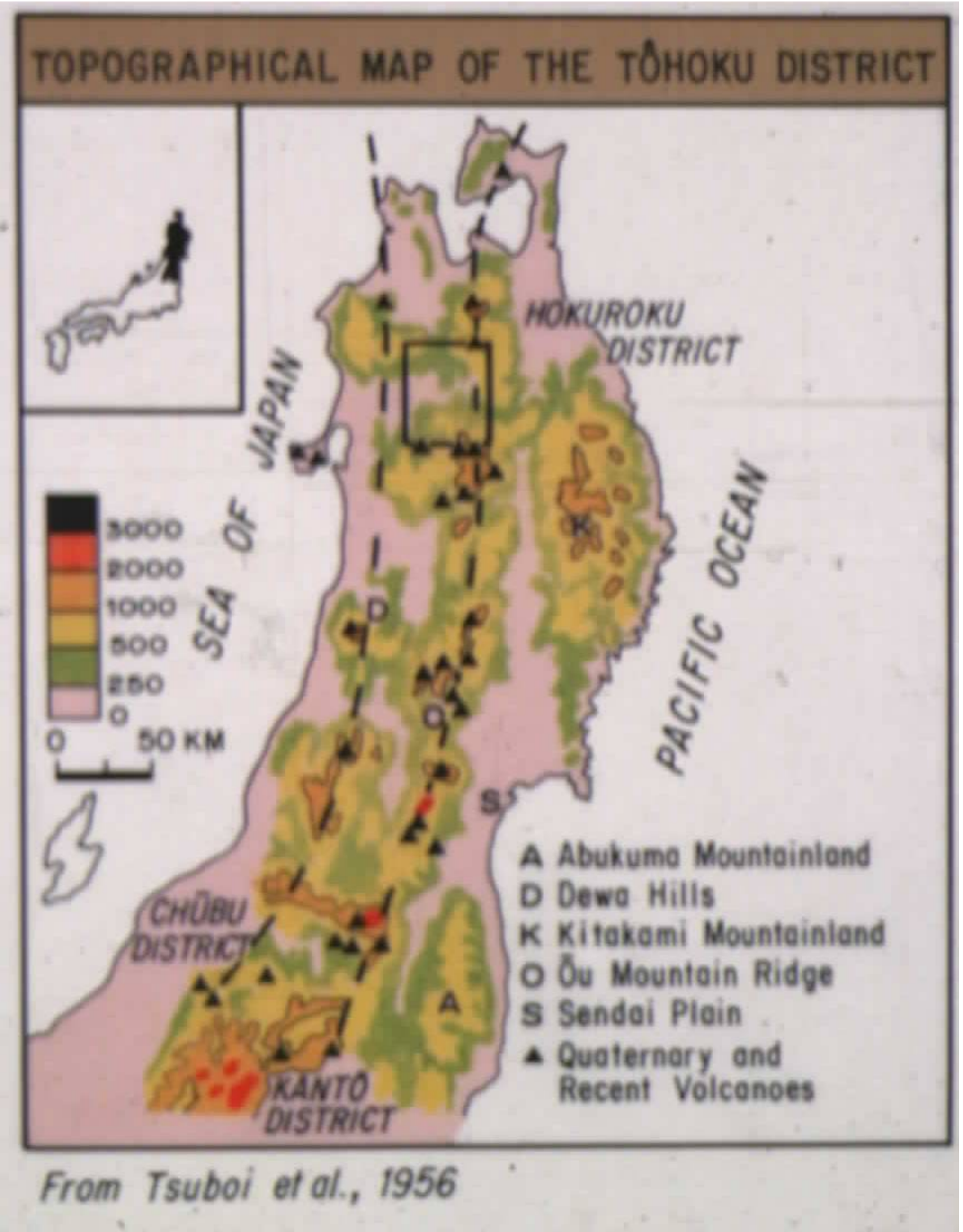


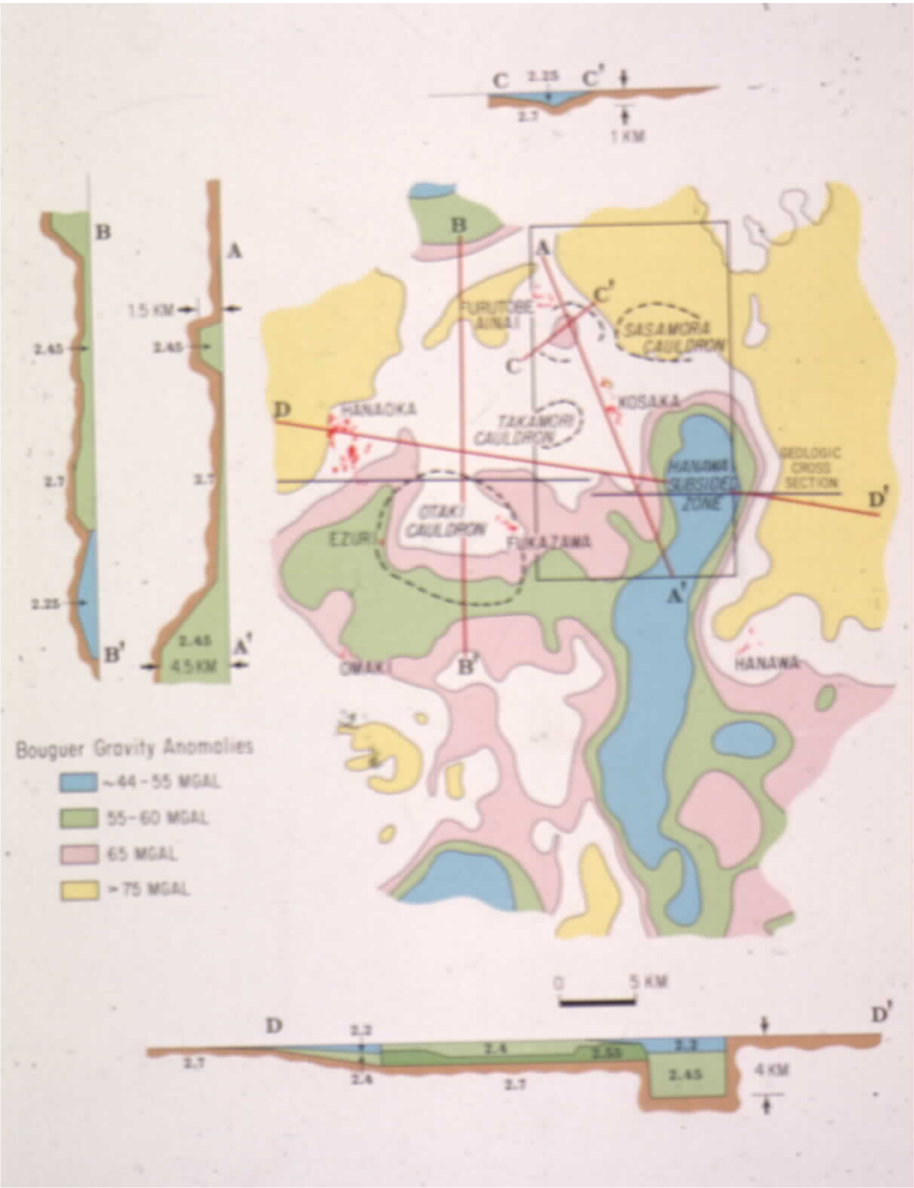
Fig. 23-3. Paleogeographic map of northeast Honshu in the Early Miocene (Stage I of Kitamura, 1959).

Hokuroku District Japan Today



TOPOGRAPHICAL MAP OF THE TÔHOKU DISTRICT

From Tsuboi et al., 1956

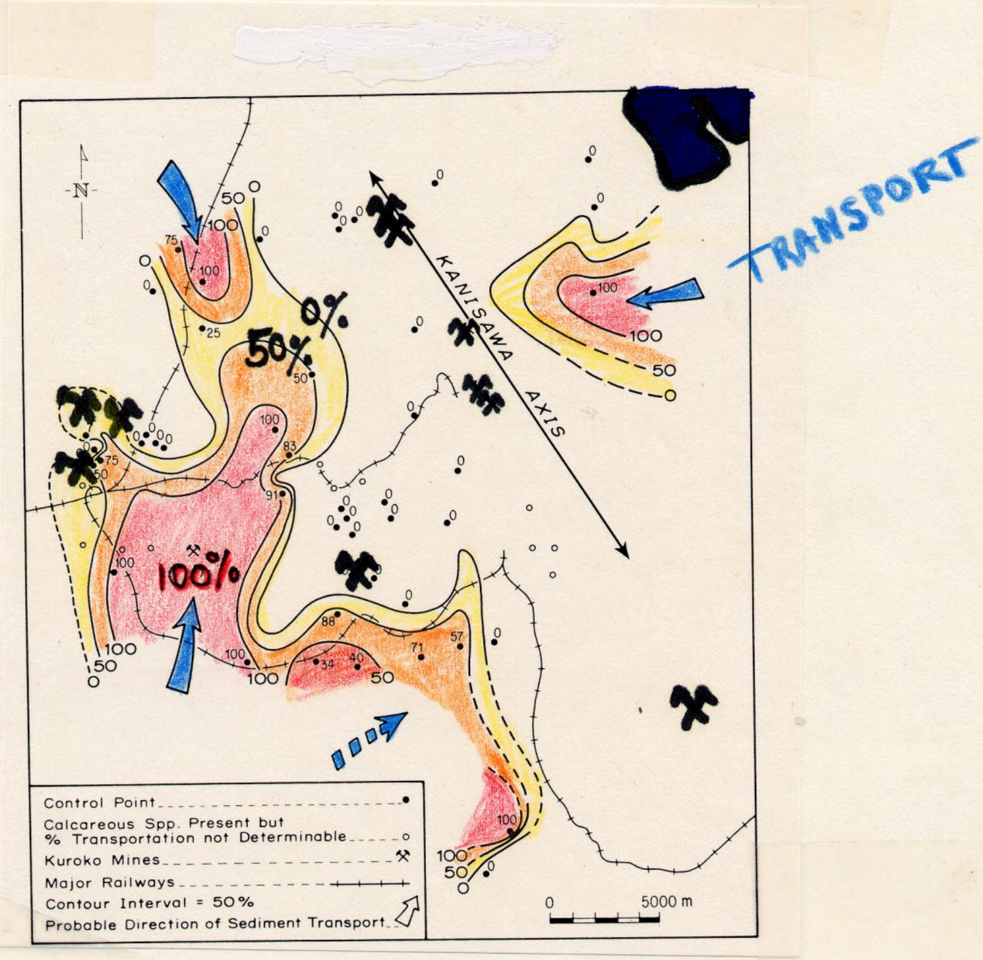


Hokuroku District

Flat rice paddies
with bordering hills

Hokuroku basin was a basin

MIXING OF SHALLOW AND DEEP WATER FORAMINIFERA SHOW TURBIDITE TRANSPORT <u>INTO</u> HOKUROKU BASIN



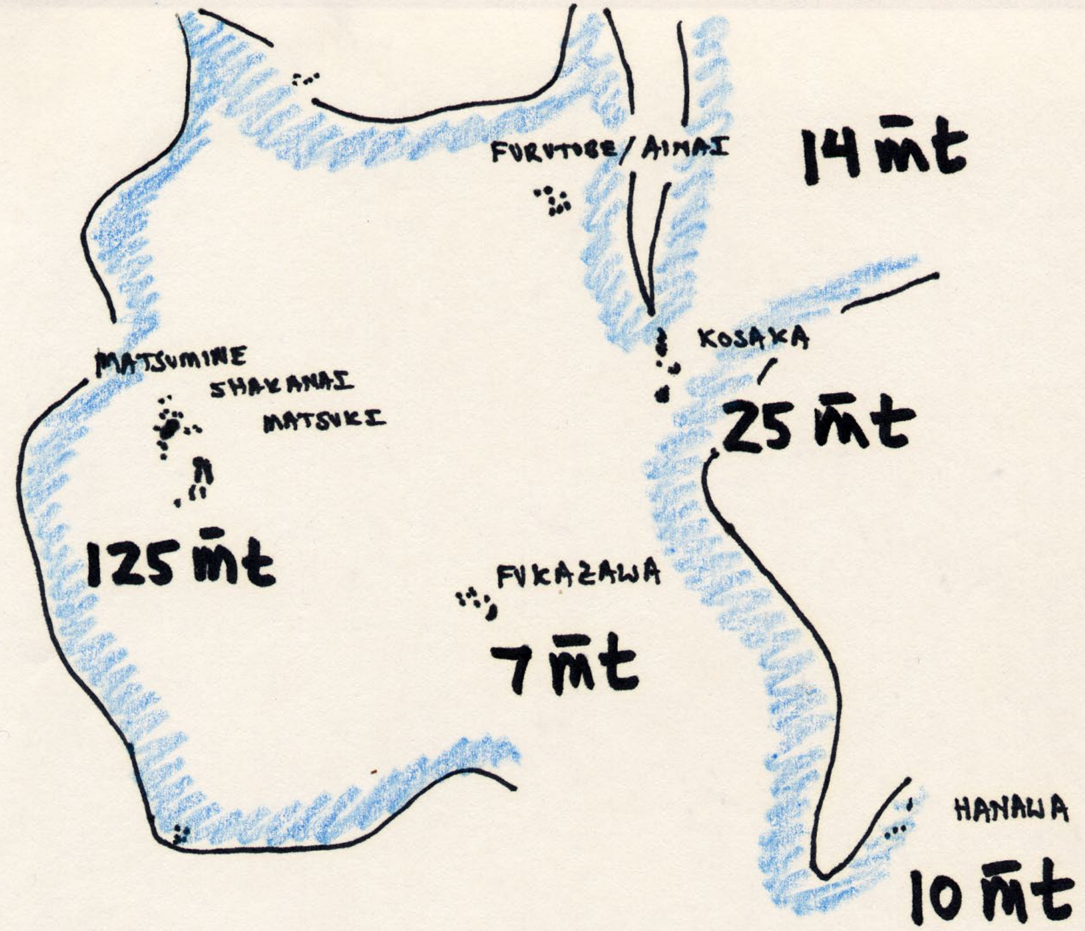
50% = Percent Shallow Water Forams

Guber + Merrill, 1983

in Economic Geology Monogr 5 (1983)

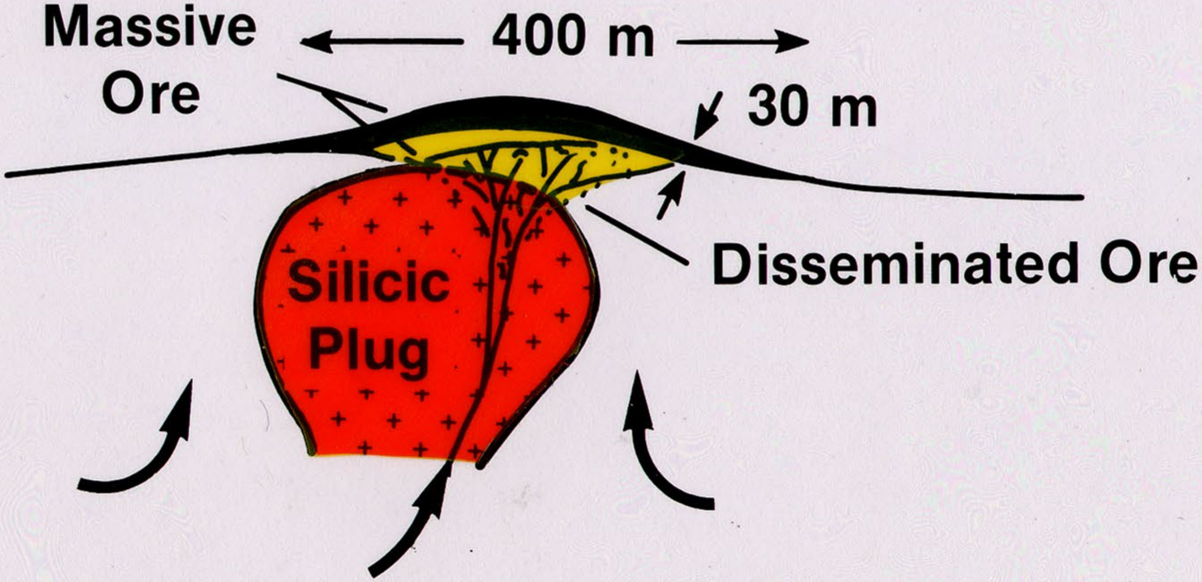
VMS deposits scattered throughout basin

ORE TONNAGES IN HOKUROKU BASIN

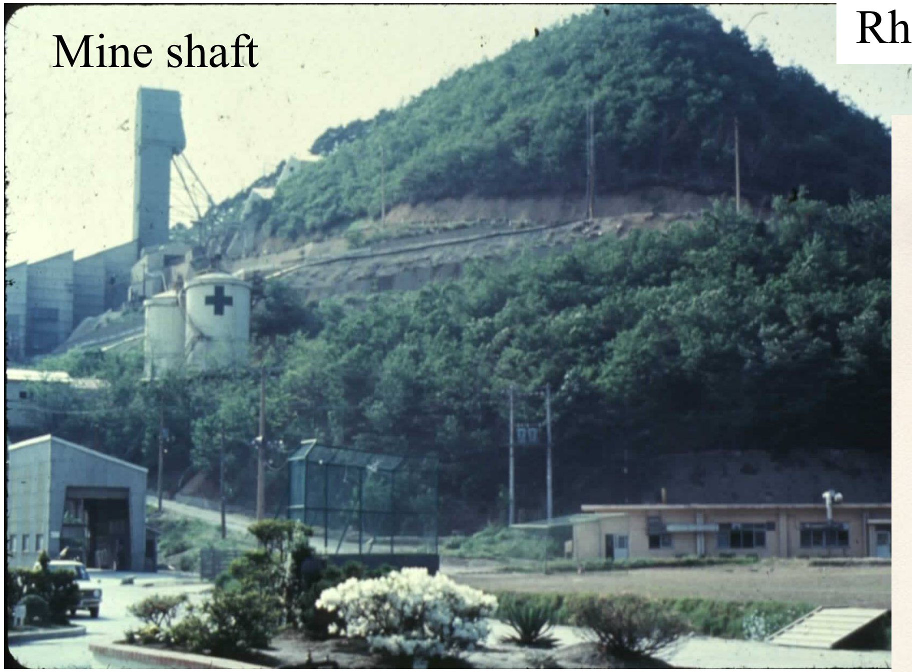


CALCULATED FROM ORE DIMENSIONS
GIVEN IN HASHIMOTO, 1977
ASSUMING 4 tonnes/m^3

Kuroko Massive Sulfide Deposits Formed When Convecting Hydrothermal Solutions Discharged on the Sea Floor

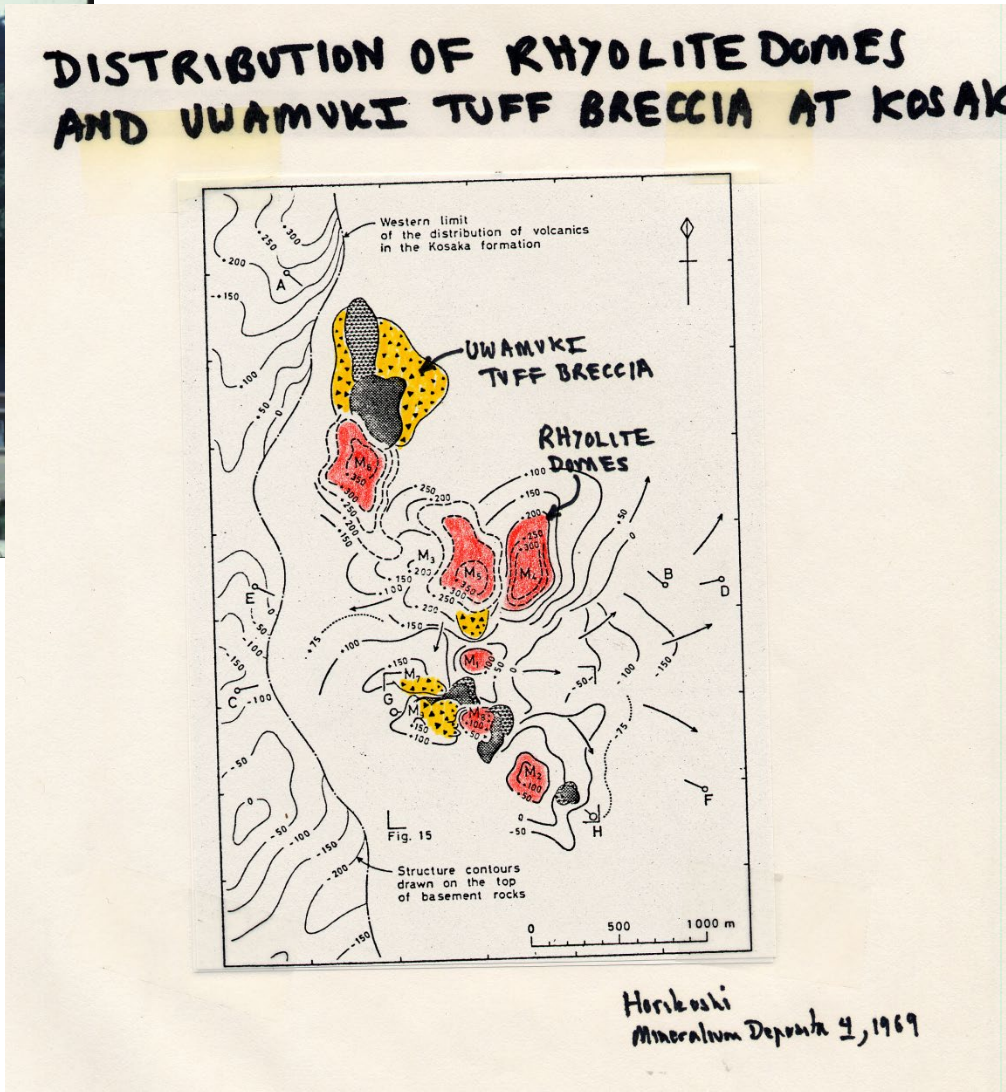


Basin invaded by basalt and rhyolite domes



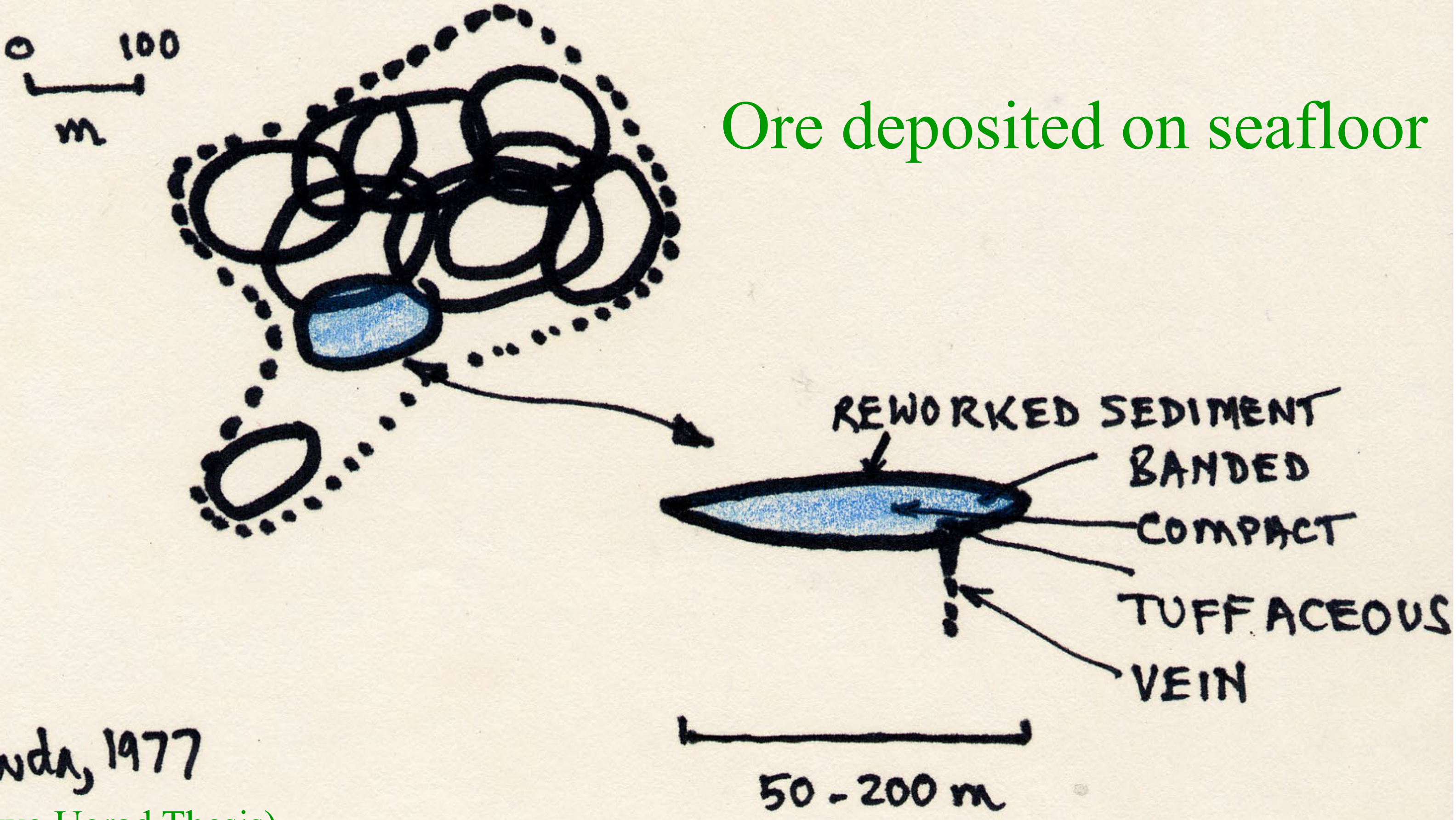
Mine shaft

Rhyolite dome



ORE LAYERS ARE MADE UP OF COMPOSIT PODS

Ore deposited on seafloor

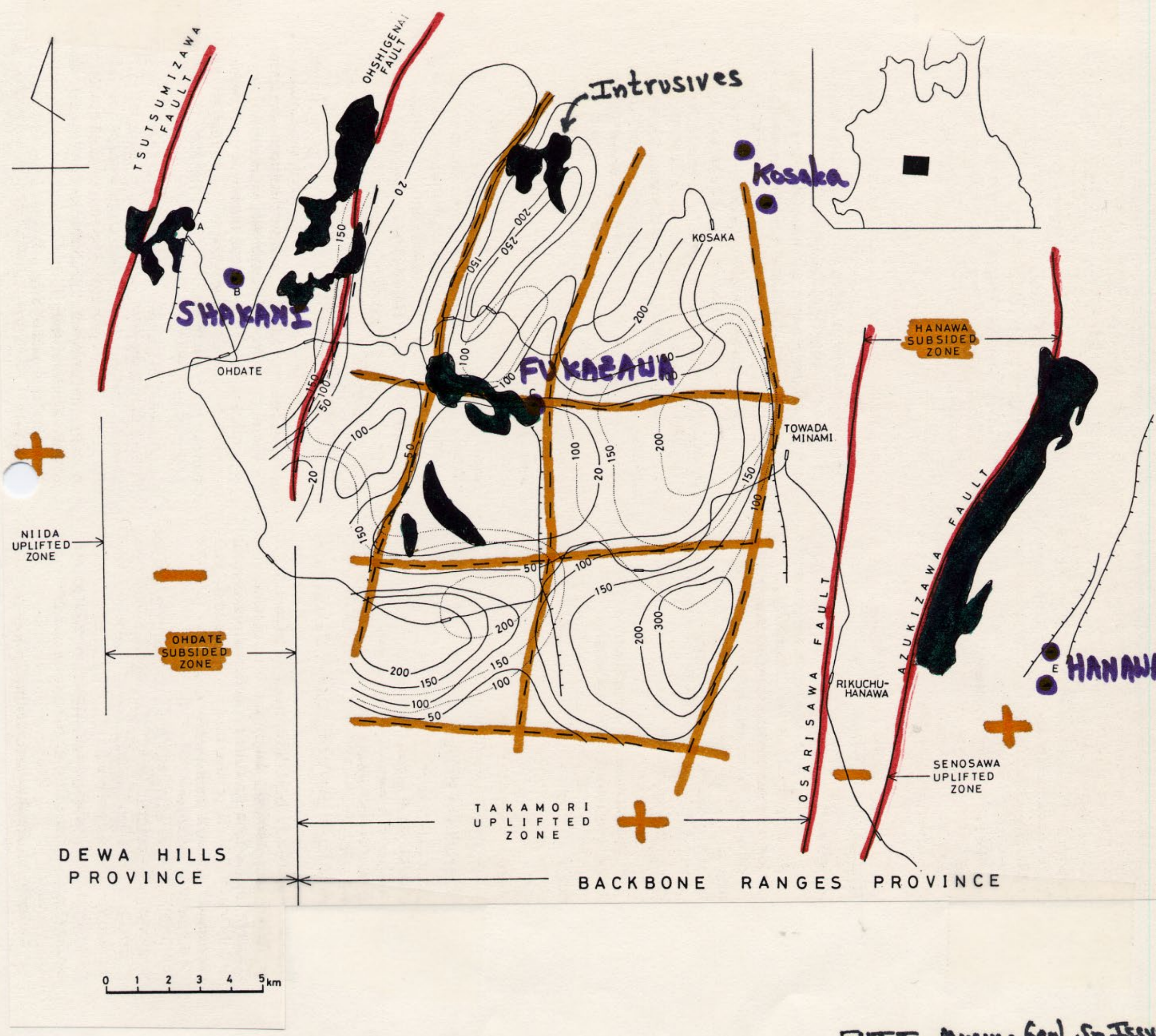


R Kouda, 1977

(U Tokyo Ugrad Thesis)

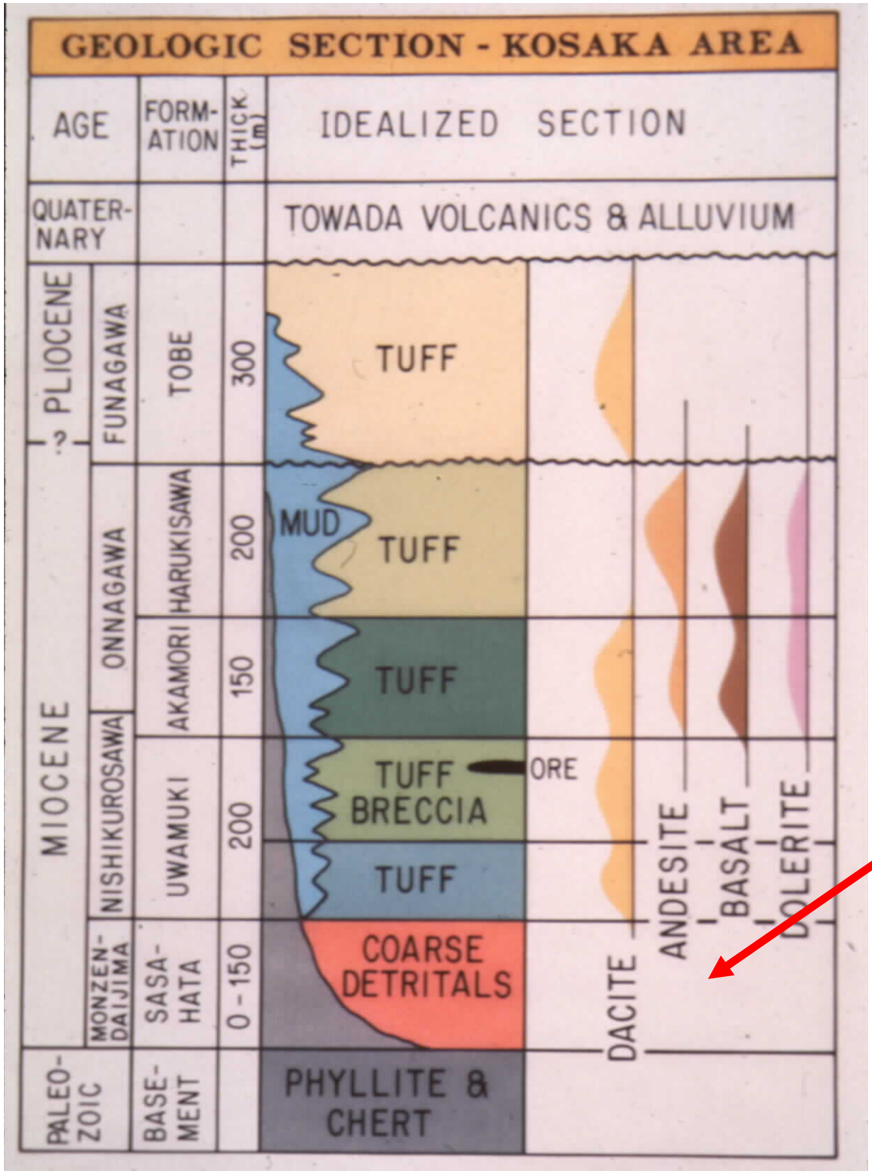
Deposits and associated intrusions controlled (?) by rectilinear fractures

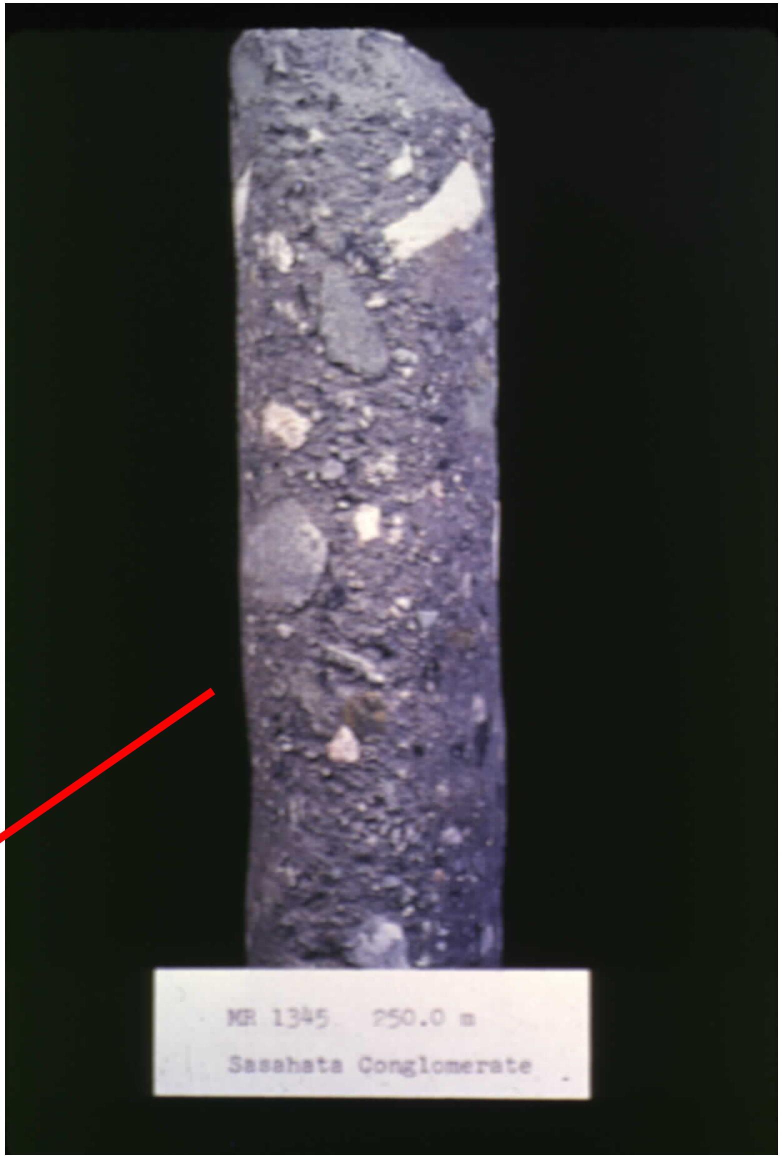
ISOPACHS AND INTRUSIVES SHOW BLOCK FAULTING IN HOKUROKU BASIN



FUJI, Mining Geol Sp Issu
1974

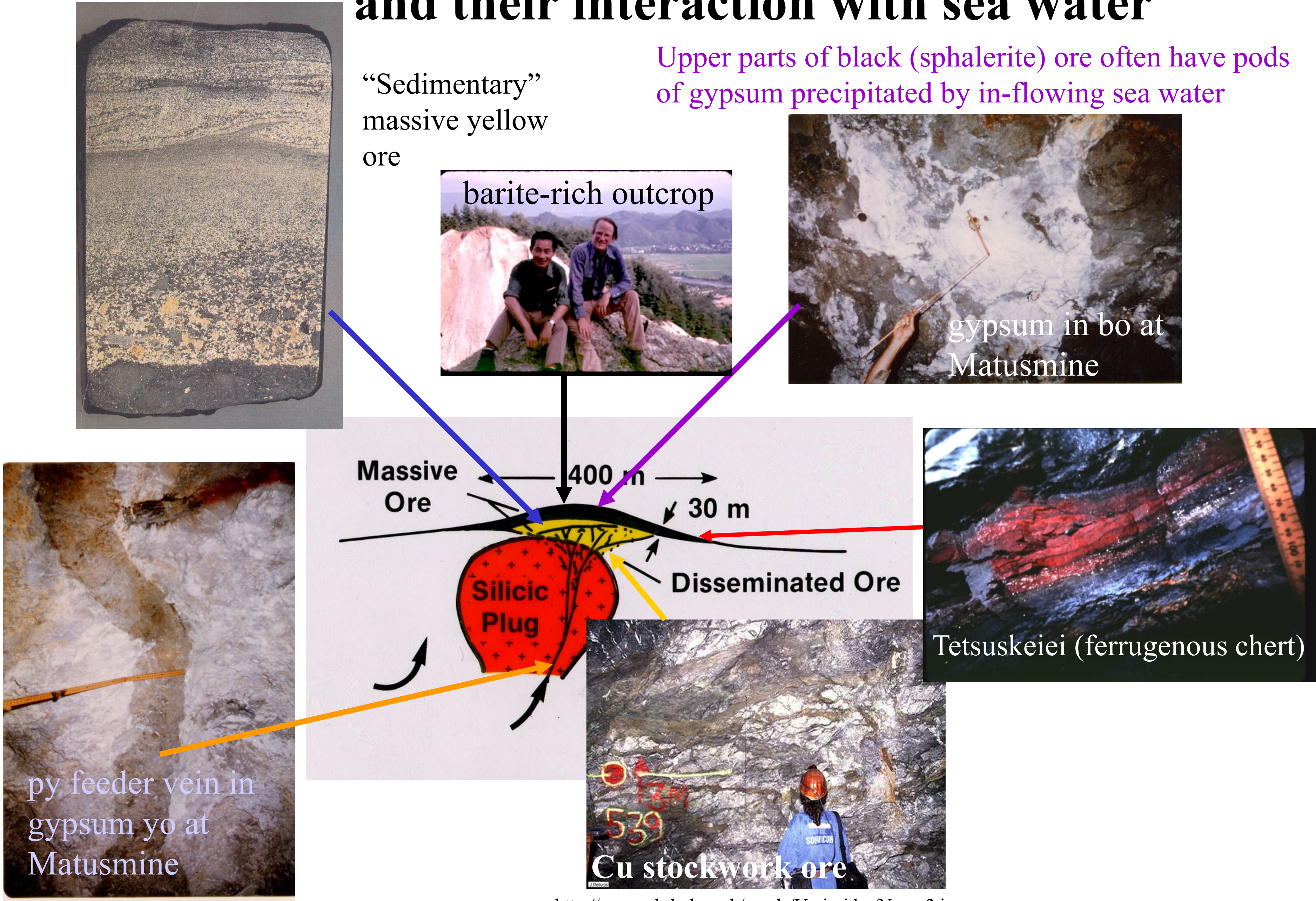
Hokuroku Basin initated rapidly





basal conglomerate

Kuroko VMS deposits zoned by venting fluids and their interaction with sea water



"Sedimentary" massive yellow ore

Upper parts of black (sphalerite) ore often have pods of gypsum precipitated by in-flowing sea water

barite-rich outcrop

gypsum in bo at Matusmine

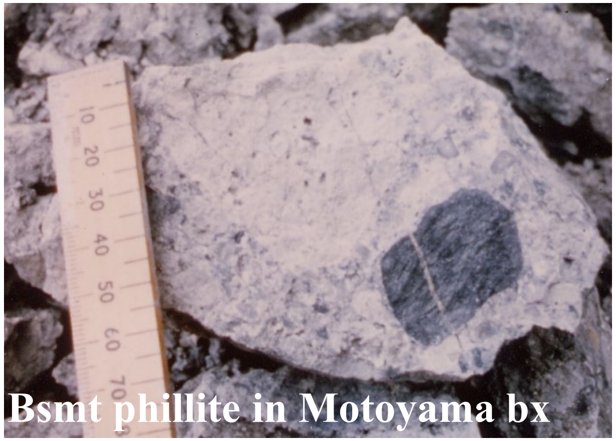
Tetsuskeiei (ferrugenous chert)

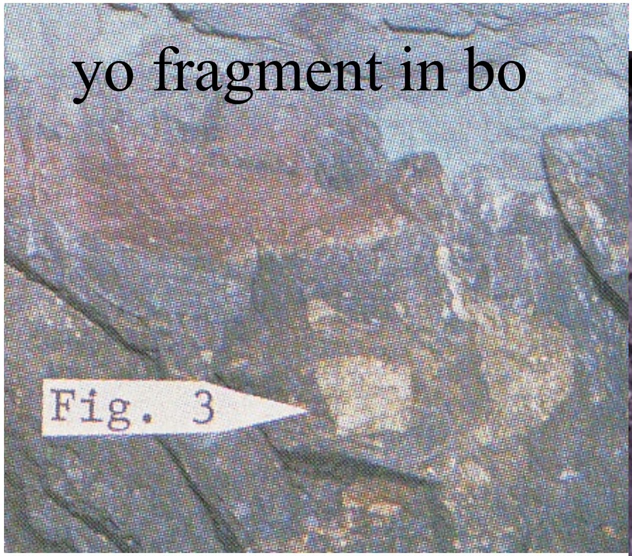
py feeder vein in gypsum yo at Matusmine

Cu stockwork ore

http://www.gl.rhul.ac.uk/geode/Variscides/Neves2.jpg

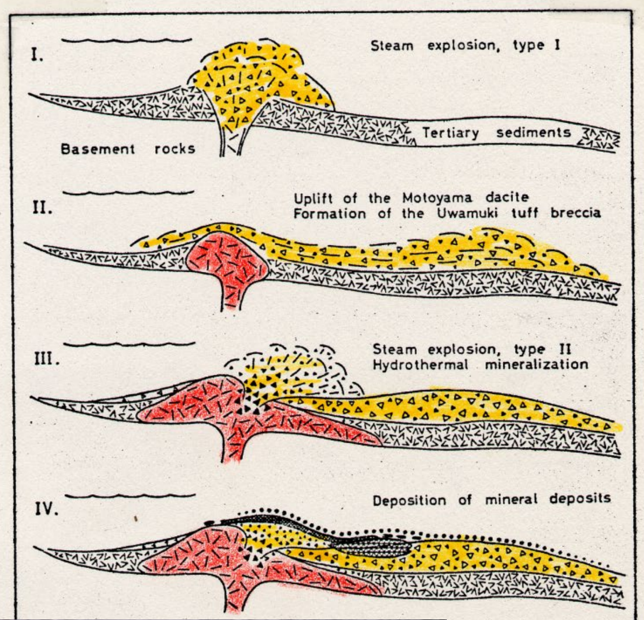
1. Lots of breccias
2. Sedimentary textures formed by slumping
3. Can be subsequently cemented


Bsmt phillite in Motoyama bx


yo fragment in bo


bx dike
Fukazawa

UWAMUKI TUFF BRECCIA CAN BE TRACED TO VENT AND UNDERLIES ORE AT KOSAKA

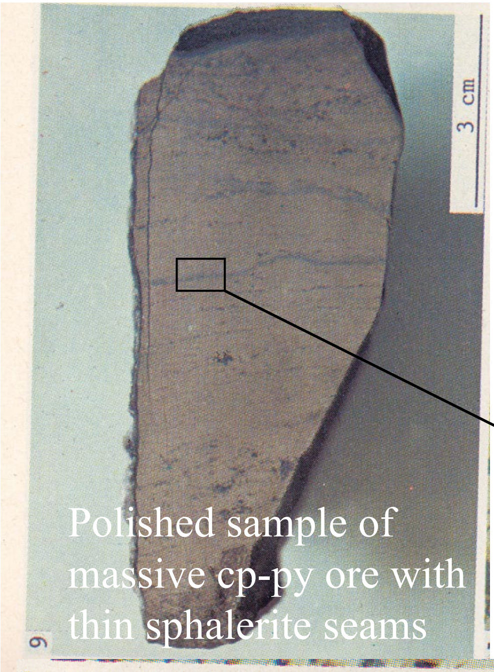


f development of the

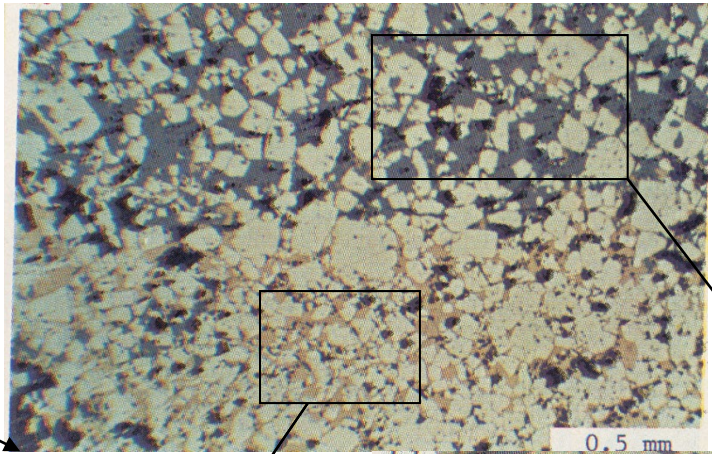
Horikoshi, Mineralium Deposita, 4, 1970

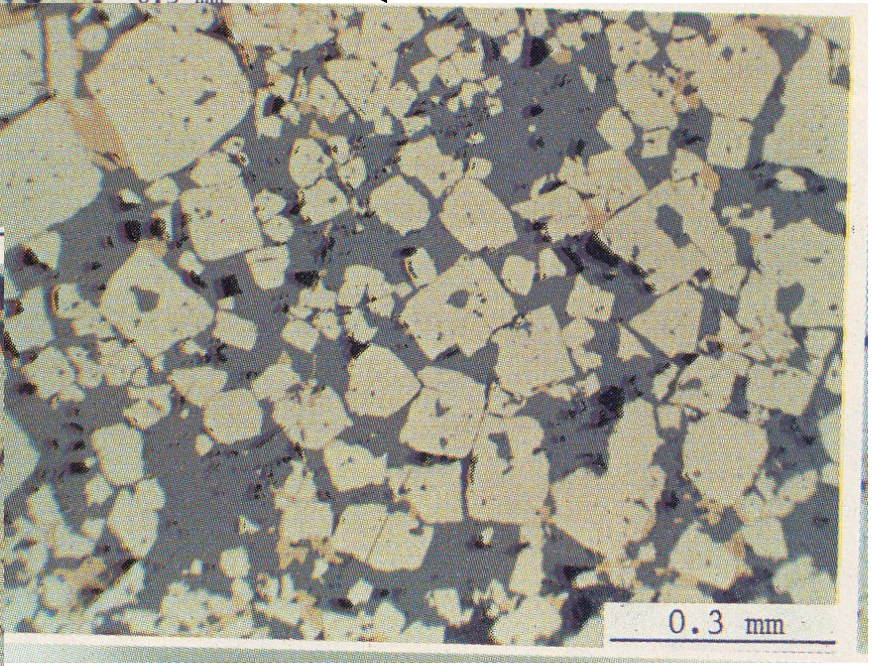
Monogr 5 (1983)

Cemented massive "sedimentary" ore

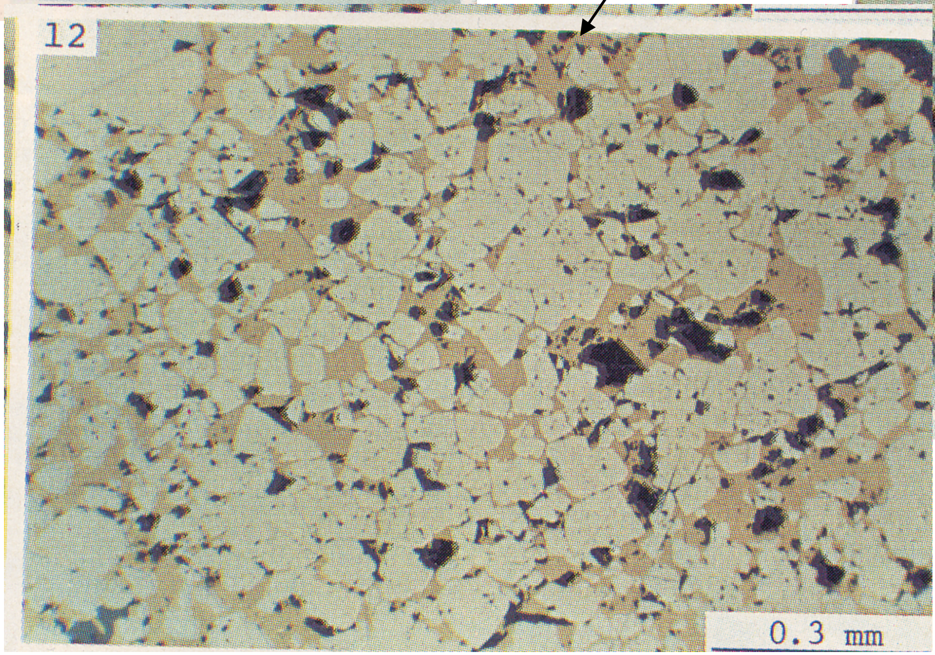


Polished sample of massive cp-py ore with thin sphalerite seams





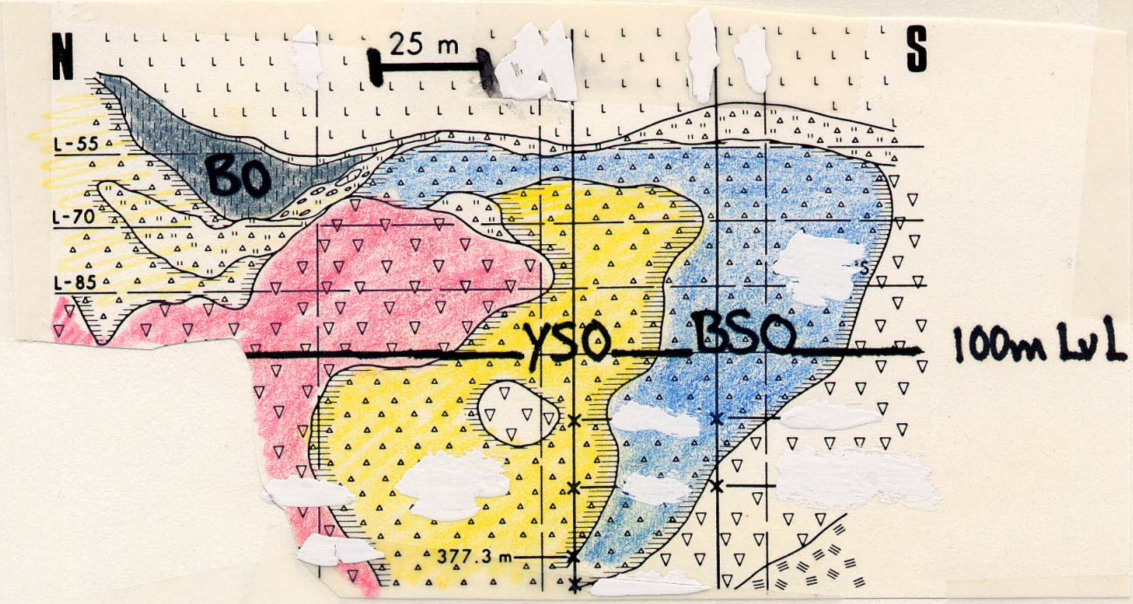
py cemented with sph

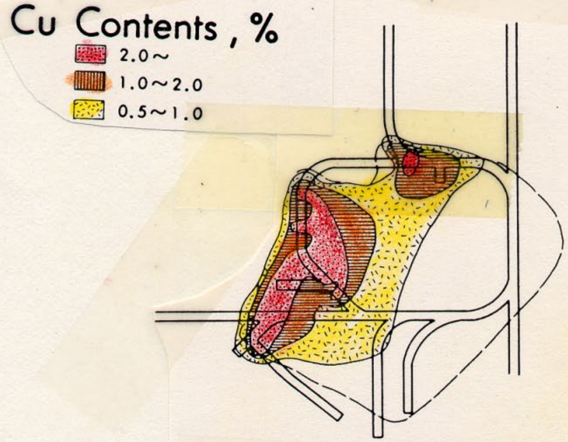


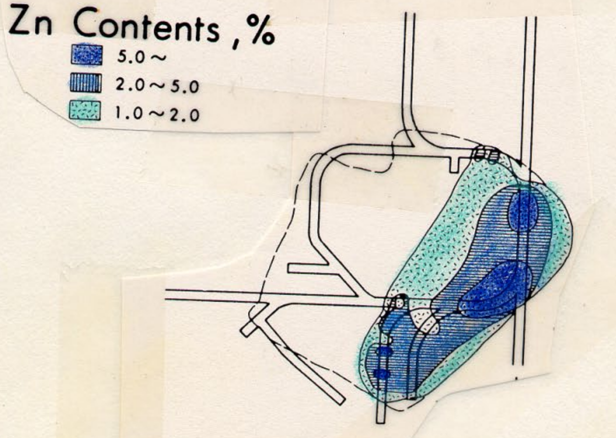
pyrite cemented with cp

Eldridge in Economic Geology Monogr 5 (1983)

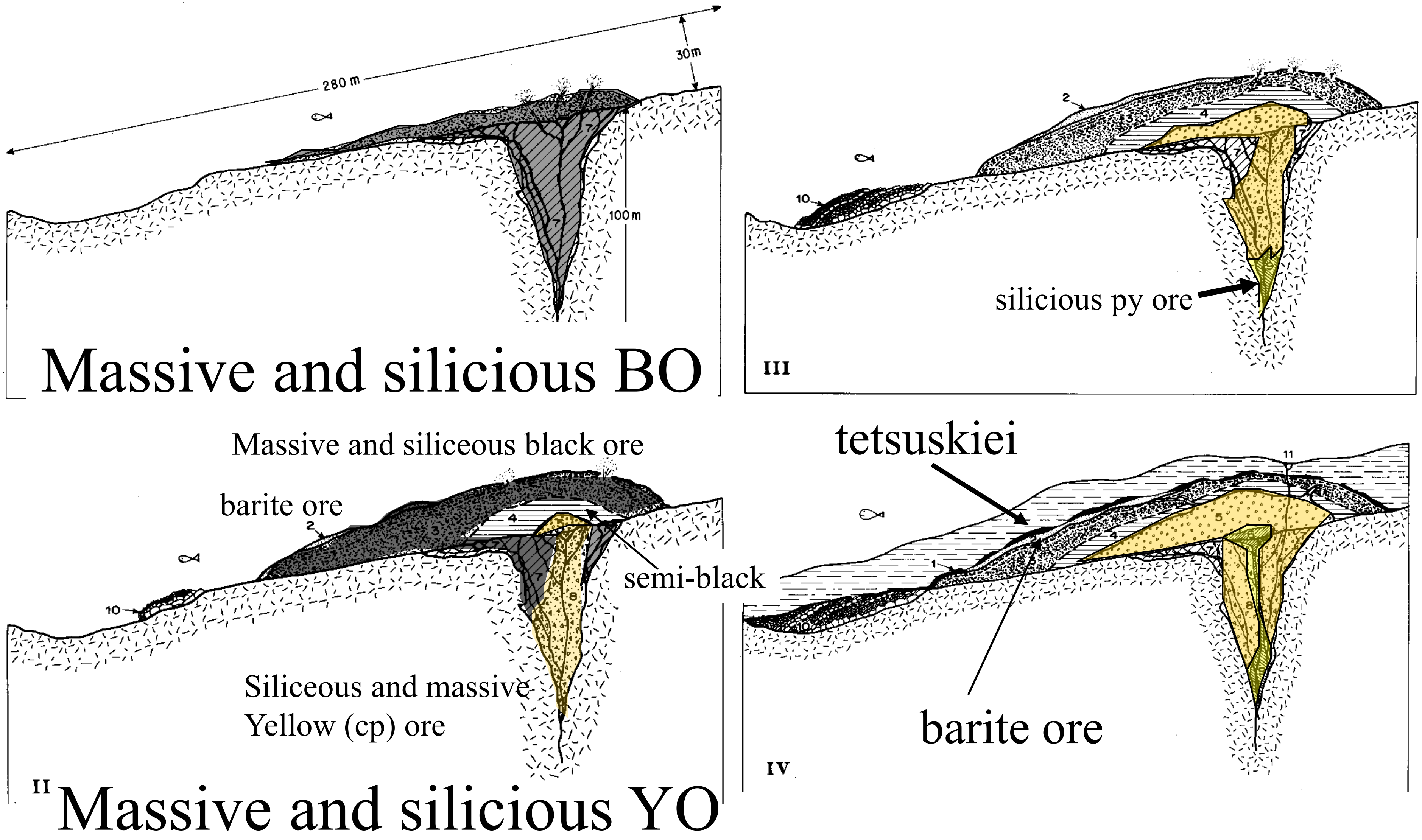
UWAMUKI #4 HAS BOTH BO & YO IN FEEDER PIPE







Zone refining of massive ore



Massive and silicious BO

silicious py ore

Massive and siliceous black ore

barite ore

semi-black

Siliceous and massive
Yellow (cp) ore

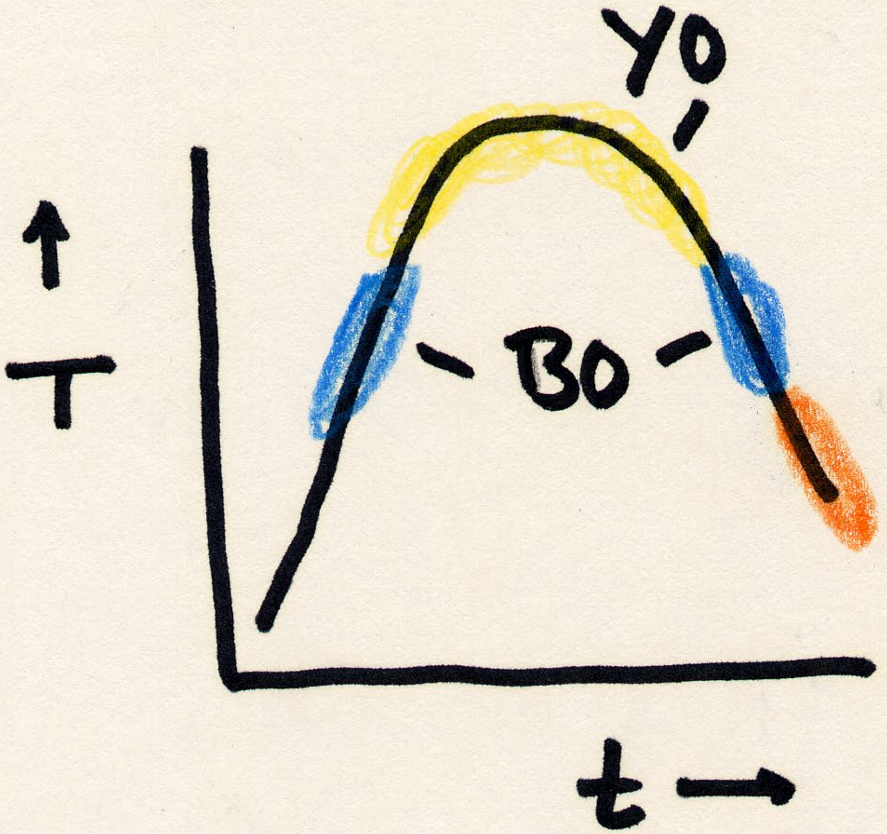
Massive and silicious YO

tetsuskiei

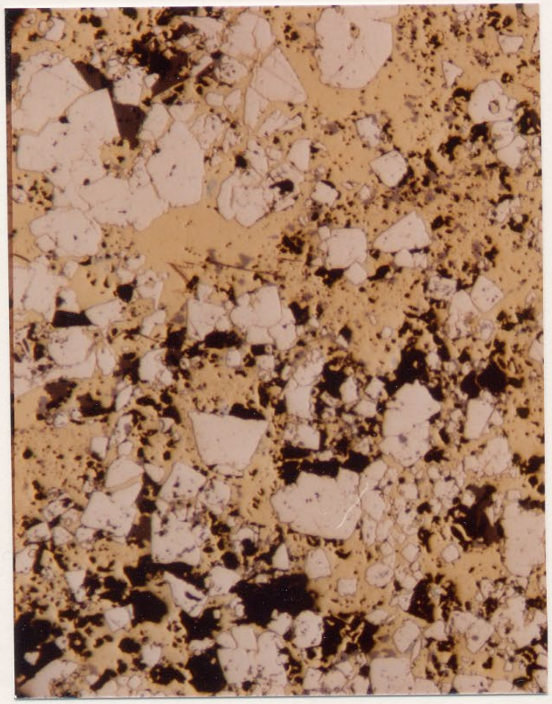
barite ore

Eldridge et al, Monograph 5, 1983

THERMAL HISTORY DETERMINES MINEROLOGY



MASSIVE YELLOW ORE FROM FURUTOBE HAS ROUNDED PY REPLACED BY CP AND GREATER POROSITY THAN BO



Eldridge, 1981

Chalcopyrite disease

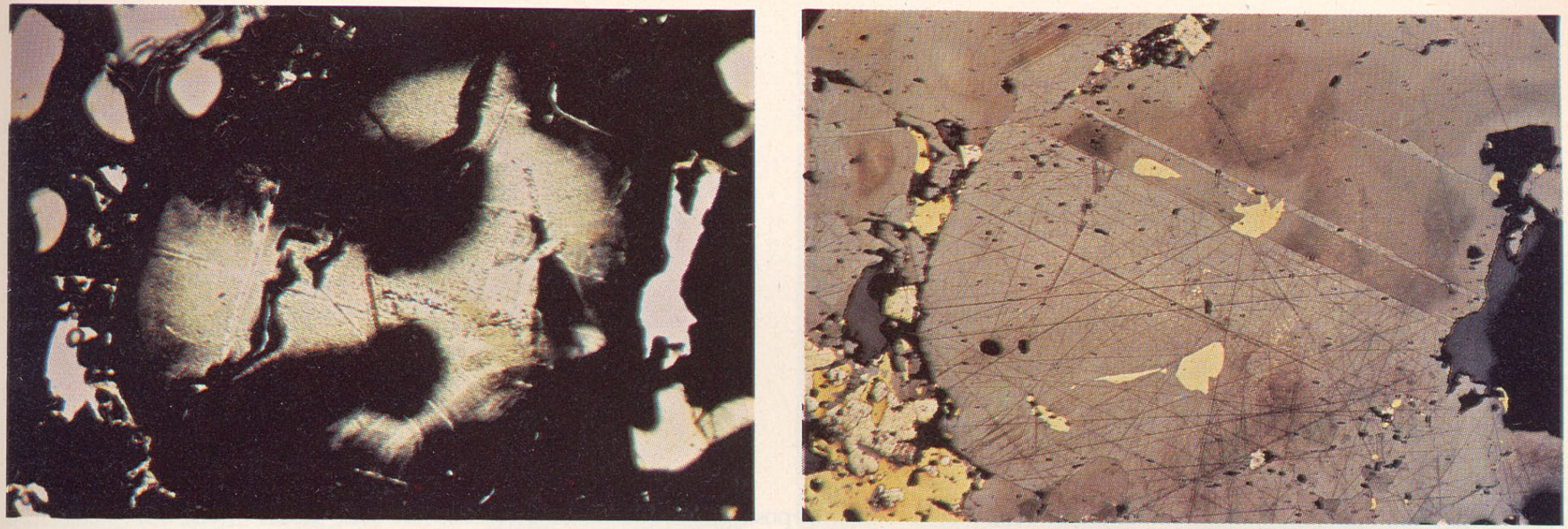


FIG. 24a and b

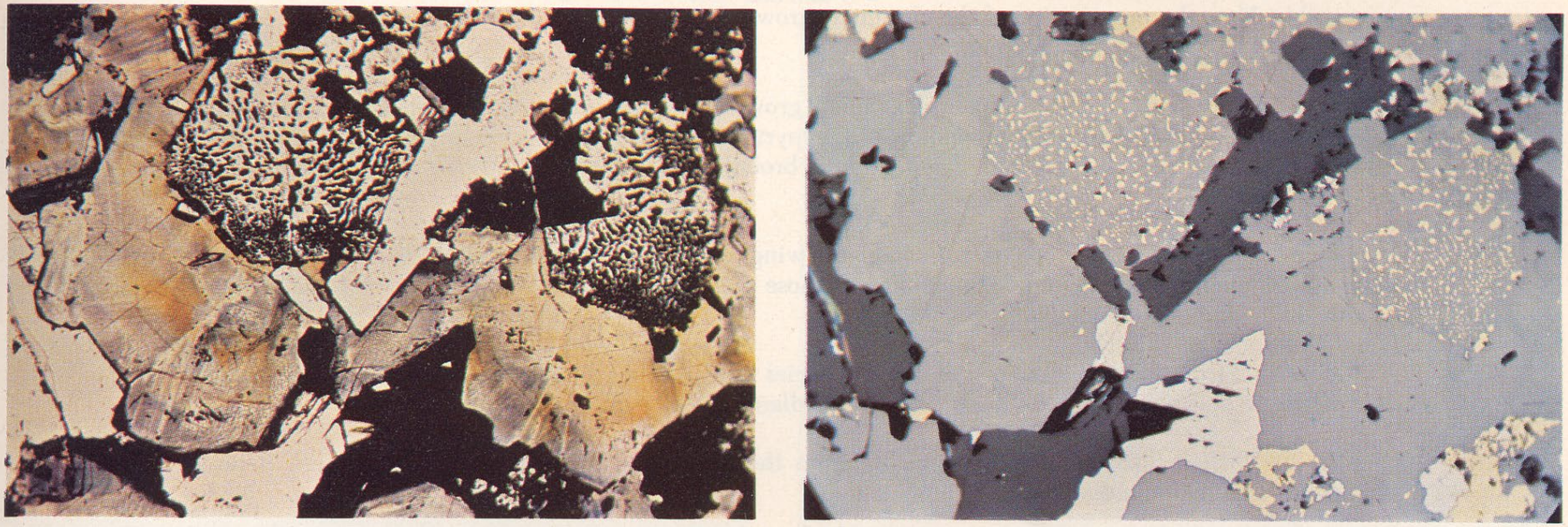
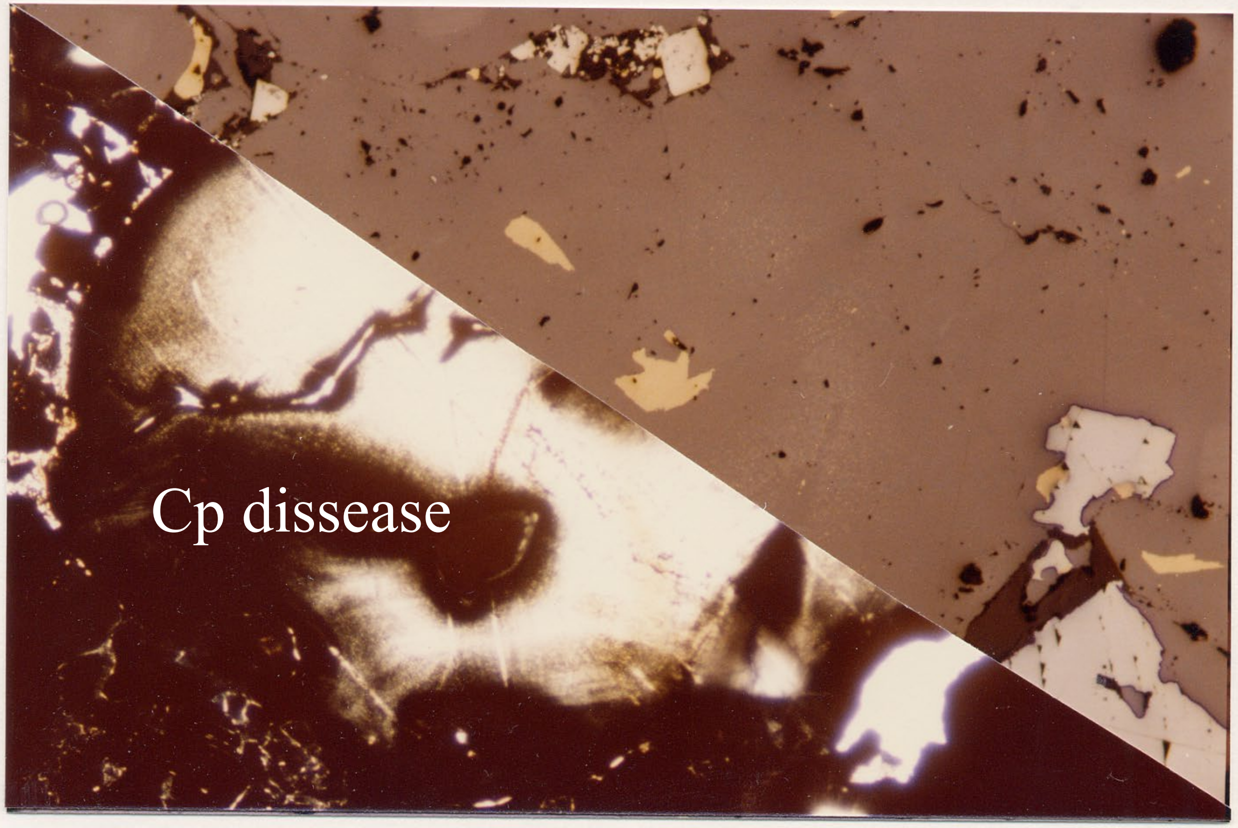


FIG. 25a and b

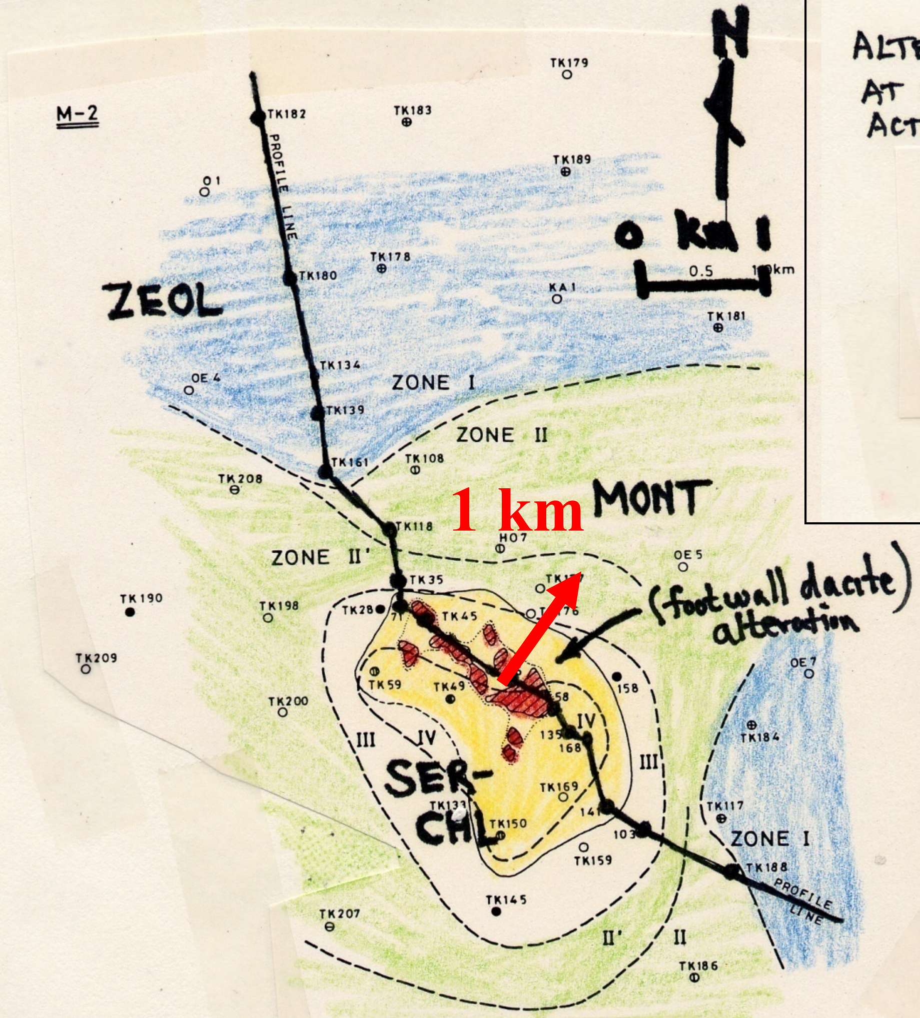
Eldridge in Economic Geology Monogr 5 (1983)

CHALCOPYRITE DISSEASE IN UWAMUKI #4 BO SPHALERITE



Eldridge, 1981

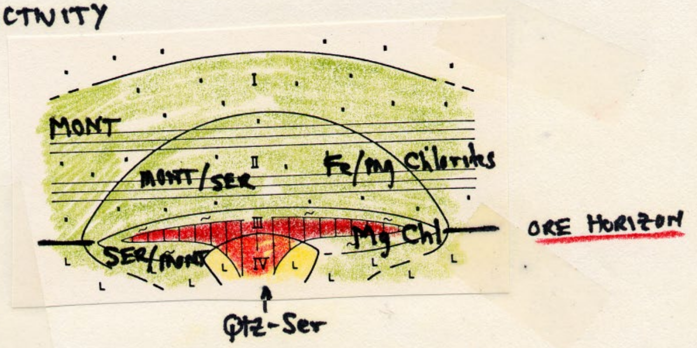
ALTERATION MINEROLOGY IS REGULARLY ZONED AROUND FUKAZAWA



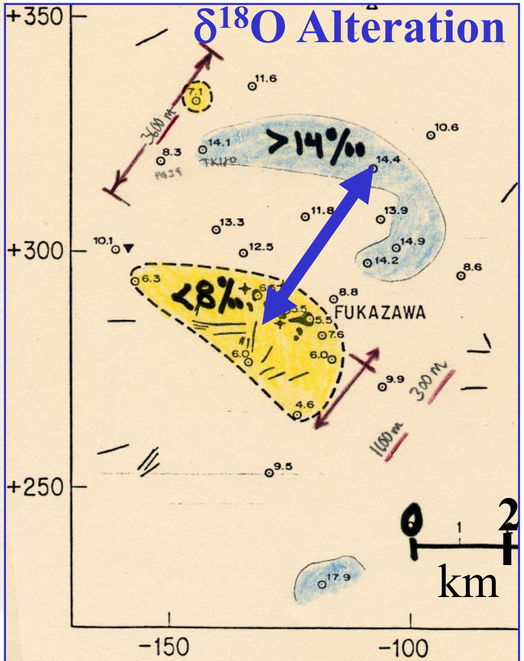
Date et al, 1983

ALTERATION EXTENDS INTO HANGING-WALL AT MATSUMINE REQUIRING CONTINUED HYDROTHERMA

ACTIVITY

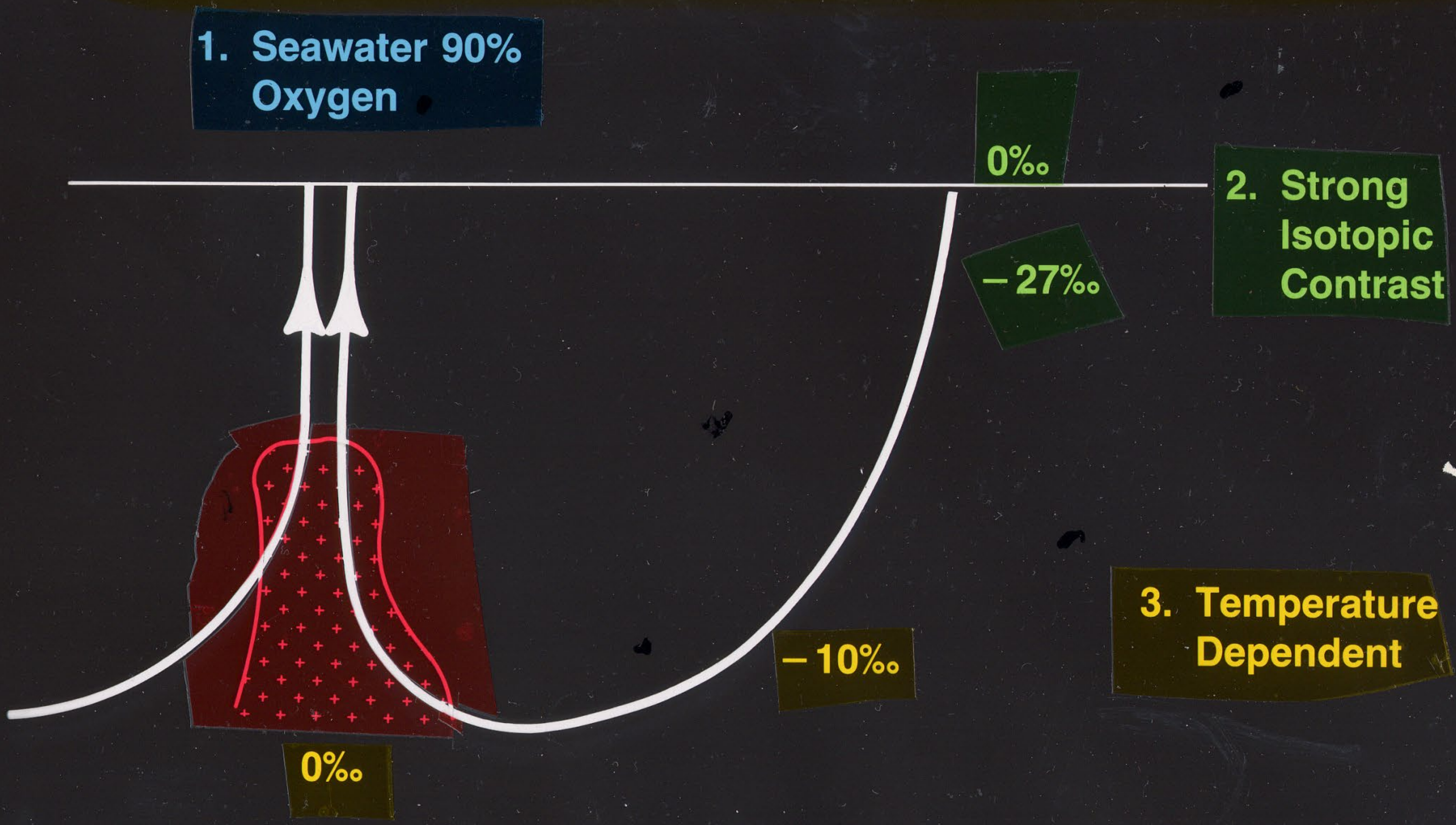


Shirozu (1974)



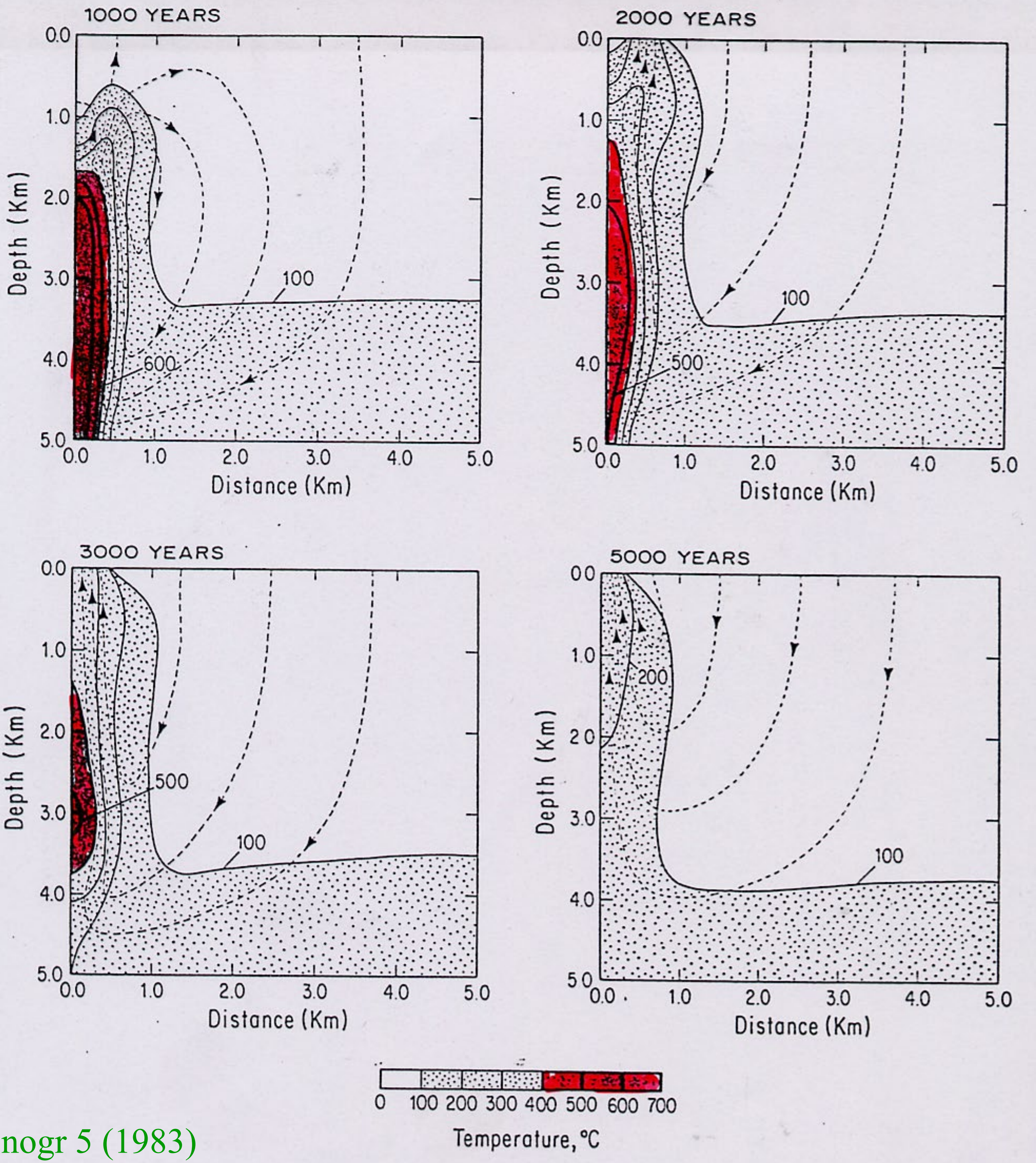
4 km

Oxygen Isotopic Alteration is Best Candidate for Intake Halo Definition



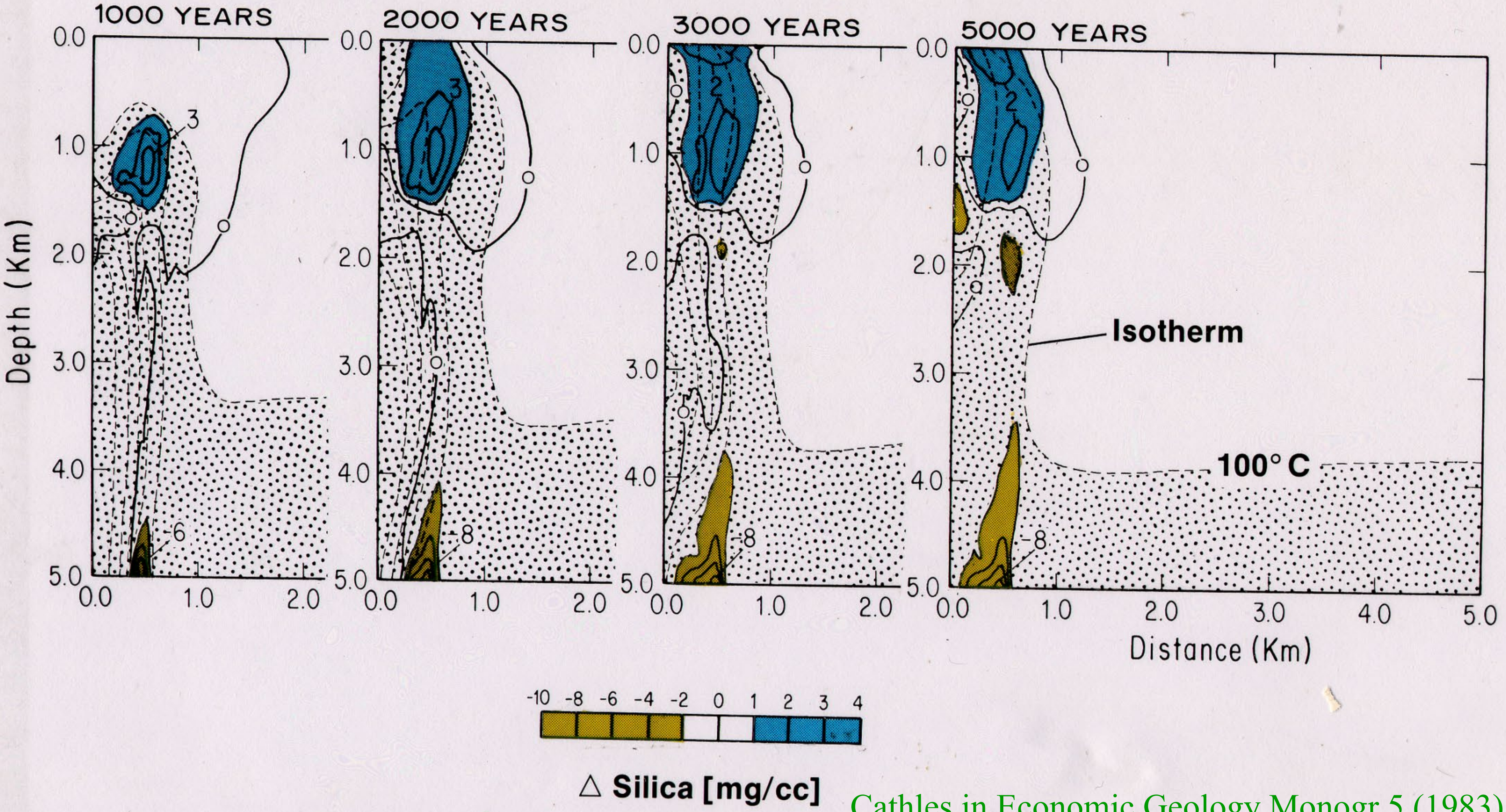
1. Seawater 90% Oxygen
2. Strong Isotopic Contrast
3. Temperature Dependent

Model Intrusion-driven convection



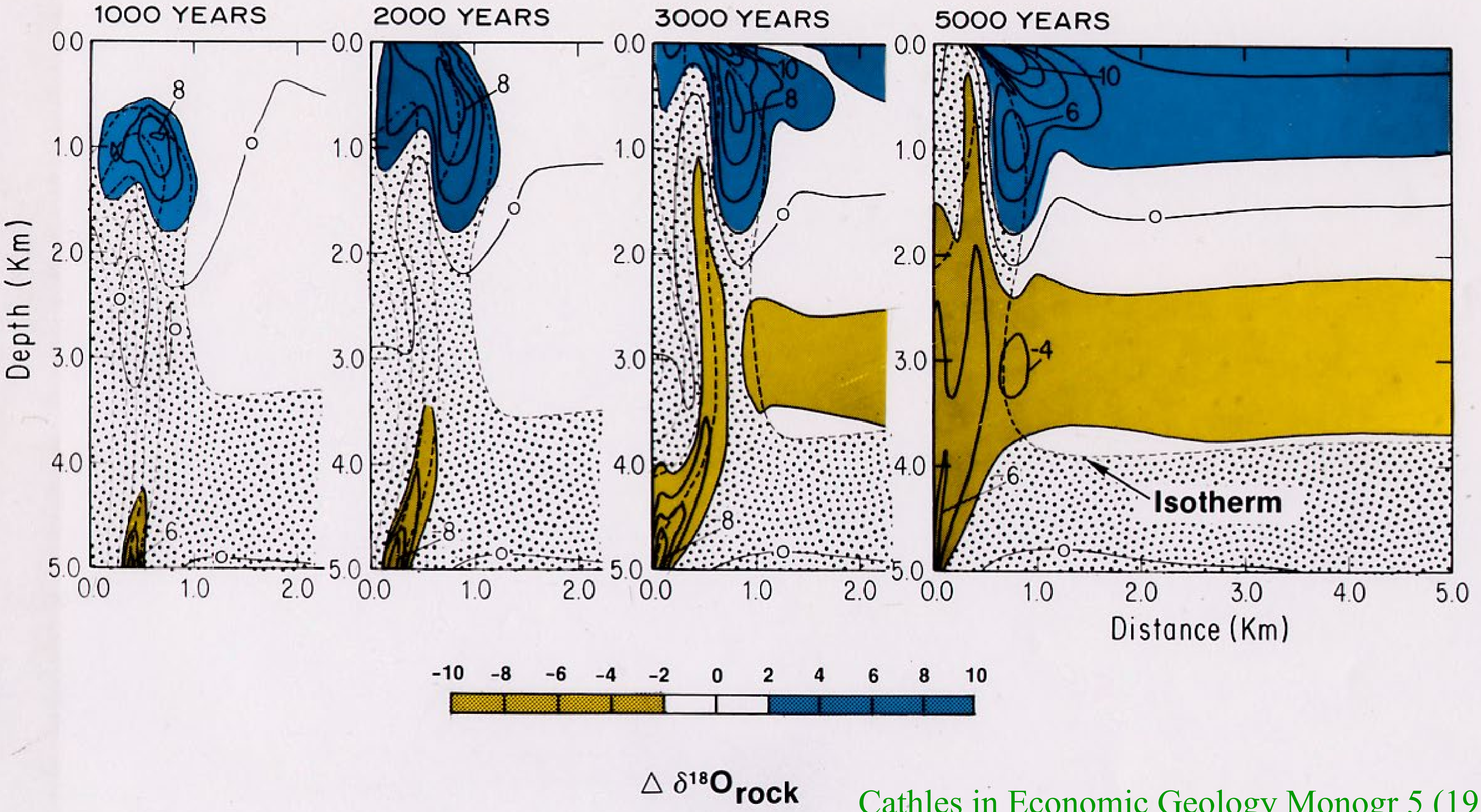
Cathles in Economic Geology Monogr 5 (1983)

A Chemical Model Can Be Added to the Physical Base



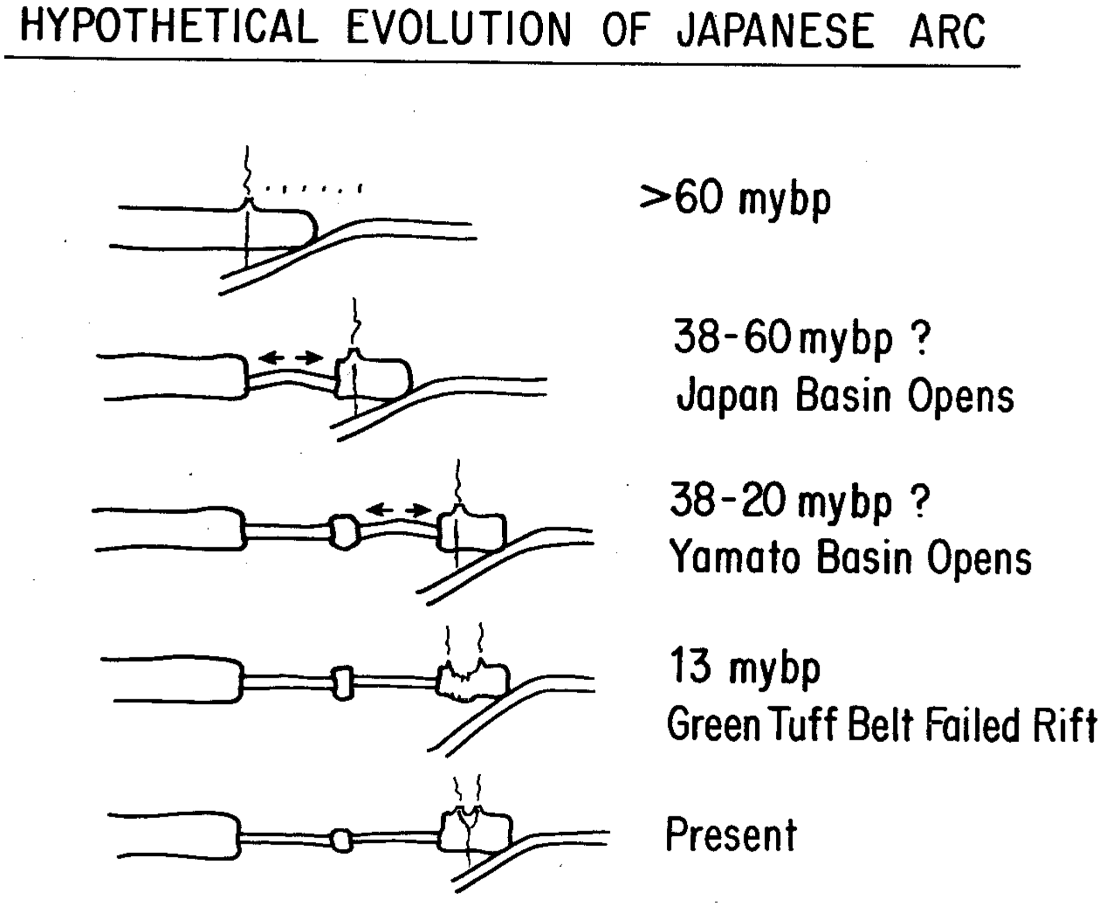
Cathles in Economic Geology Monogr 5 (1983)

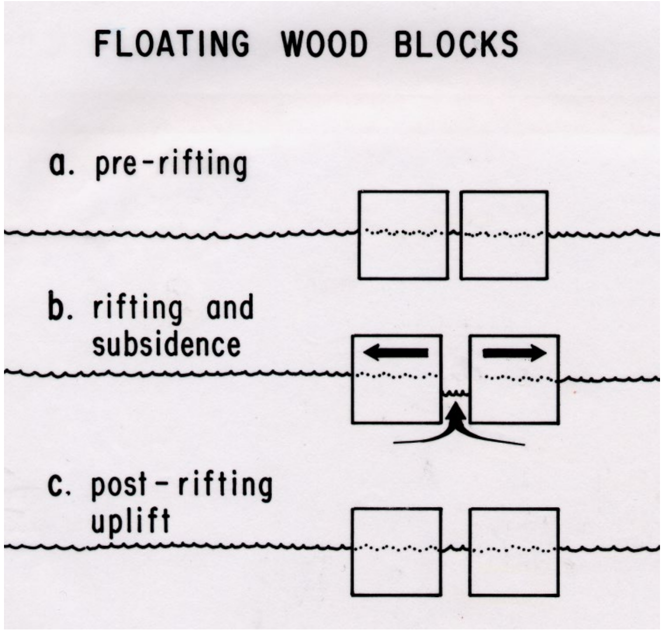
The Predicted Intake Halo Is a Distinctively Layered Heavy/Light Pair



Cathles in Economic Geology Monogr 5 (1983)

Failed rift produced VMS

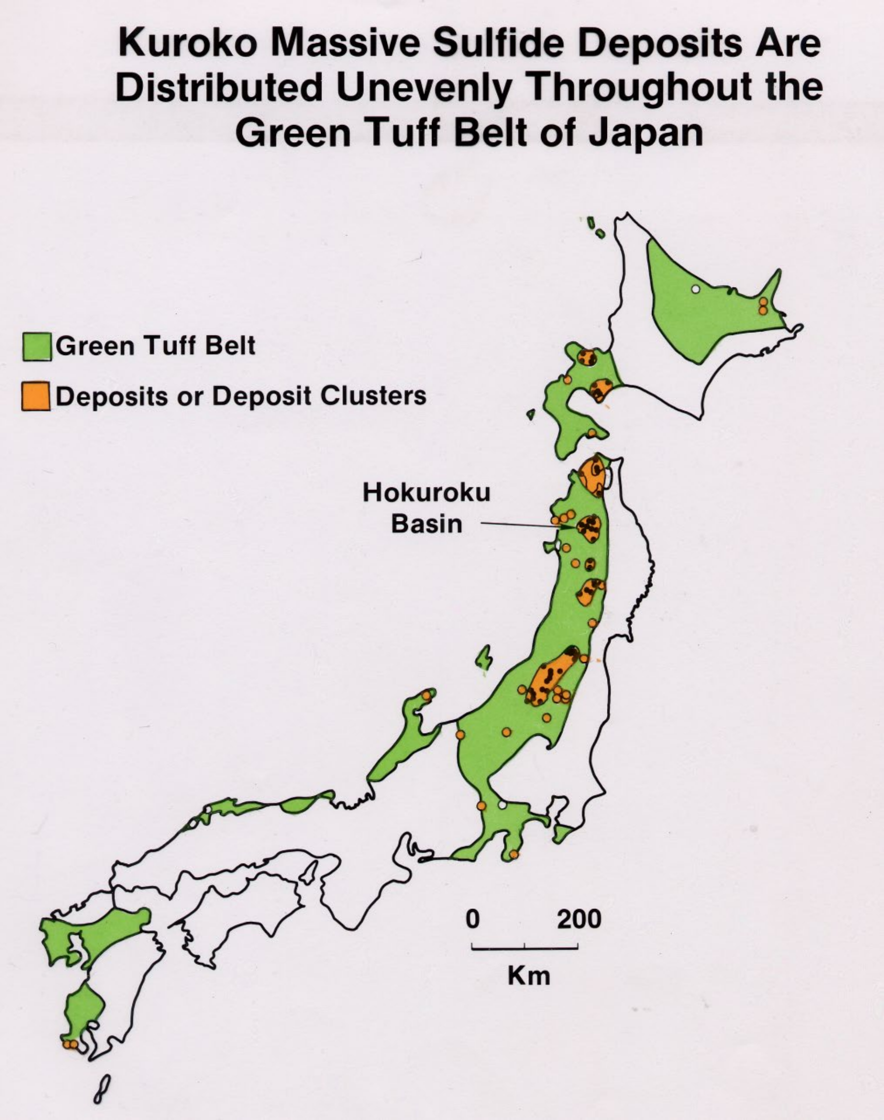


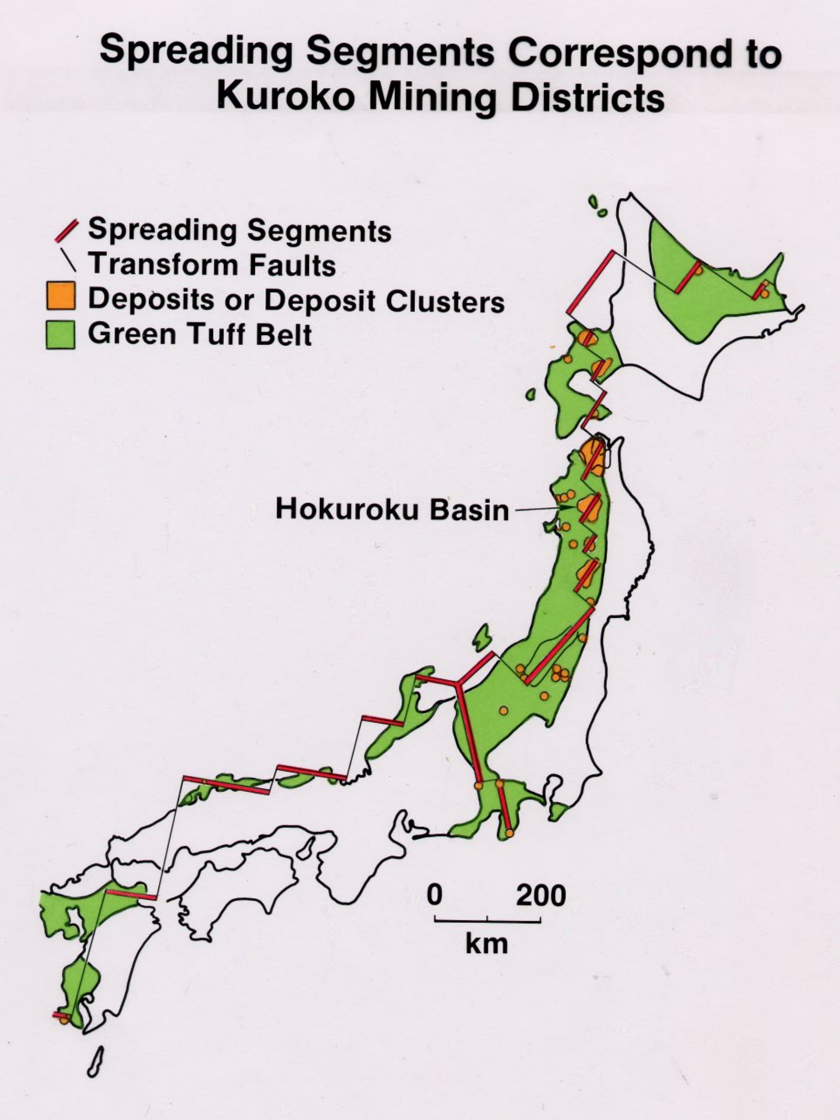


Vertical movements due to dynamic loss of fluid head

Cathles et al. in Economic Geology Monogr 5 (1983)

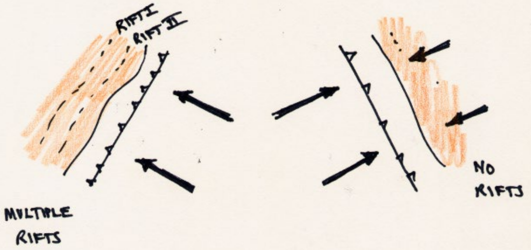
Mid-Miocene aborted rifting of Japan


Kuroko Massive Sulfide Deposits Are Distributed Unevenly Throughout the Green Tuff Belt of Japan

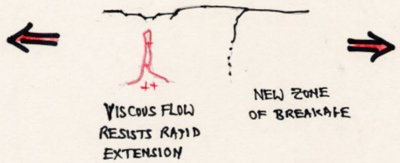

Spreading Segments Correspond to Kuroko Mining Districts

Cathles et al. in Economic Geology Monogr 5 (1983)

REGIONS WILL BE RIFT PRONE (AND PROSPECTIVE) OR RIFT IMMUNE



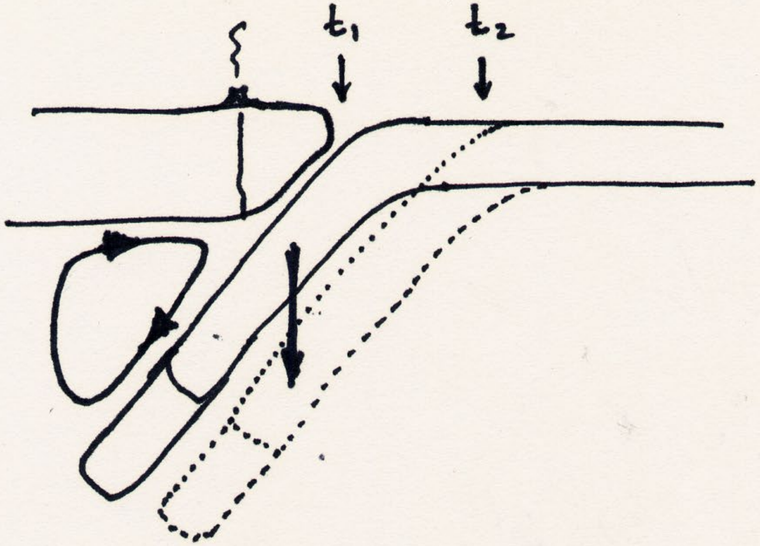
MULTIPLE RIFTING MAY OCCUR BECAUSE RIFTS BECOME STRONGER THAN SURROUNDING AREAS WHEN MAGMAS INTRUDE



ALL RIFTS GOOD BUT FAILED RIFTS PRESERVE ORE DEPOSITS

ORE DEPOSITS IMBEDDED IN CRATON AT OR SOMEWHAT BELOW SEA LEVEL

CONVECTION AND TRENCH MIGRATION (TRENCH SUCTION) PUTS ARC IN TENSION UNLESS CONTINENT MOVES OCEANWARD



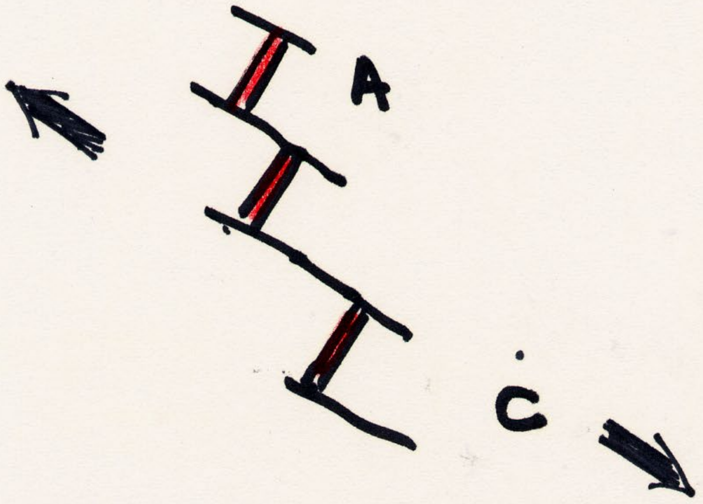
RIFT PRONE : WEST PACIFIC
CENTRAL AMERICA

RIFT IMMUNE : EAST PACIFIC <u>EXCEPT</u>
CENTRAL AMERICA

IN RIFT, ONE TIME (SPREADING PULSE) GENERALLY PRODUCES BEST DEPOSITS

- LOOK FOR TIME HORIZON
- LOOK FOR EVIDENCE OF RAPID SUBSIDENCE

TIME HORIZON WILL APPLY TO ALL MINING DISTRICTS IN A RIFT SYSTEM



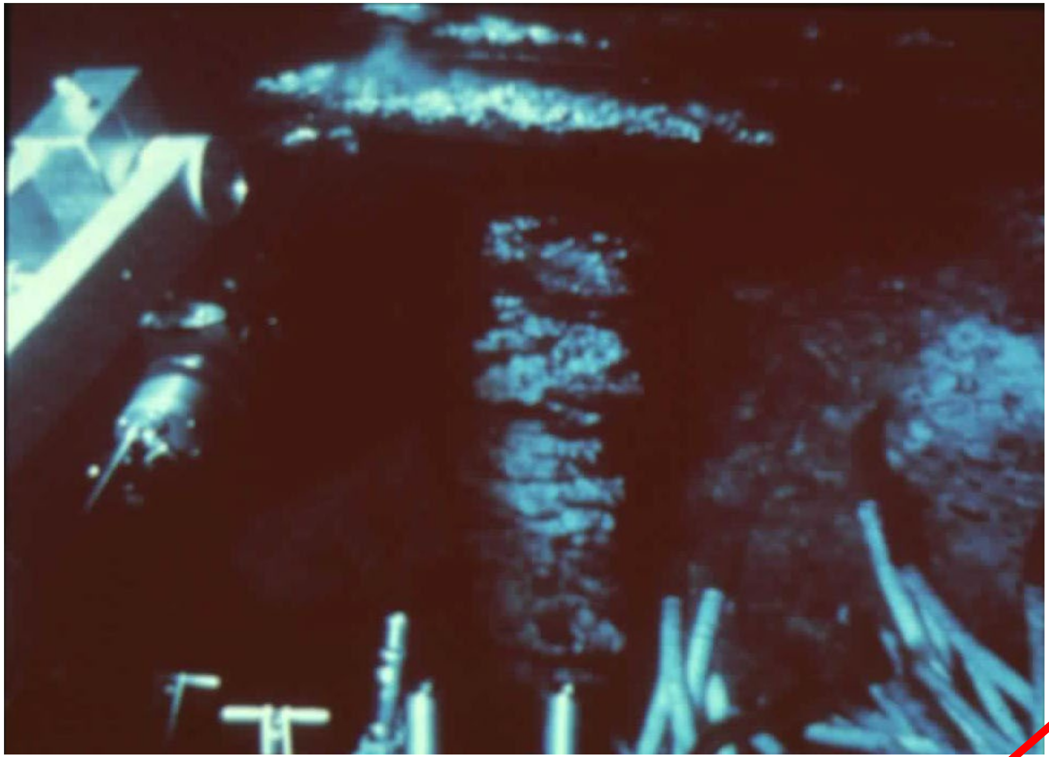
- EXTENSIONAL PULSE APPLIES EVERYWHERE ALONG PLATE BOUNDARY

- ONE GOOD DISTRICT SUGGESTS OTHER DISTRICTS ALSO GOOD

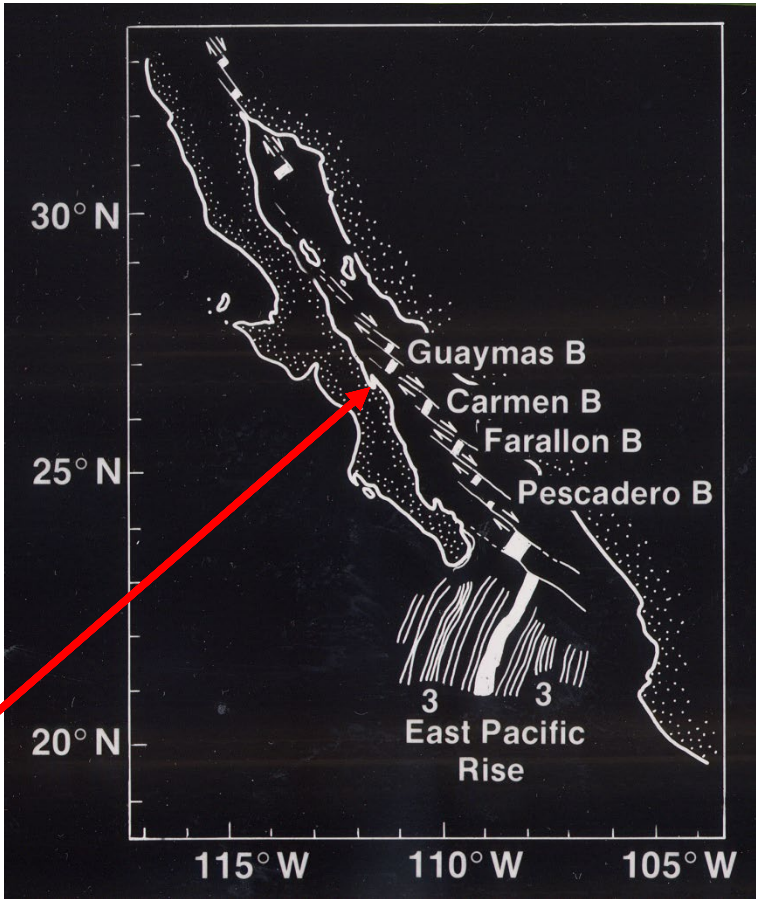
MINING CAMPS SHOULD BE LOCAL DEPRESSIONS LIKE GUAYMAS BASIN

- FOLLOW TURBIDITE FLOWS INTO DISTRICT

Spreading centers are “basins”

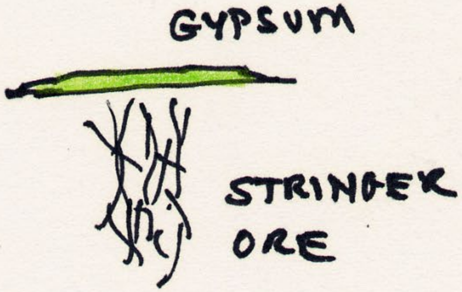


Black smoker chimney in Guaymas Basin



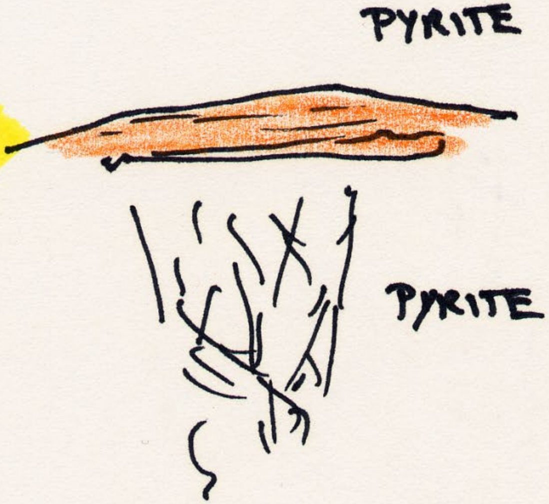
STAGE OF EVOLUTION CAN BE IMPORTANT

DIED TOO YOUNG



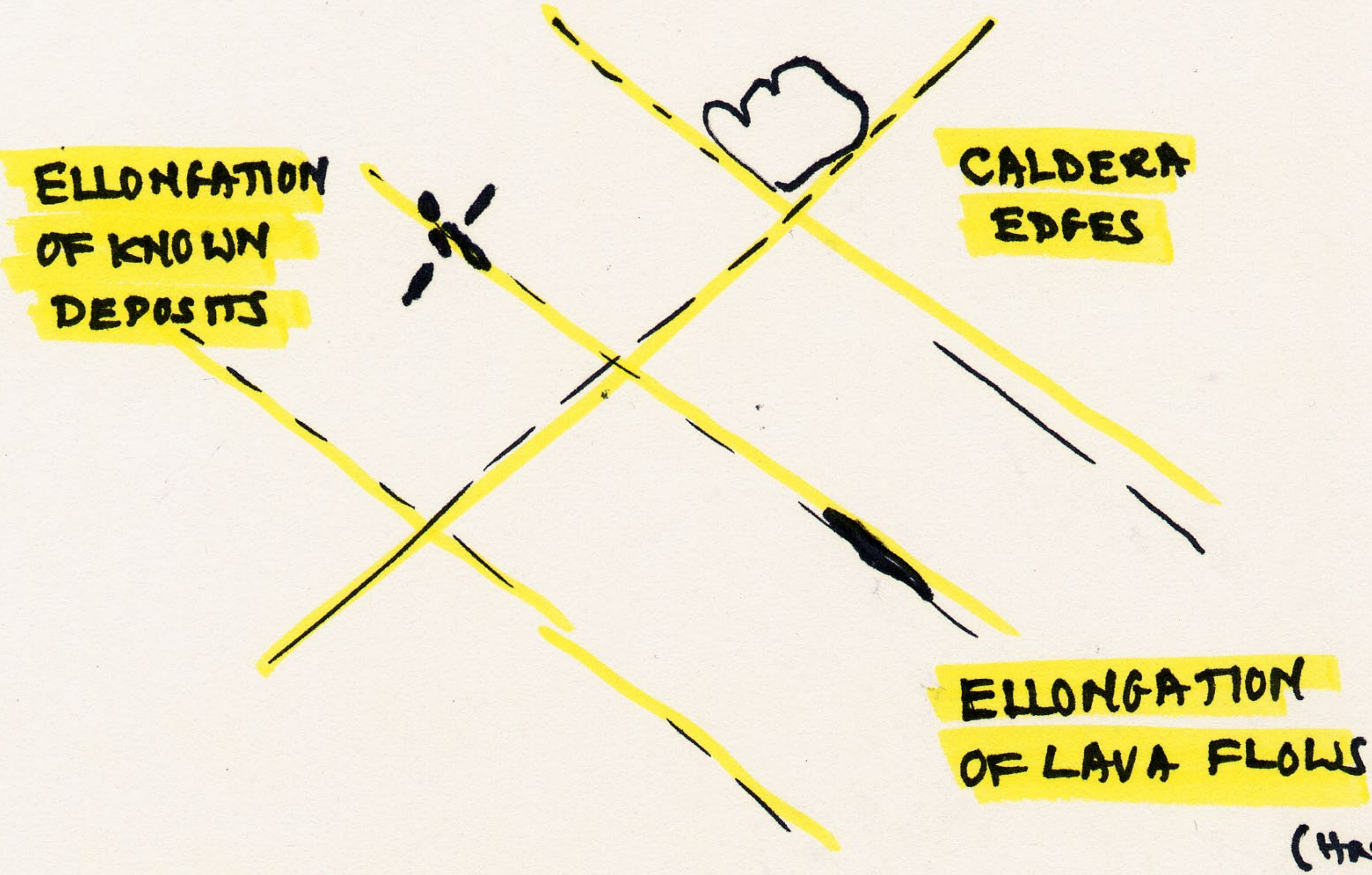
- MAY NEVER HAVE HAD MASSIVE SULFIDE CAP

LIVED TOO LONG



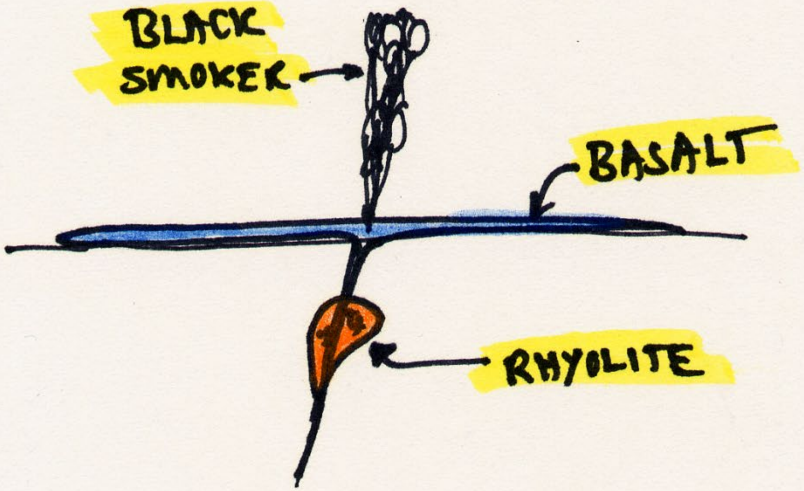
- ALL BASE METALS MAY BE FLUSHED

IDENTIFY AND USE PERMEABLE STRUCTURES IN EXPLORATION



(Hashimoto)

LOCALLY MAFIC AND FELSIC MAGMAS EQUALLY PROSPECTIVE



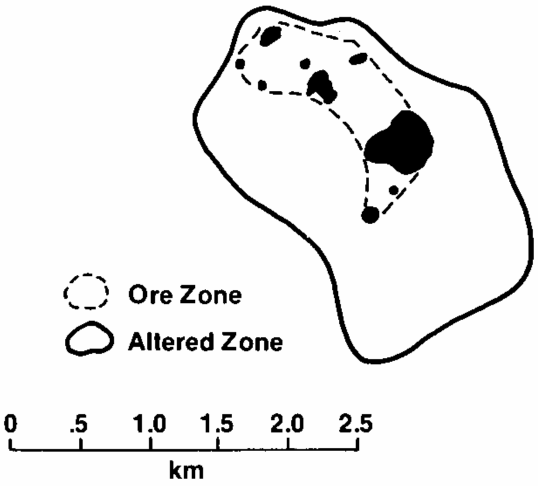
- ALL FLUIDS USE SAME PERMEABLE STRUCTURES

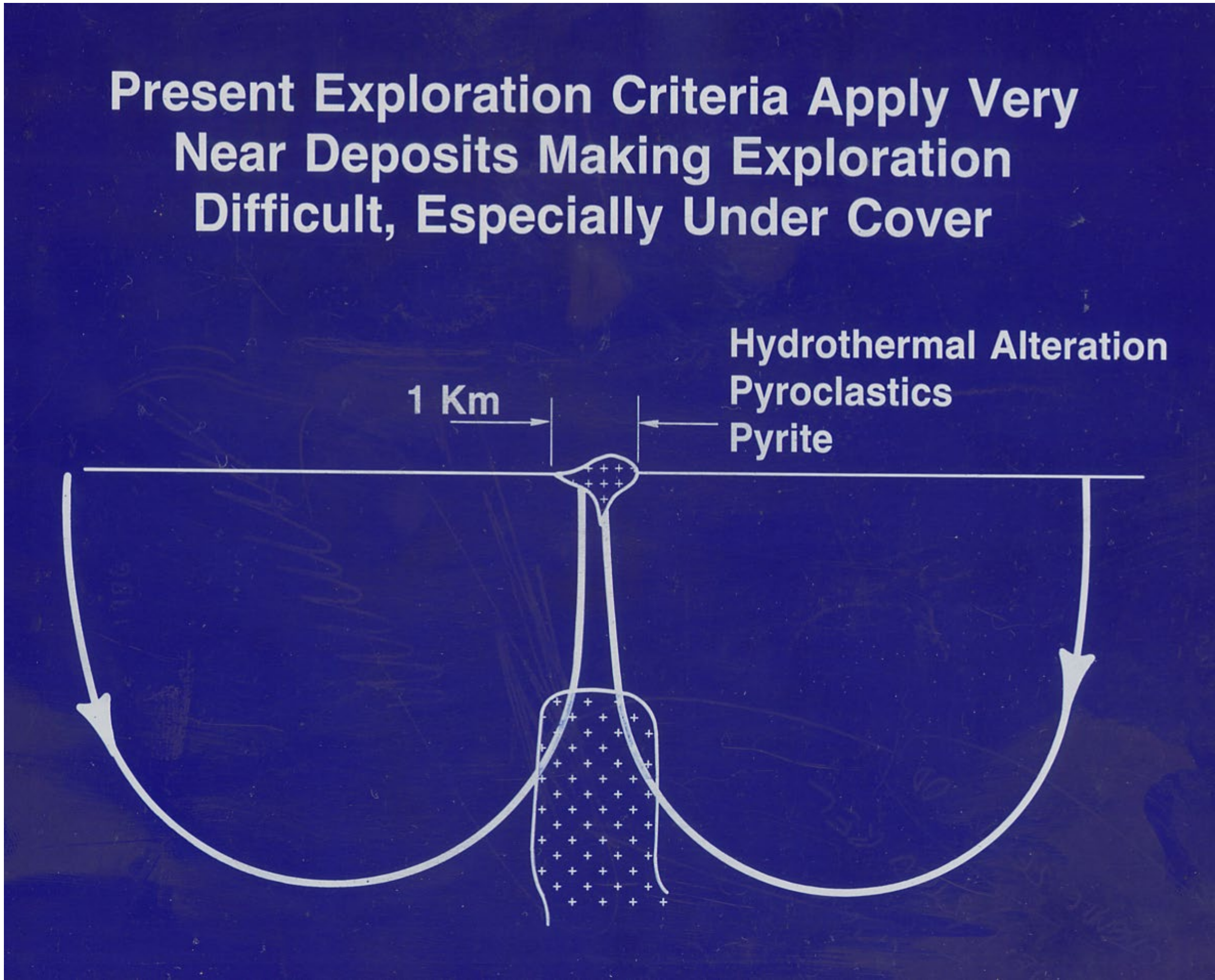
(Horikoshi Sr + Jr)

Volcanogenic Massive Sulfide Deposits Are Hard to Find Because Their Hydrothermal Alteration Halo Is Not Much More Extensive Than the Deposits

Intake alteration huge target compared to discharge alteration

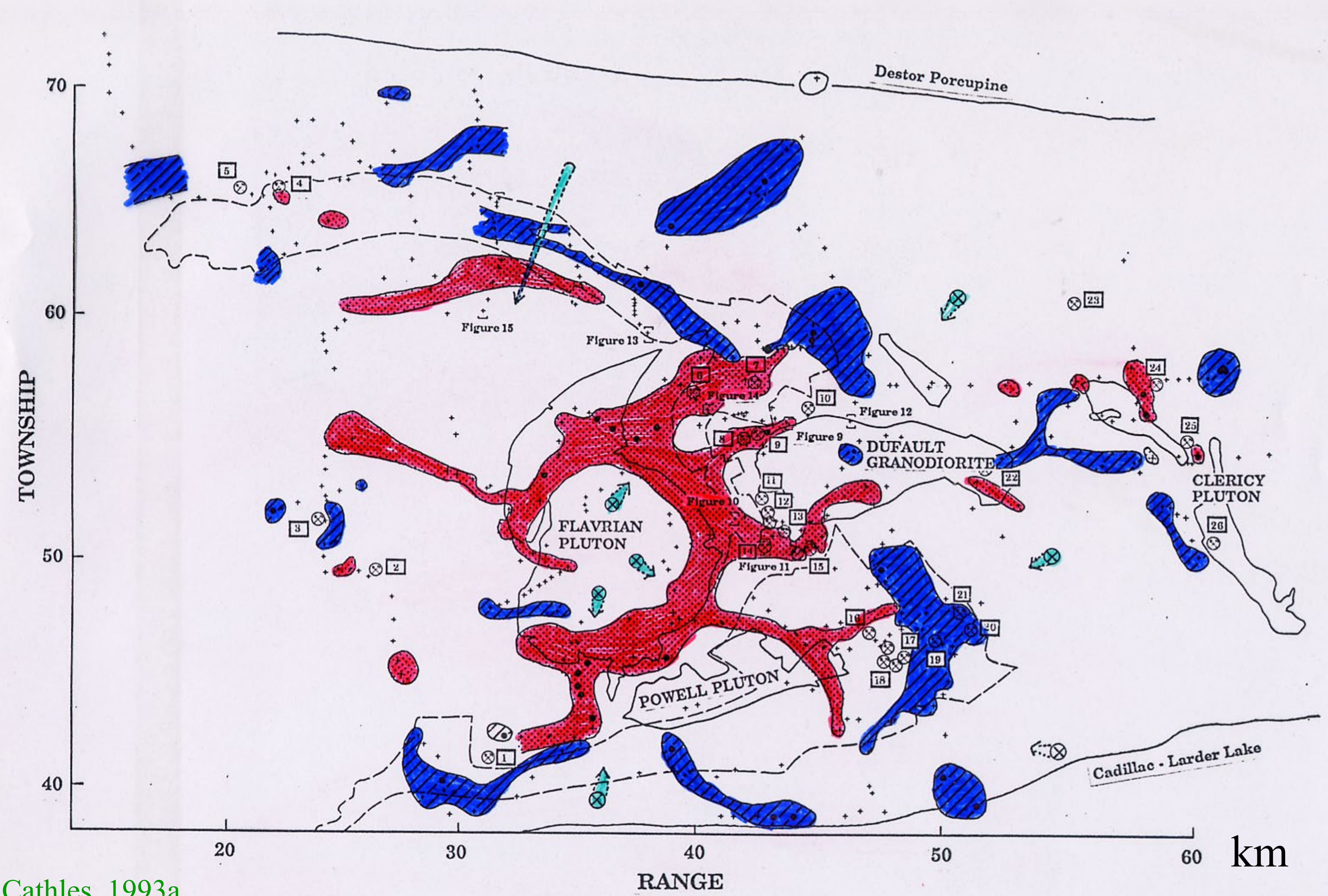
Fukazawa Deposits, Japan





Present Exploration Criteria Apply Very Near Deposits Making Exploration Difficult, Especially Under Cover

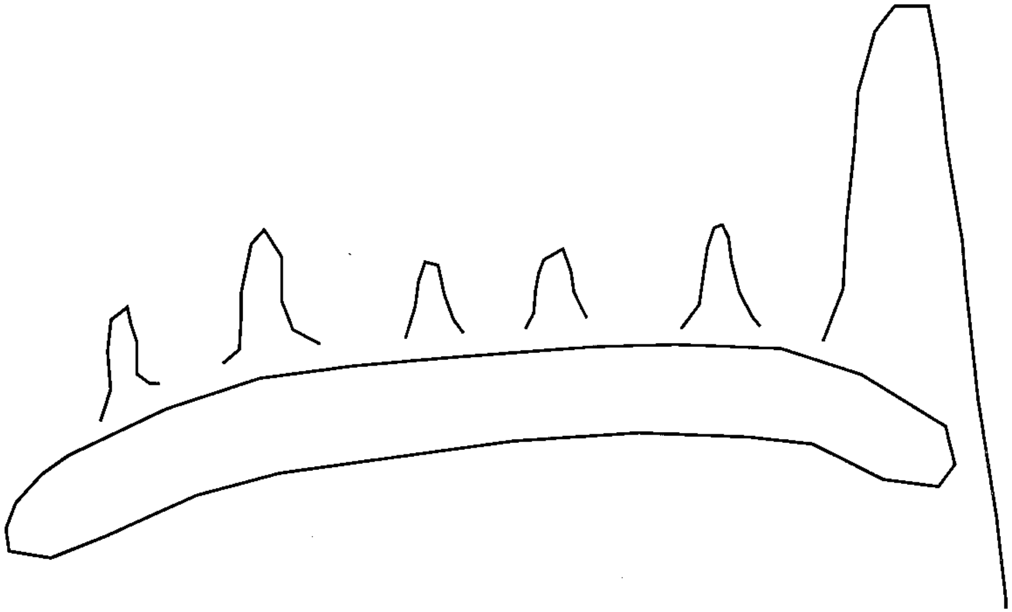
Noranda VMS Intrusion lit up like isotopic light bulb



km

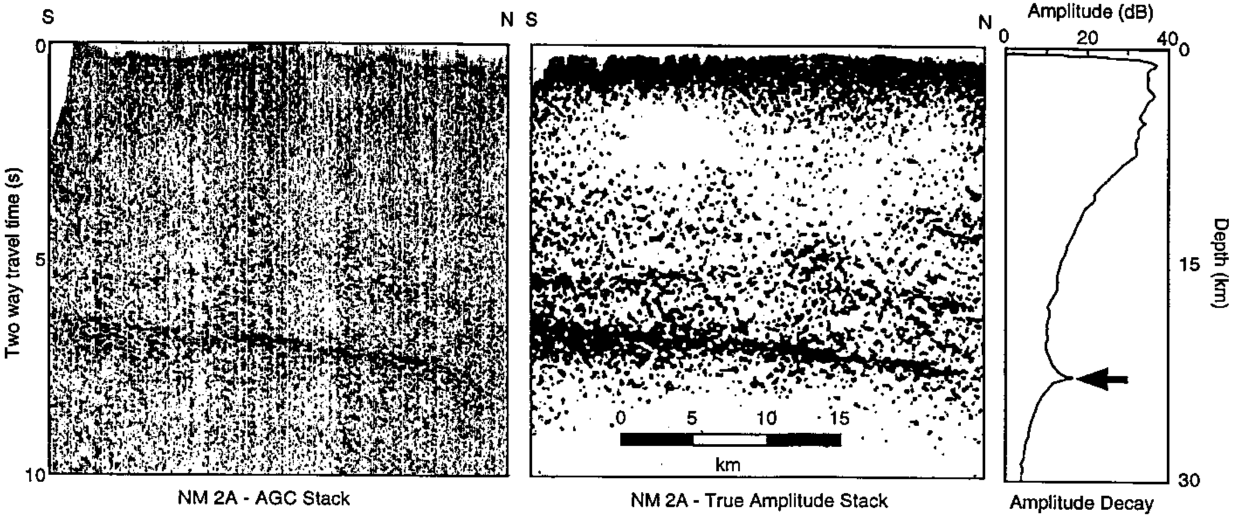
Cathles, 1993a

Sills Can Explain Critical Features of VMS Districts



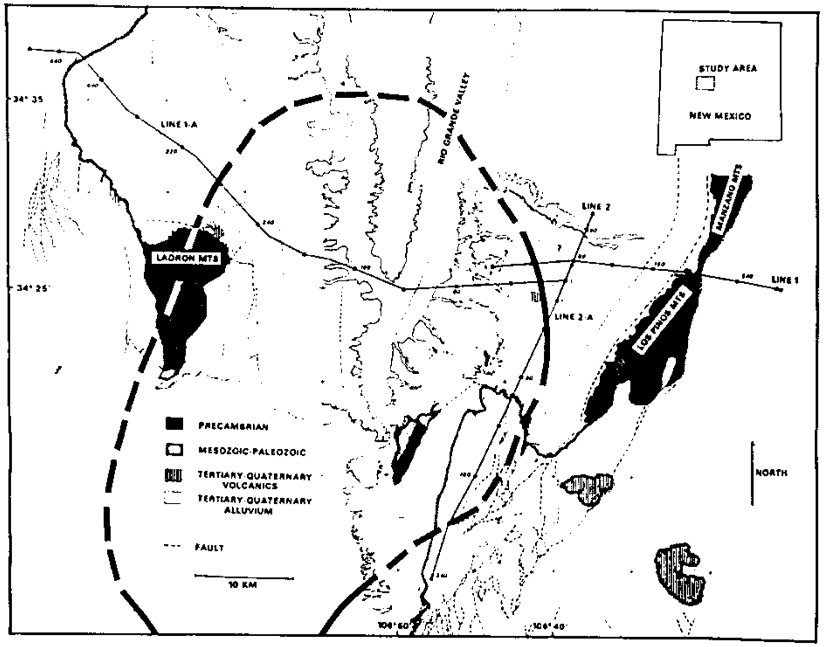
- * Snow White and 7 Dwarfs
- * Occult Intrusives
- * Size Variations Between Districts

Socorro New Mexico Bright Spot
~50 km Diameter, 18-20 km depth

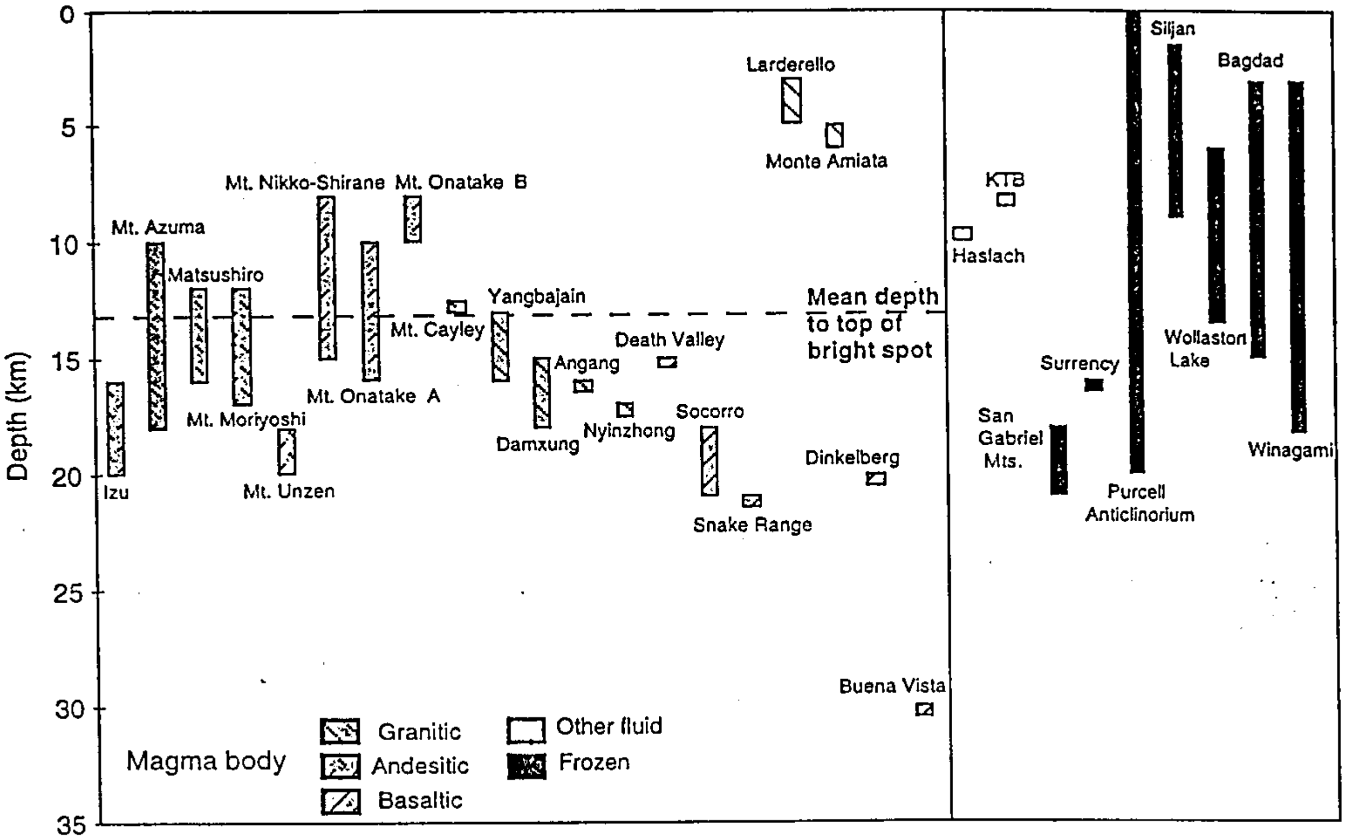


Ross and Brown, Reviews Geophysics, Accepted 1997

50 km diameter sills are common

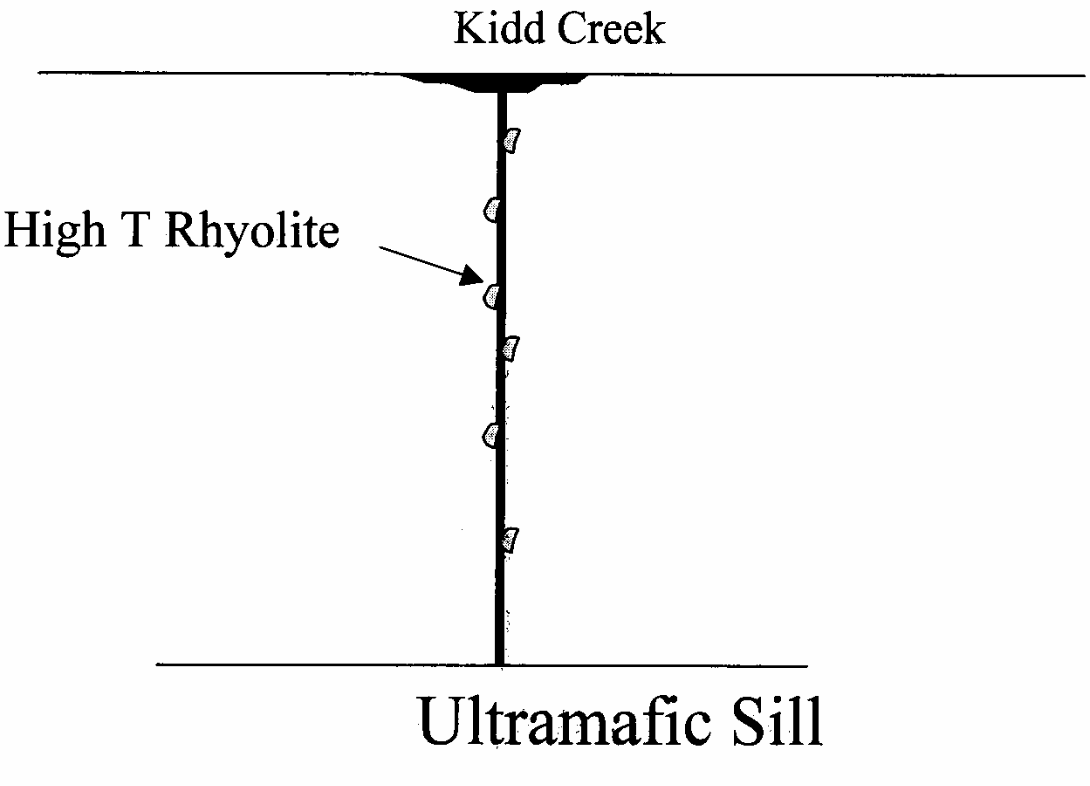


Depth to Top Crustal Bright Spots ~Brittle-Ductile Transition



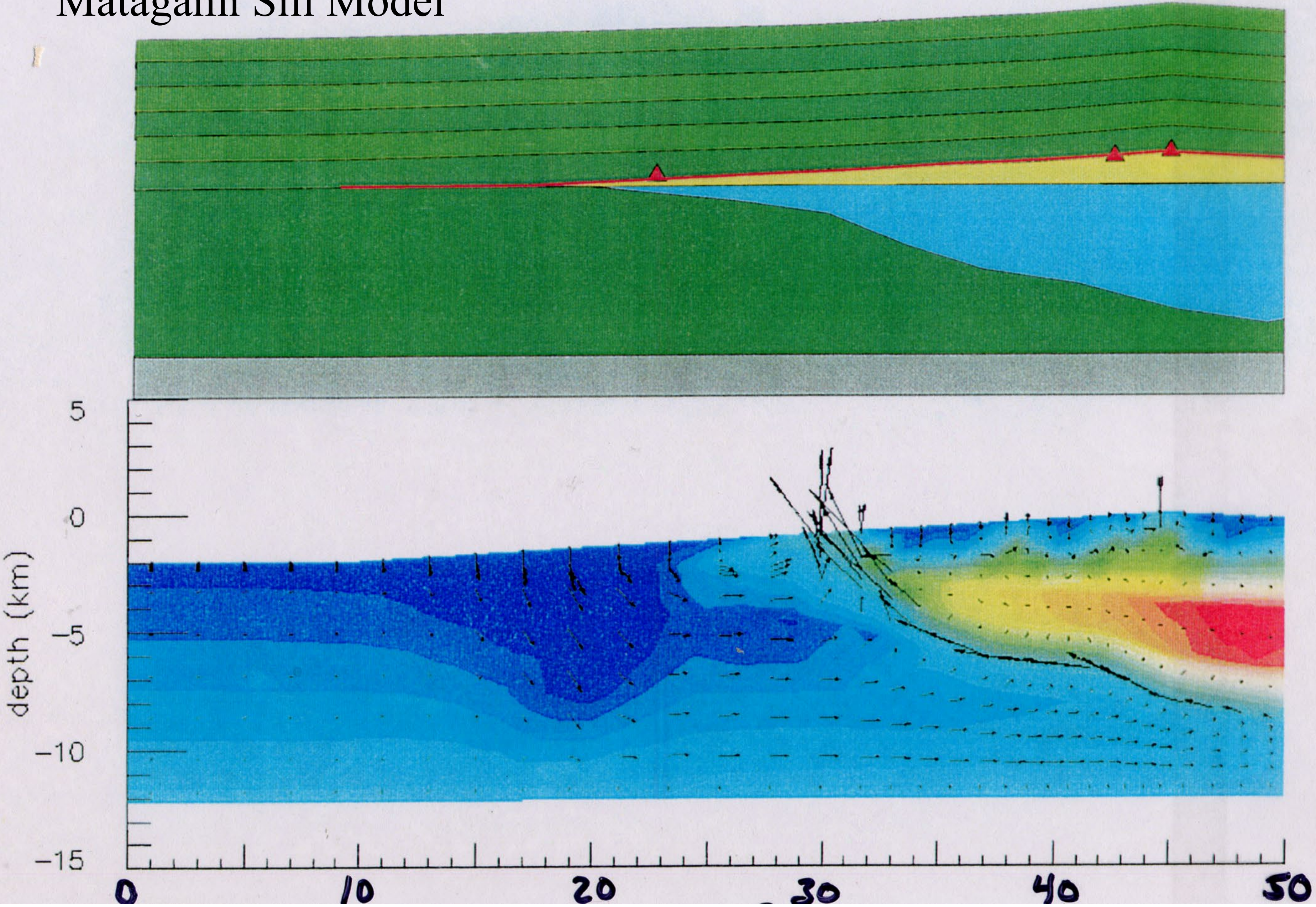
Ross and Brown, Reviews Geophysics, Accepted 1997

Mattagami	$\Delta = 2.3$ km	M=10 Mt x 6
Iberian Py Blt	$\Delta = 30$	M=100 Mt x 7
Kidd Creek	$\Delta = \infty$	M=140 Mt x 1



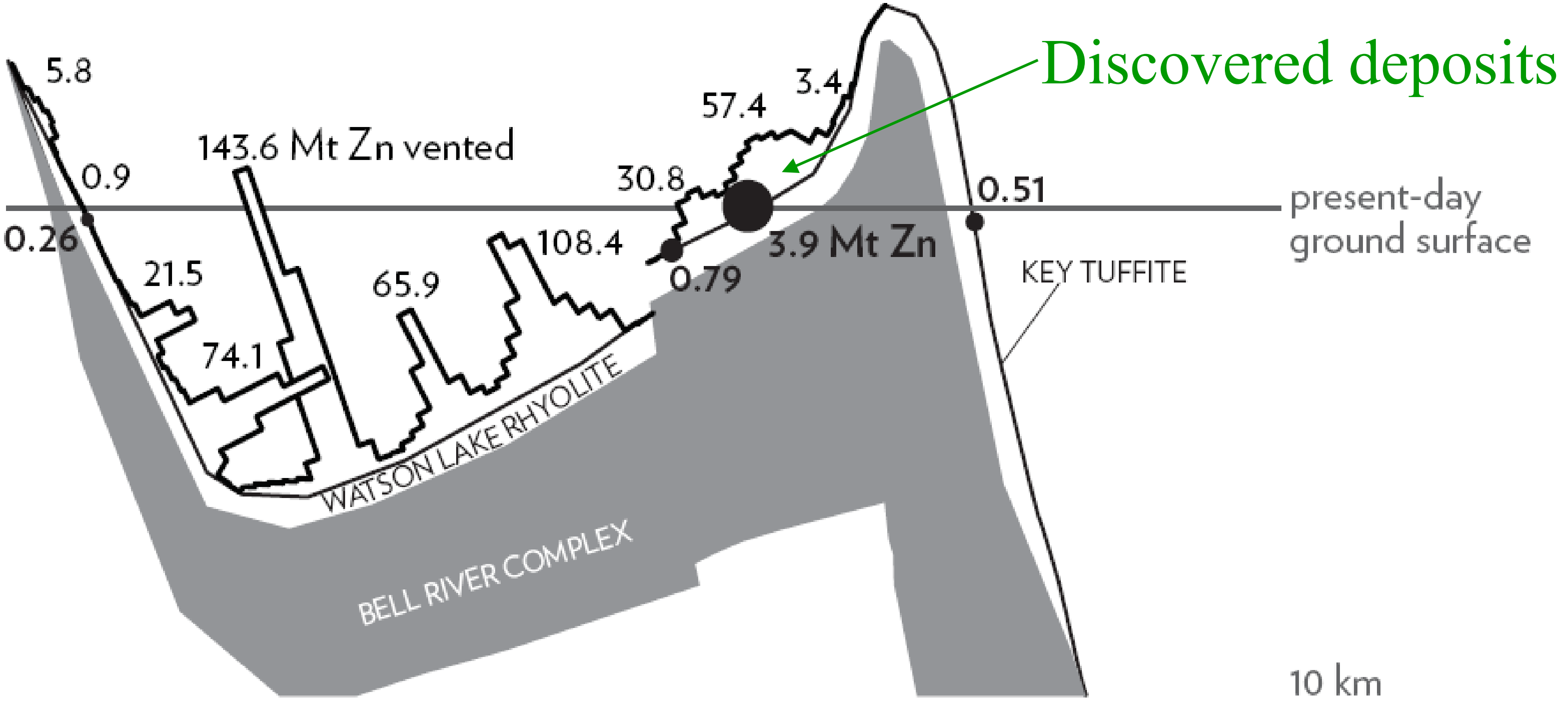
Barrie et al. (1999)

Matagami Sill Model



Distance [km]

Matagami Sill Model in present-day context



Discovered deposits

Carr et al. (in review)

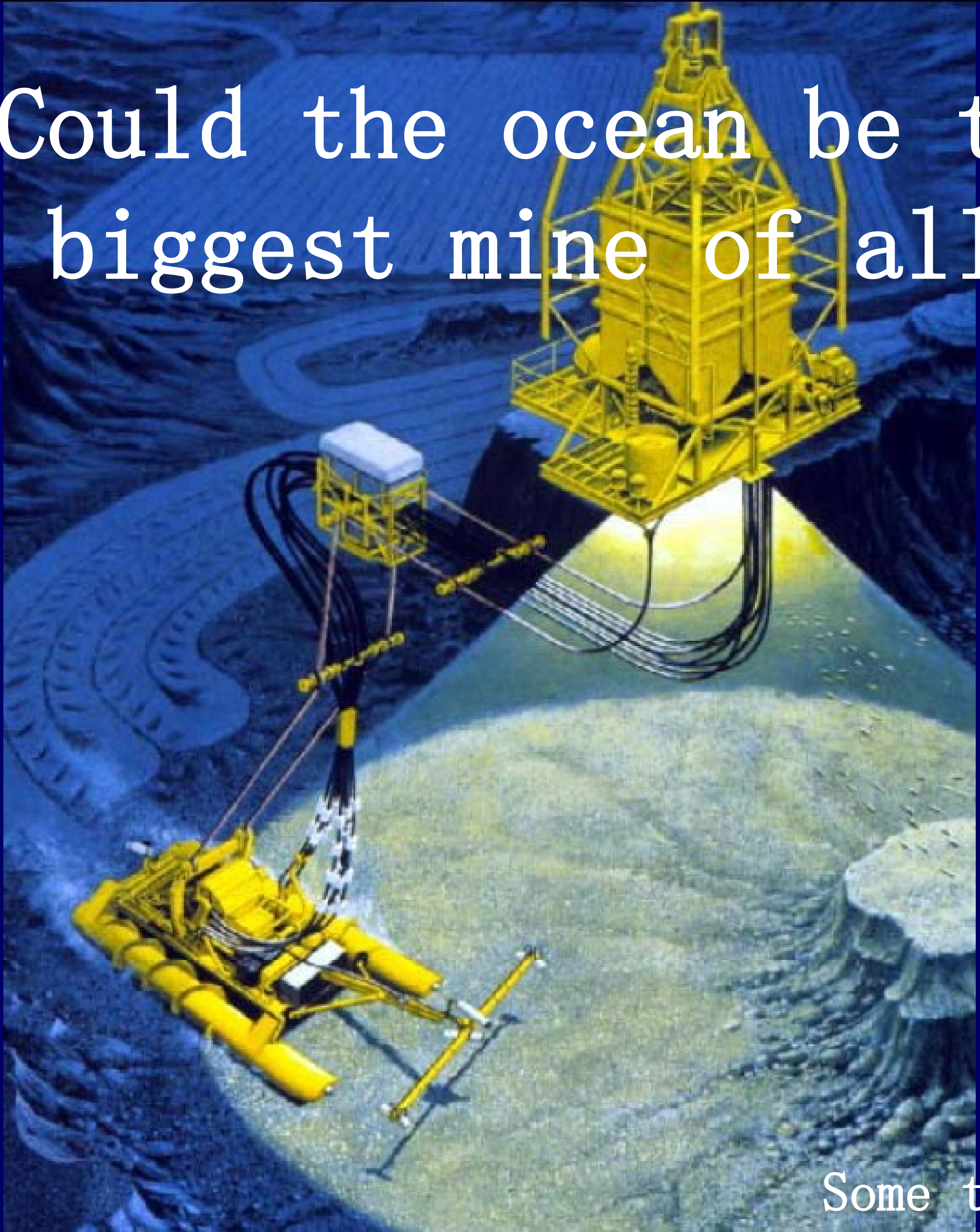
Summary

- VMS deposits products of first order planetary process (sea floor spreading)
- Character unchanged over all of geologic time
- Deposits reflect (and are comprehensible in terms of) fundamental principles
  - Heat and mass balance
  - T-dependent metal solubility
  - Vertical tectonics
- Complexities result from integration/interaction of physical and chemical processes over time and space
  - sulfide accumulation and its zone refining
  - kick start convection with dike injection
- Exploration guided by observations, scientific principles, and computer modeling

Future

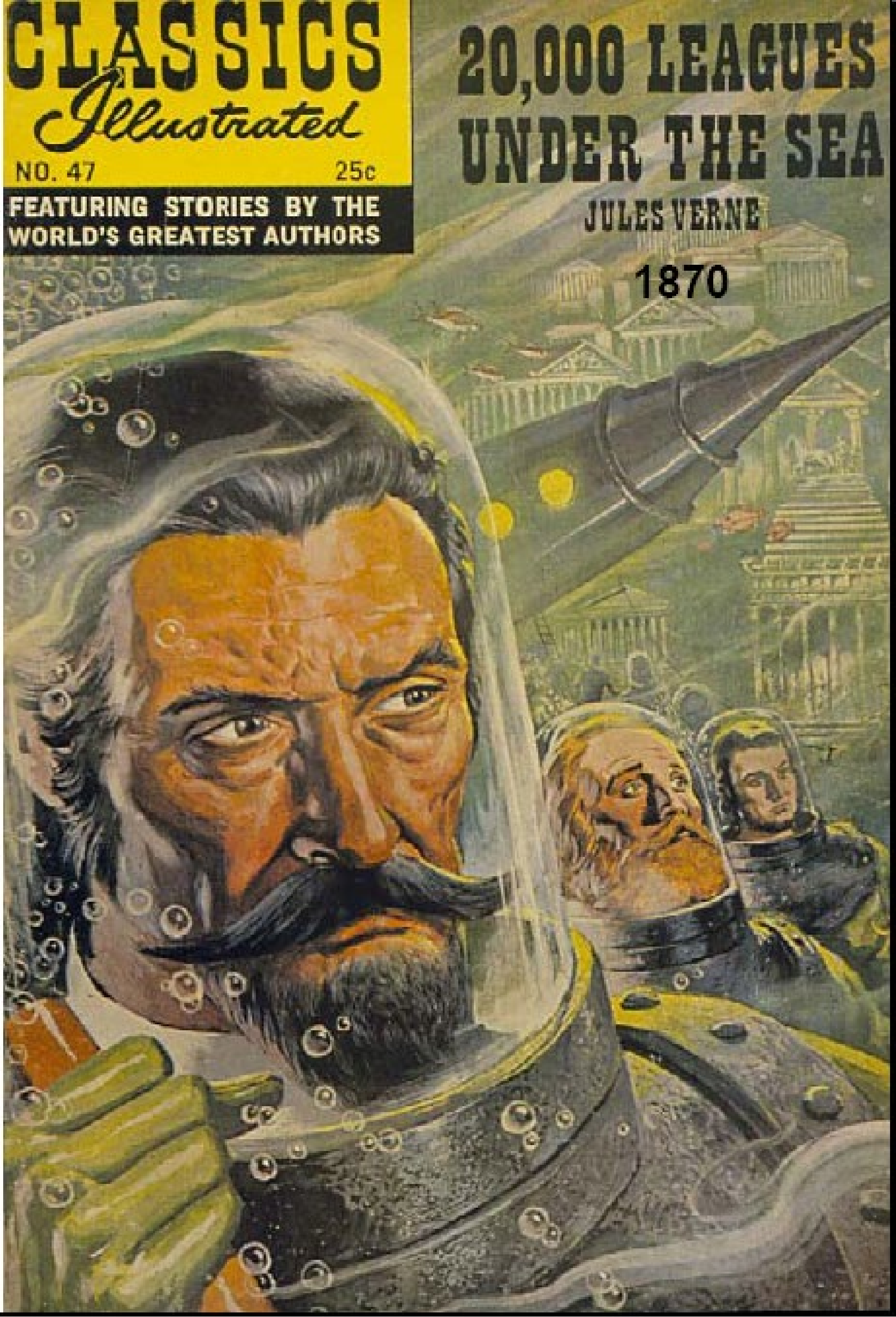
1. Controls on intrusion styles in spreading centers
    1. How/when are sills emplaced
    2. Influence of hydrothermal convection on magma dynamics
    3. Influence of magma on hydrothermal convection (dike kick start of Kidd Creek system)
    4. Role of minor explosions (clearing of throat)
2. Predicting (modeling) details of chemical change
    1. Evolution of ore (replacement, dissolution, zone refinement)
    2. Volume change
    3. Chemical fingerprint of intake halo
3. Simultaneity of failed rifting events
    1. Implications for absolute plate movements in past
    2. Factors controlling rift failure
4. **Ocean Mining….**

Could the ocean be the biggest mine of all?



Some think so….

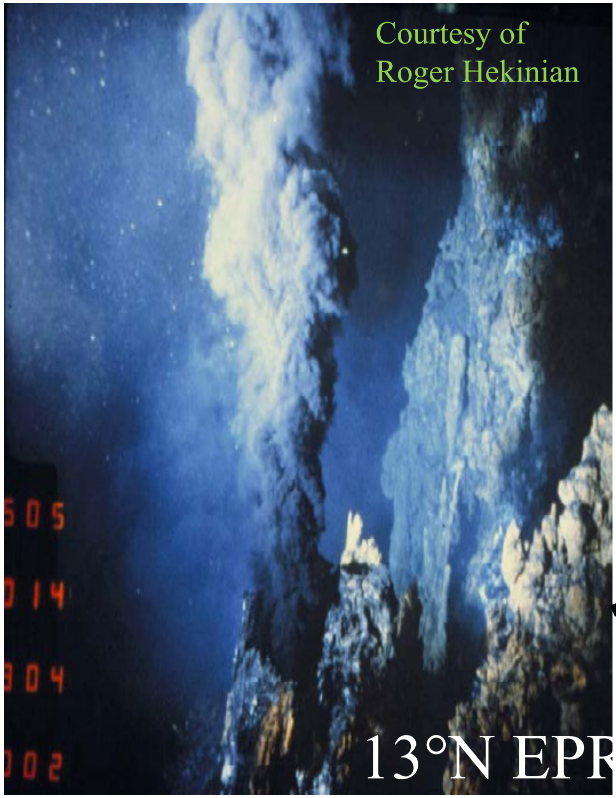
"… in the ocean depths, there are mines of zinc, iron, silver and gold that would be quite easy to exploit"

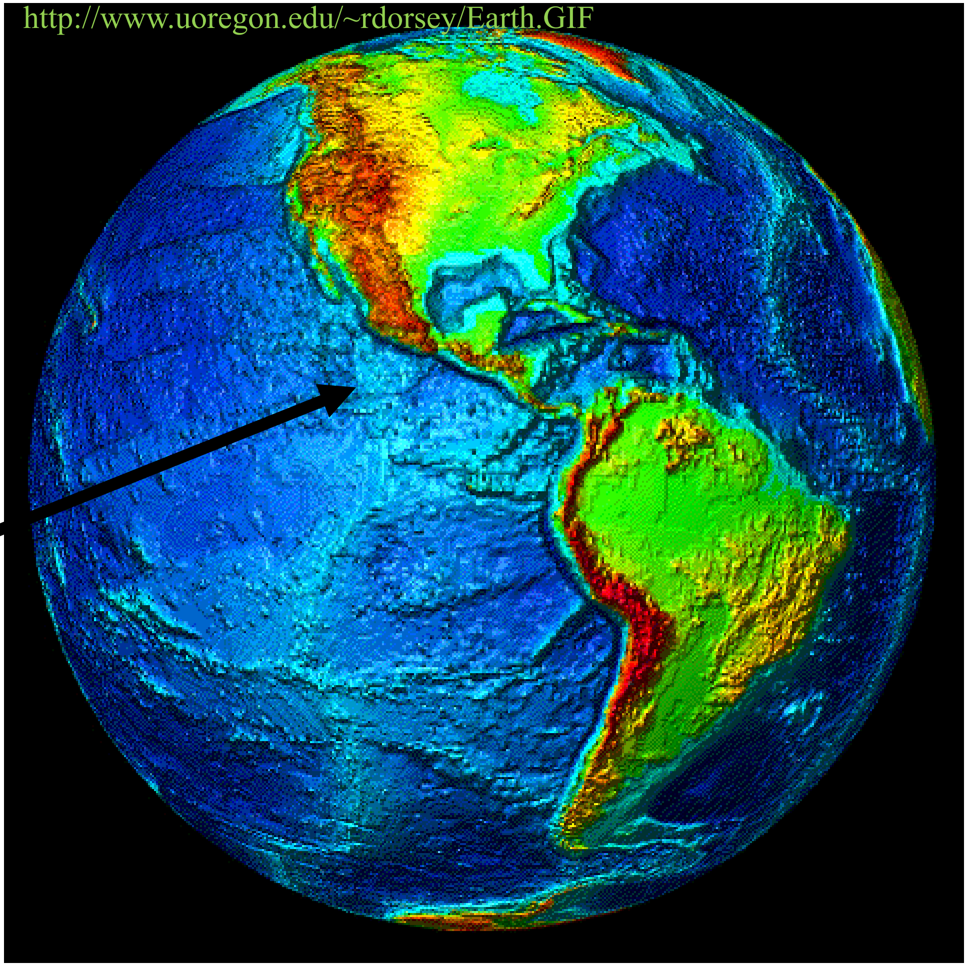


1870

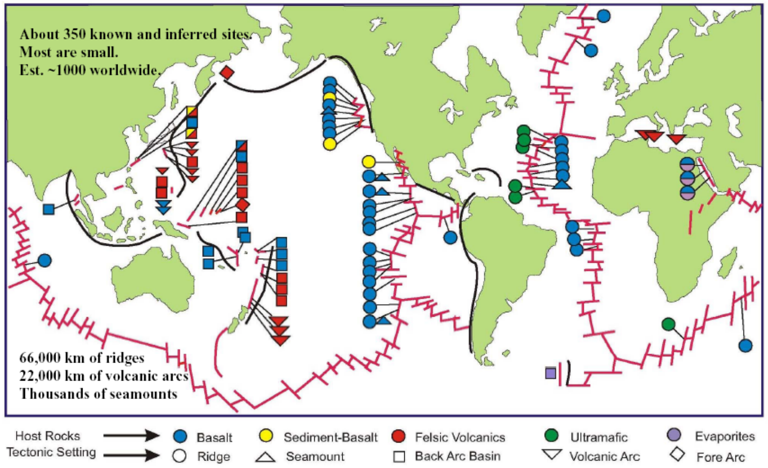
Little did Jules Vern know how right he was…

- Oceans likely contain VMS resources **>600 times the currently knows VMS (Au, Cu, Zn) reserves**
- Mining of the first VMS could occur in 2010
- Many advantages over land-based mining
- Energy needed to mine first resources locally available
- Area ocean = 2 moons + 2 Mars: Vast potential for other resources (Mn, Ni, Co, Sn, …)


Courtesy of Roger Hekinian


http://www.uoregon.edu/~rdorsey/Earth.GIF

Seafloor Hydrothermal Deposits
(Updated 2007 from Fouquet, IFREMER, 2002)



Spreading Ridges are source of metals and energy

- 66,000 km of ridges
- 22,000 km of volcanic arcs
- ~350 known sites with hydrothermal deposits

Cleft Segment of Juan de Fuca Ridge

3 km axial valley with 30-50 m wide "cleft" 20 m deep

★ high T vents occur in cleft

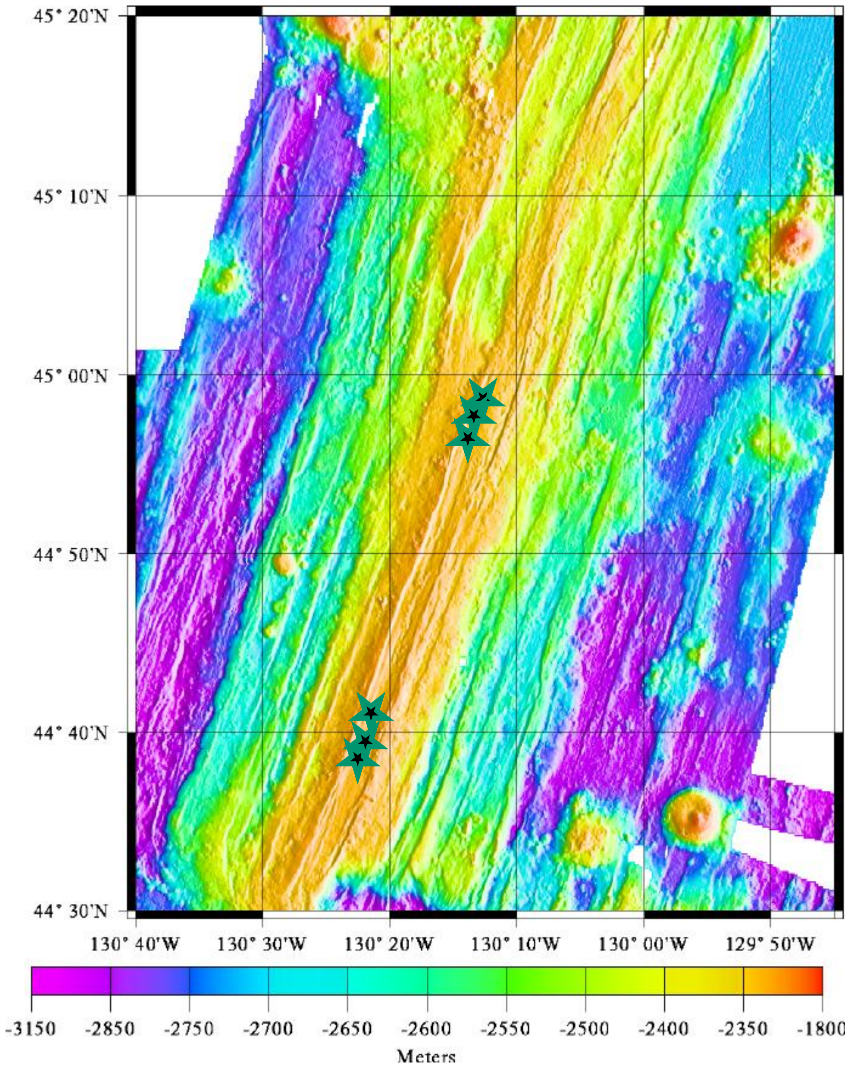
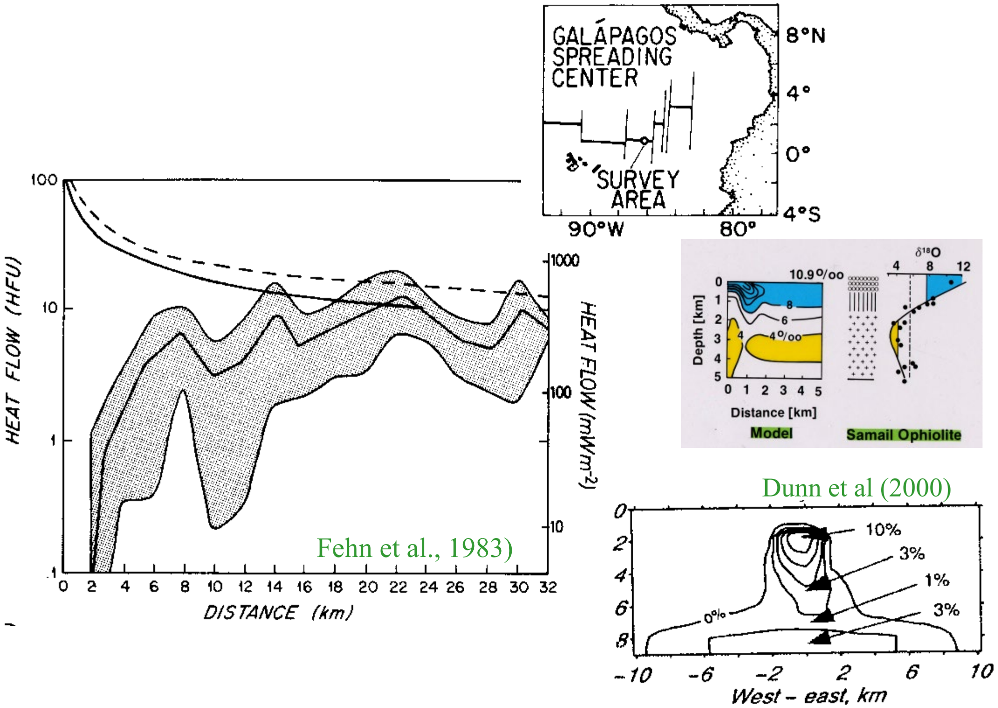


Image from http://www.pmel.noaa.gov/vents/geology.cleft.html

Vent locations from Fig. 16 in Fournari and Embley (1995)

1. High T vents are on spreading axis
   on white line in middle of axial graben highway

2. At Galapagos, venting cools entire crust at the ridge axis



3. Narrow axial magma chamber requires

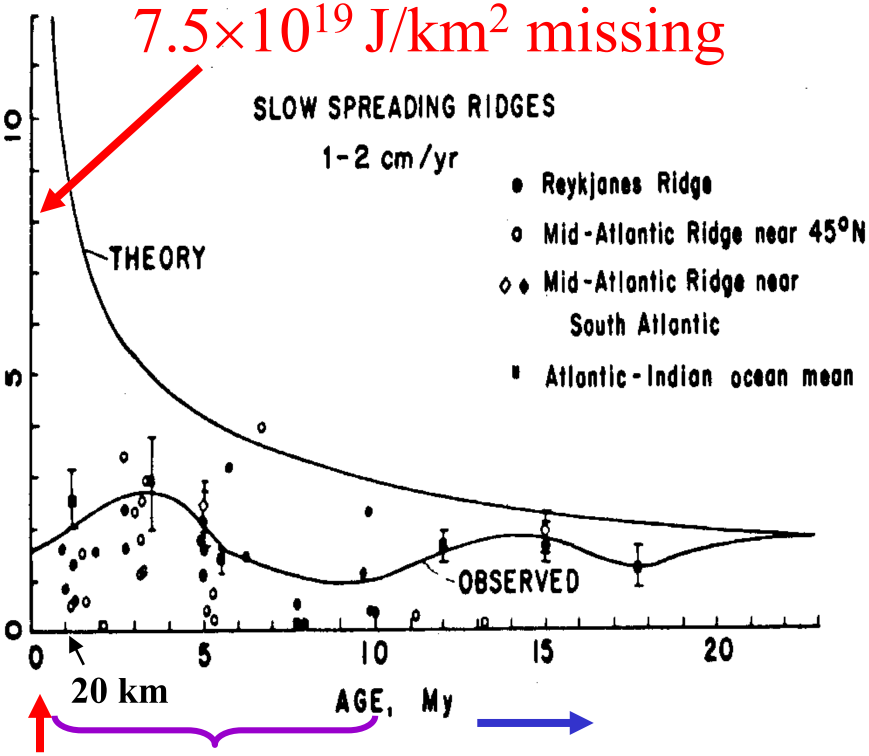
4. Topography ⇒ whole crust axial heat extraction general (Cochran and Buck, 2001)

5. δ^{18}O indicates whole crust convection (Cathles, 1993)

Cooling crust releases ~2.9 x 10^{19} J km^{-2} as ~350°C vent fluids

Heat removal inferred from heat flow

7.5×10^{19} J/km^2 missing



2.9×10^{19}J km^{-2}
0 to 0.1 Ma
>300 C
Black Smokers

2.9×10^{19}J km^{-2}
0.1 to 10 Ma
150C?
White Smokers

1.7×10^{19}J km^{-2}
>10 Ma
weak leakage

39% 39% 22%

(Sleep and Wolery, 1978)

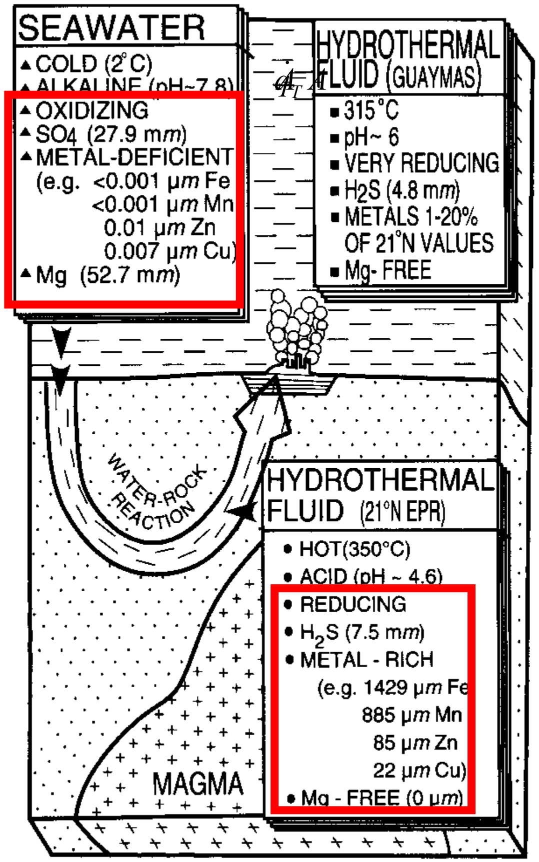
Calculated heat released in cooling crust

H = Thickness of oceanic crust	**6.5±0.75 km** (0.7 flows, 1.2 dikes, 4.6 gabbro)	Mottl (2003)
C_c = Heat capacity of mafic crust	**1.2±0.15 J g^{-1} K^{-1}**	Mottl (2003)
L = Latent heat crystallization and alteration	**420 J g^{-1}**	Norton and Cathles (1979)
T_o = Temperature of ridge magma	**1200 °C to 1450 °C**	Mottl (2003) to Stein and Stein 1994
h_c = Heat released in cooling from T_o to 350 °C	**1020 to 1320 J g^{-1} K^{-1}**	= $C_c(T_o-350)$
h_T = Total heat released	**1420 to 1870 J g^{-1} K^{-1}**	= $L+Q_c$
ρ_r = density of ocean crust	**2800 kg m^{-3}**	
q_T = heat introduced by sea floor spreading to each m^2 of new crust, discounting heat in flows	**2.3 to 3.0x10^{13} J m^{-2}** **2.3 to 3x 10^{19} J km^{-2}** **Supplied by magma**	= H ρ_r h_T = (5.8×10^3)(2800)(1420 to1870x10^3) (note: 5.8×10^3 = thickness gabbro plus dikes)

Heat released by 350°C venting
= heat supplied to crust by magma

At 50% conversion, electrical generating capacity of SFS is similar to present total human electrical consumption of 1.7 TW

q_T = SFS Heat	2.9×10^{13} J m^{-2}	$= H \rho_r h_T$
$\dot{A}$ = rate formation ocean crust	3.3×10^6 m^2 yr^{-1} 0.105 m^2 s^{-1}	Parsons (1981)
Q_T = watts (joules per second) from SFS	3×10^{12} W **=1.5 TW at 50% convn**	



Scott (1997)

h_{sw} heat to warm SW to 350°C	$1540 \pm 200 \times 10^3$ J kg^{-1}	Mottl (2003)
m_{350} = mass of 350°C seawater discharged per m^2 of new ocean crust	1.5×10^7 kg m^{-2}	Elder's Rule: mass intrusion =mass 350°C circulated $H\rho_r = \frac{q_T}{h_T} \approx \frac{q_T}{h_{sw}} = m_{350}$
350˚C vent fluid compsn lo Scott hi	S Fe Zn Cu 2900 750 40 9.7 μm kg^{-1} 7500 1429 85 22 12,200 6470 106 44	Elderfield and Schultz (1996)
Zn vented per m^2	1280 mol m^{-2} 83 kg m^{-2} <2.5 kg m^{-2} VMS	$= m_{350}$ (85×10^{-6} mol kg^{-1})
Cu vented per m^2	329 mol m^{-2} 21 kg m^{-2} <2 kg m^{-2} VMS	$= m_{350}$ (22×10^{-6} mol kg^{-1}) Sangster 1980)
kg FeS_2 vented per m^2	3480 kg m^{-2} 110 kg m^{-2} VMS	$= \sigma_{Fe}$ (mol wt pyrite = 0.12 kg mol^{-1})

⇒ 3% deposition efficiency

Low Me Venting x 3% ⇒ Seafloor resource* of 5.3×10^{11} t

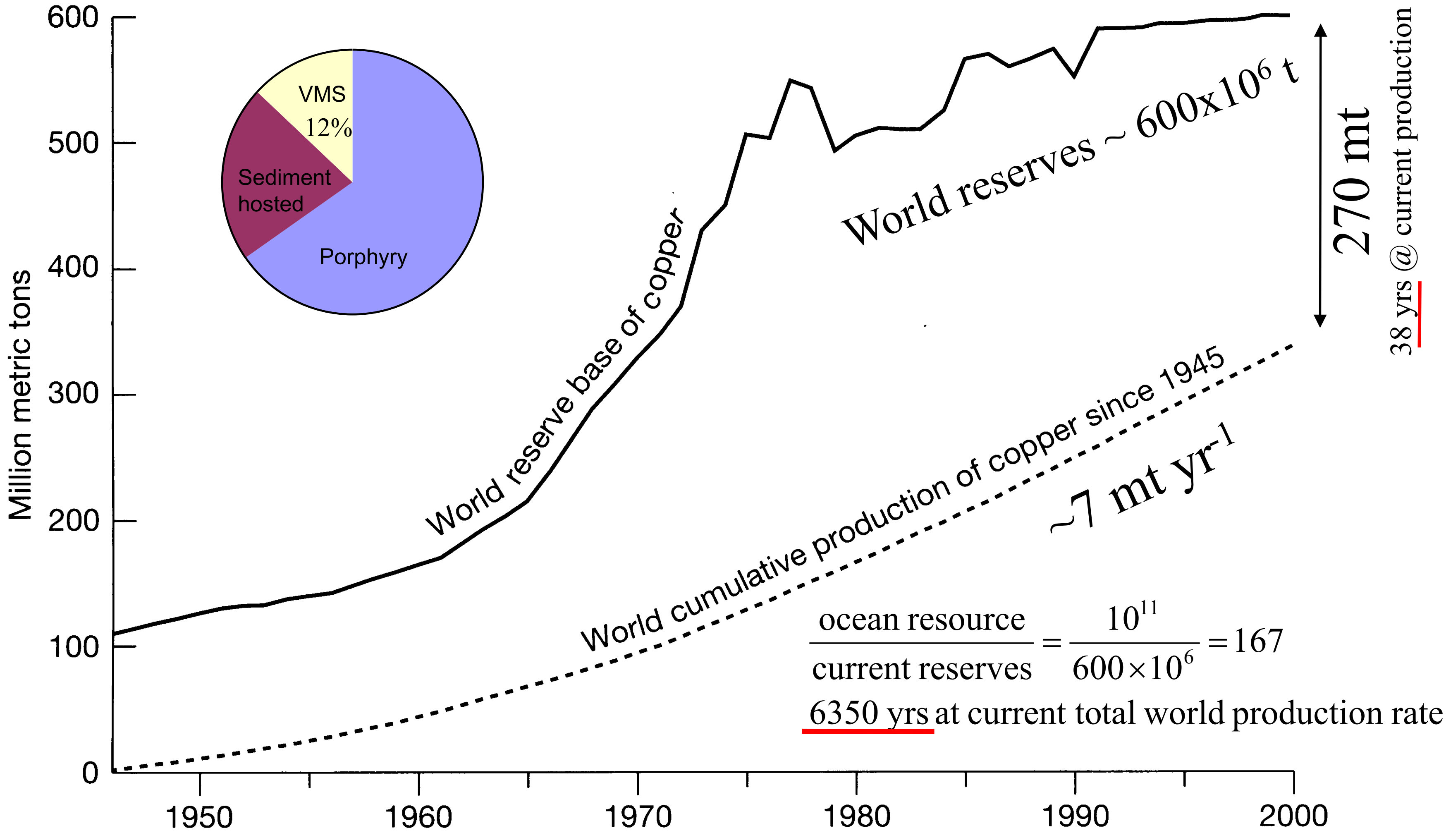
Present VMS reserves = 850×10^6 t metal (Franklin et al, 2005, Table 2)

Seafloor resource > 624 times VMS reserves

* $\frac{9.7+40}{85+22} \times 0.03 \times 104$ kg m^{-2} $\times 3.62 \times 10^{14}$ m^2 $= 5.3 \times 10^{14}\,kg$

Cu resources in ocean are very large

$$\text{Ocean Cu} = \left(9.7\times10^{-6}\, mol\, kg^{-1}\right)\left(1.5\times10^{7}\, kg\, m^{-2}\right)\left(0.063546\, mol\, kg^{-1}\right)\left(3.62\times10^{14}\, m^{2}\right)\left(0.03\right)\left(10^{-3}\, t\, kg^{-1}\right) = 1\times10^{11}\, t\, Cu\, metal$$



$$\frac{\text{ocean resource}}{\text{current reserves}} = \frac{10^{11}}{600\times10^{6}} = 167$$

6350 yrs at current total world production rate

Craig et al. (2001)

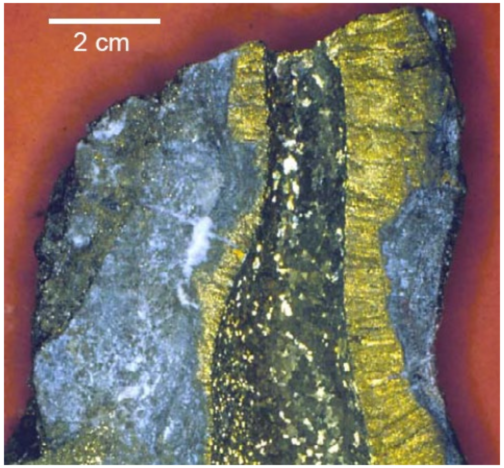
600,000 vs 167 must represent disproportionate production from VMS

1. Metal demand strong and increasing

China Cu use ↑ 250% 1998-2007

8/6/08

$3.50/lb



Cu and Zn-rich chimney
Photo by Yves Foquet
IFREMER

2. Ocean deposits as rich or richer than land

Comparison of Solwara 1 with selected land mines

District	Hokuroku, Japan	Noranda, Canada	Solwara 1 Golder Associates February 1, 2008.
In situ value per metric ton on August 6, 2008	$258	$313	$757
Wt %			
Copper	1.6	2.1	**7.2**
Zinc	3.0	1.4	0.6
Lead	0.8	~0	-
g/t			
Silver	93	21	31
Gold	0.6	4.1	**6.2**

From Scott IGC 2008

Strong Industry and Government Interest

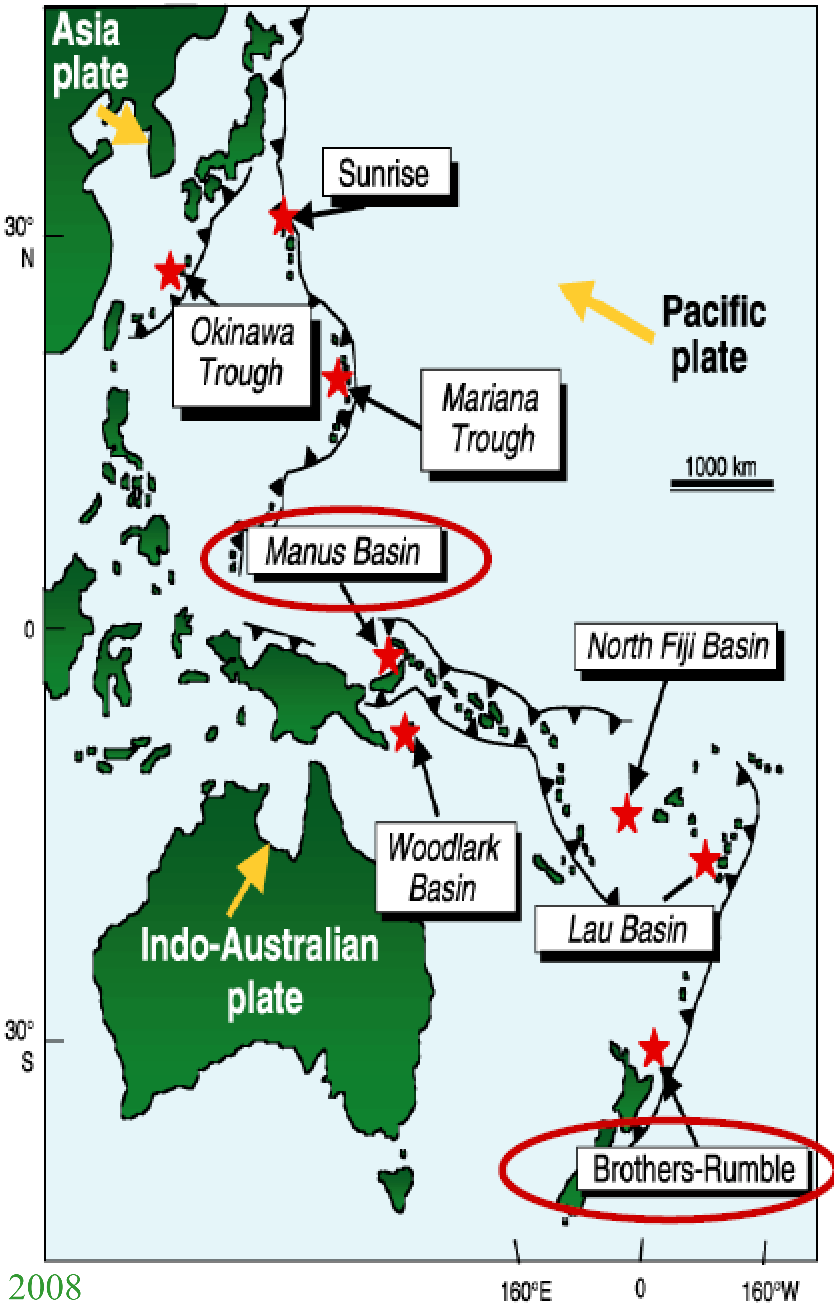
Nautilus Minerals (partners Teck Cominco, Anglo American, Epion Holdings, Barrick Gold; Toronto and AIM Exchanges: NUS) and Neptune Minerals (partner Newmont; AIM Exchange: NPM), have exploration licenses (approved and pending) covering large areas offshore Papua New Guinea and New Zealand, respectively, and elsewhere.

Bluewater Metals is a new company being formed. Has pending licenses.

KORDI (Korea) has exploration licenses from Tonga covering 20,000 km² (*Chosun Ilbo*, April 3, 2008).

DORD (Japan) has applied for concessions in the Japanese EEZ.

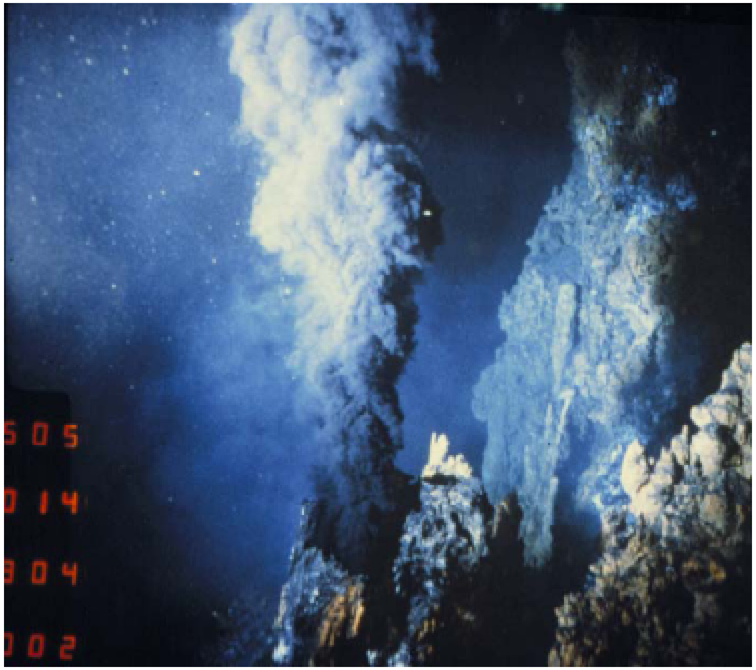
COMRA (China) has an active exploration program for sulfides.



From Scott IGC 2008

Advantages of Ocean Mining

- Reusable infrastructure - no shaft*, no extensive excavations**, no roads, no town, no power plant:
  - * mine shafts $4500 - 7500 per meter
  - ** mine tunnels $1200 - 2300 per meter
- Small footprint of "surgical mining". No waste rock to remove.
- Can mine small deposits.
- Worker safety.
- Little social disturbance.



13°N EPR black smoker
Courtesy of Roger Hekinian

From Scott IGC 2008

Environmental Problems on Land: Acid Drainage & Excavations

None of these are a problem on the seafloor. Biggest problem will be loss of habitat → environmental assessment.

From Scott IGC 2008

Mining system to be deployed by Nautilus Minerals

Courtesy Nautilus Minerals

North Sea Shipping (Bergen, Norway) to provide a new 160m dynamic positioning Mining Support Vessel (MSV) on 5 year lease with an option for 5 more years

Courtesy Nautilus Minerals and their technical alliance partner, Soil Machine Dynamics

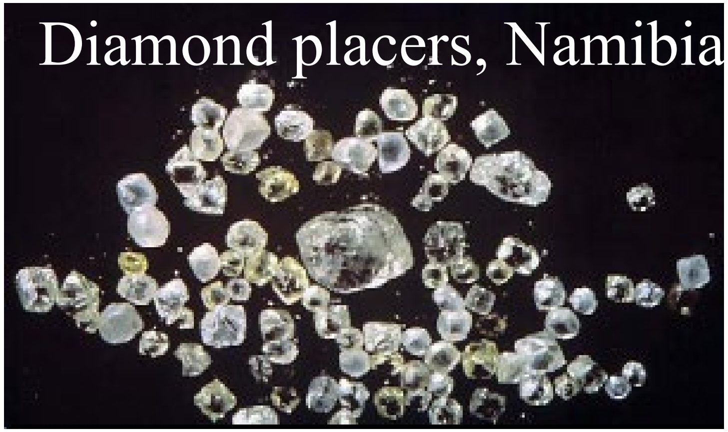
Technip (Houston) to build RALS using offshore oil technology and Soil Machine Dynamics (UK) to build two 6000 peak tpd SMTs

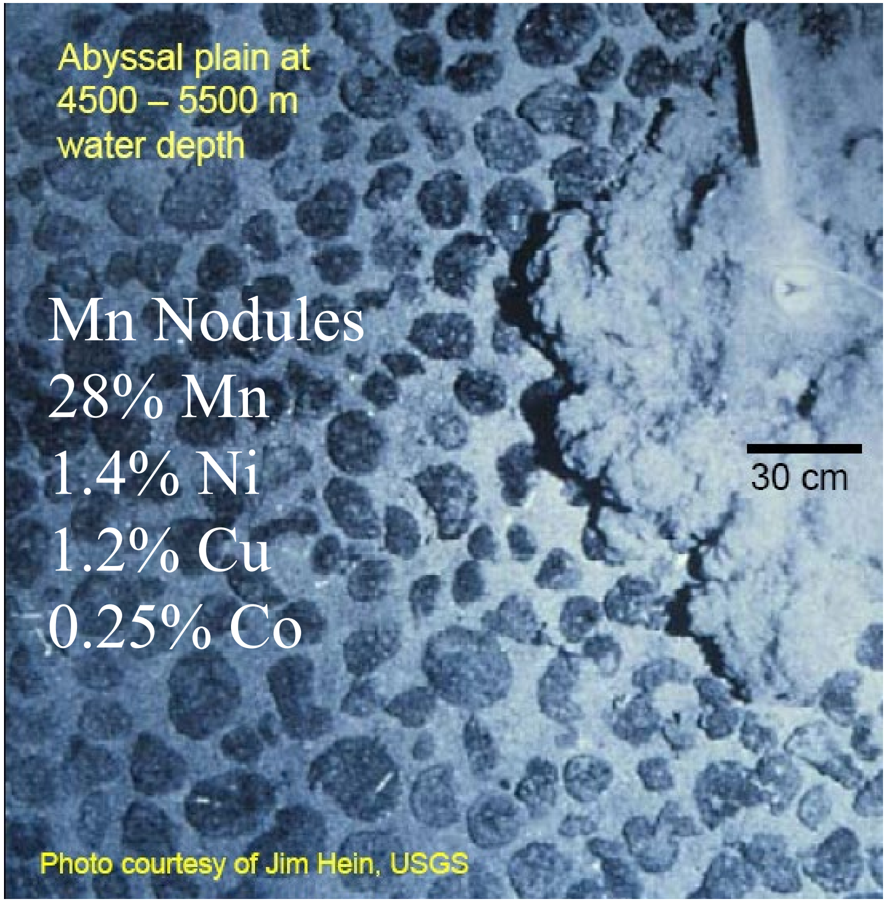
Mining to start in Q4 2010 subject to timely permitting by PNG

Solwara, offshore Papua New Guinea

From Scott IGC 2008

Other resources also…


Diamond placers, Namibia



Abyssal plain at
4500 – 5500 m
water depth

Mn Nodules
28% Mn
1.4% Ni
1.2% Cu
0.25% Co

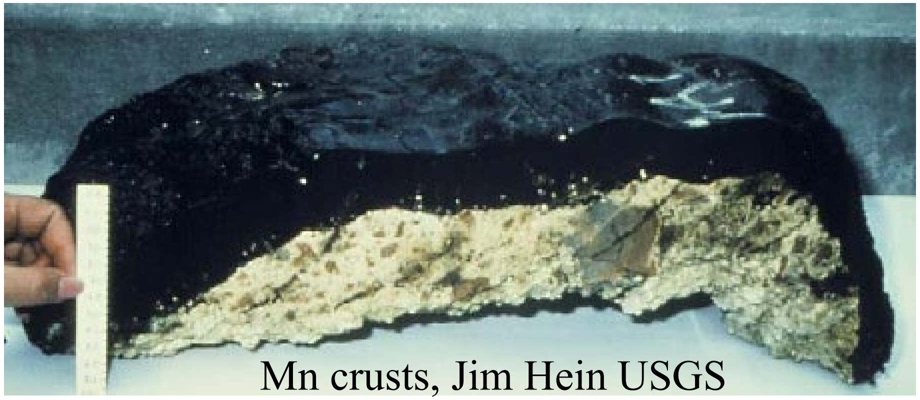
Photo courtesy of Jim Hein, USGS

Gas

Phosphorite

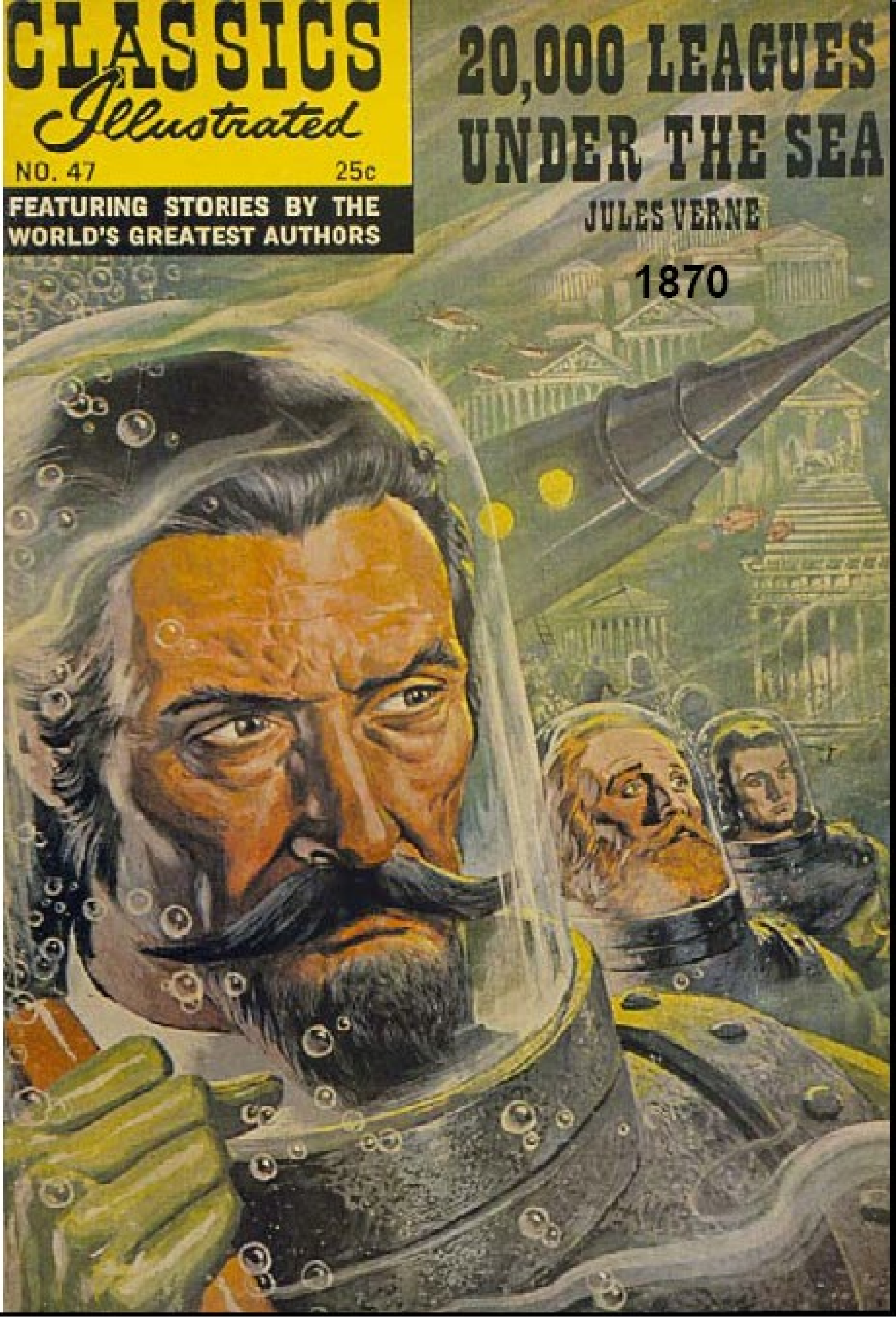
Oil

Methane Hydrate


Mn crusts, Jim Hein USGS

From Scott IGC 2008

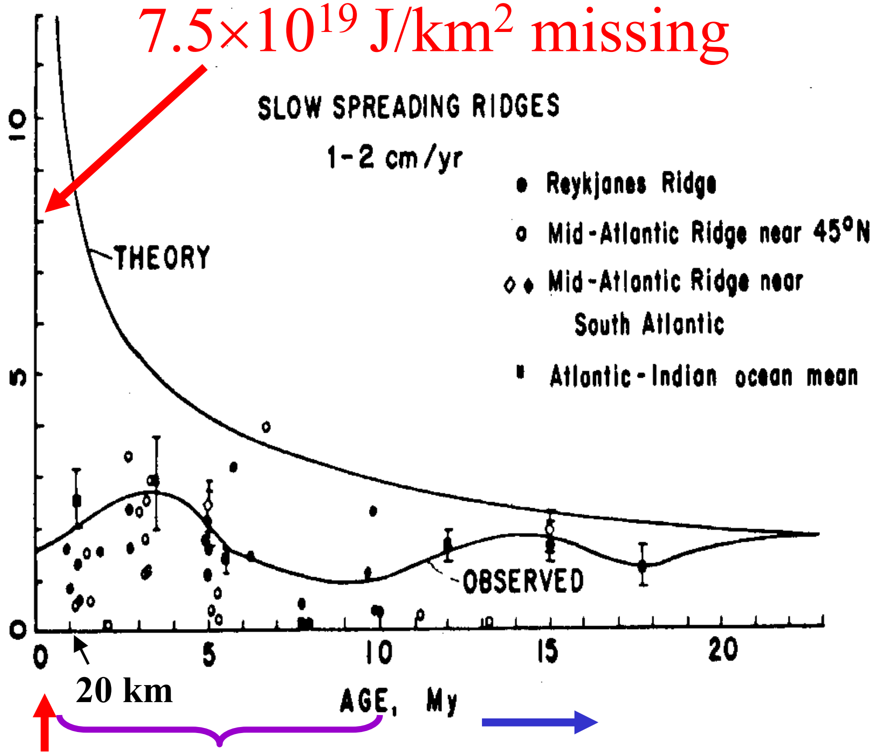
"… in the ocean depths, there are mines of zinc, iron, silver and gold that would be quite easy to exploit"



1870

A few more scientific points…

Ocean circulates through ocean crust every ~4 Ma



7.5×10^{19} J/km^2 missing

20 km

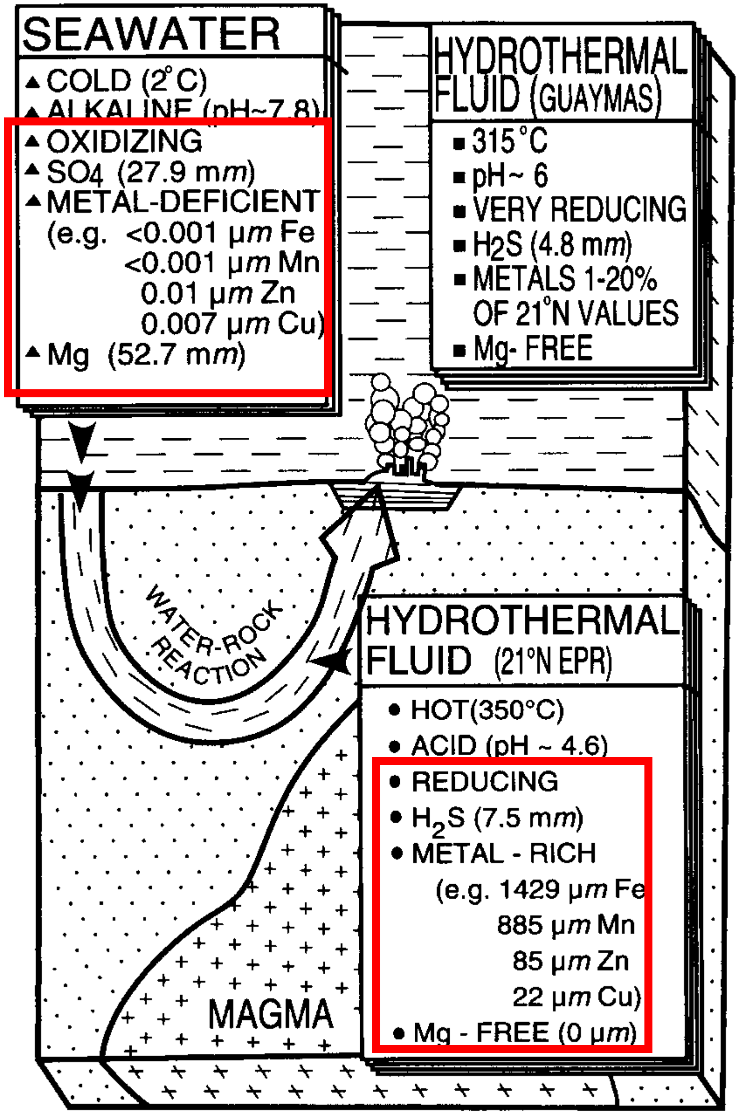
2.9×10^{19}J km^{-2}	**2.9×10^{19}J km^{-2}**	**1.7×10^{19}J km^{-2}**
0 to 0.1 Ma	**0.1 to 10 Ma**	**>10 Ma**
>300 C	**150C?**	**weak leakage**
Black Smokers	**White Smokers**	
39%	39%	22%

Venting Temperature	**Turnover time ocean**
300°C	7.8 Ma
150°C	3.9
50°C	1.3

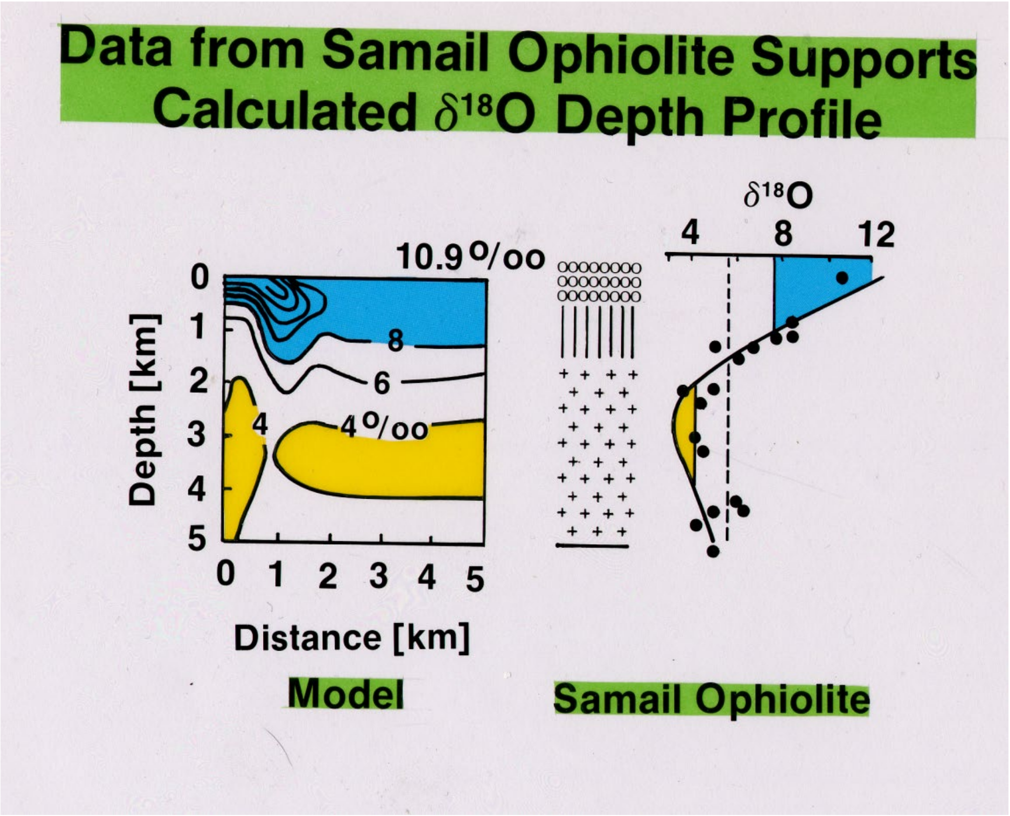
Ocean volume = 1.4×10^{9} km^3

(Sleep and Wolery, 1978)

Convection massively alters ocean crust



Scott (1997)



Data from Samail Ophiolite Supports Calculated $\delta^{18}O$ Depth Profile

Cathles (1993a)

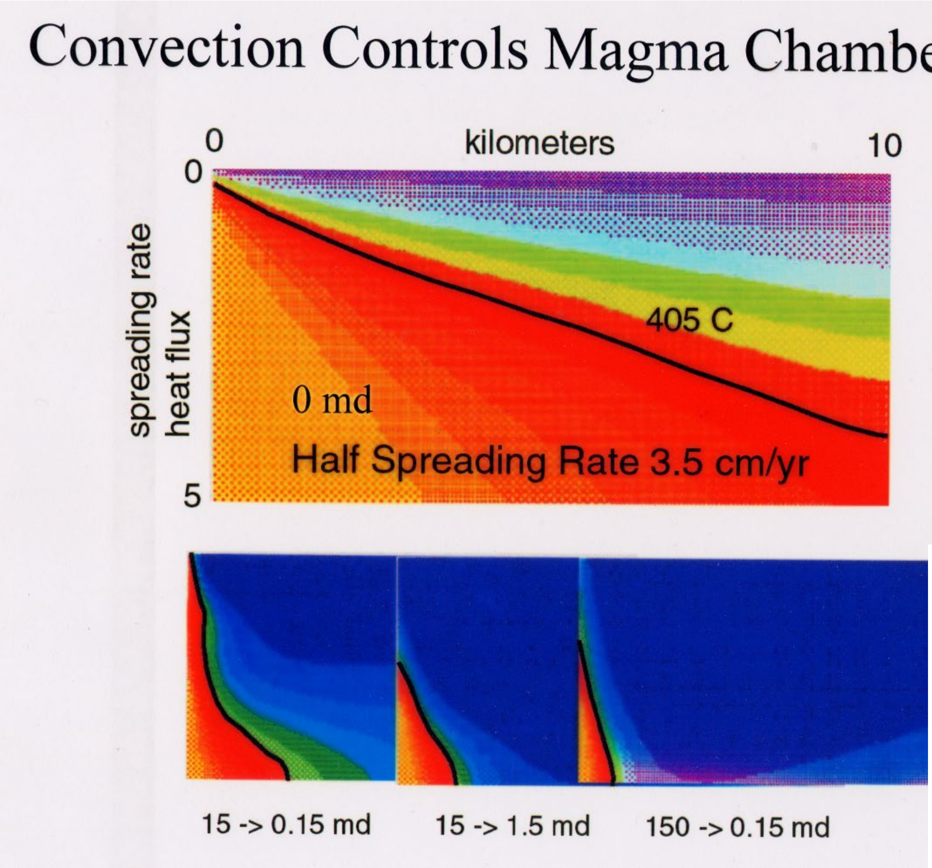
Chemical change*

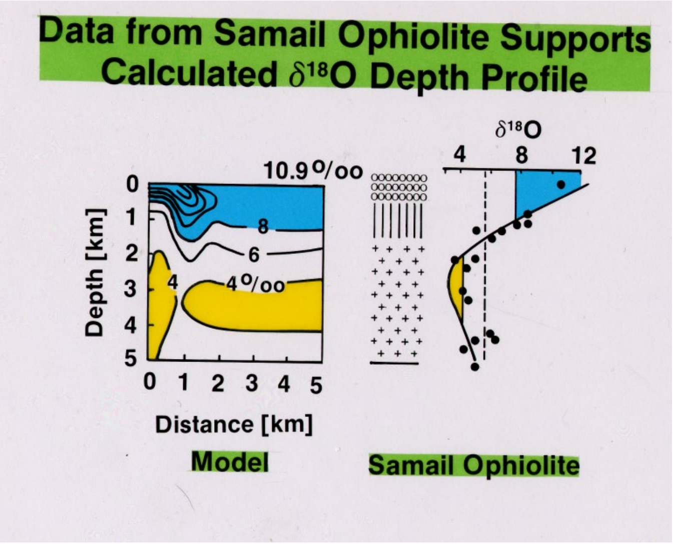
	Δ [mmol]	At Wt	10^{12} mol/yr	10^{6} t/yr
S	-20.4	32	3.7	**120**#
Mg	-52	24.3	9.3	**226**#
Fe	1.492	55.84	0.27	**15**
Mn	0.885	54.93	0.16	**8.8**
Zn	0.085	65.37	0.015	**1**
Cu	0.022	63.54	0.004	**0.25**+

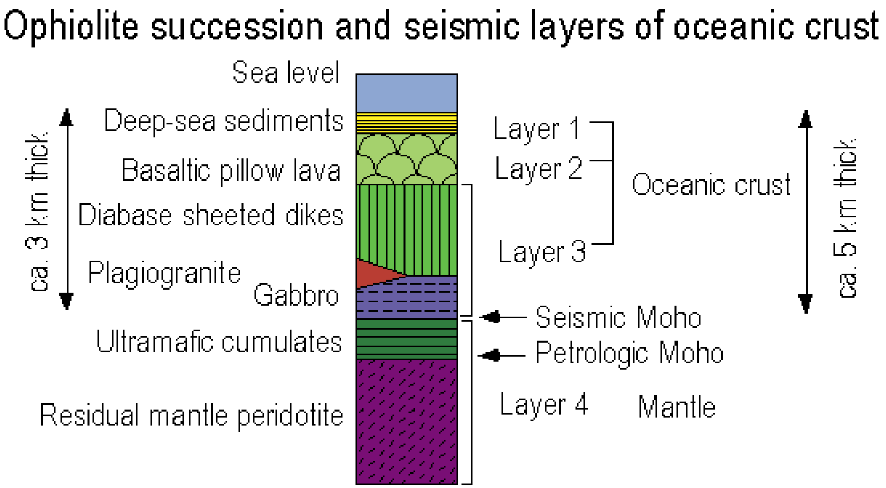
* @ 180 km^3 yr^{-1} 300°C discharge
\# 3 times larger considering >150°C discharge

\+ Cumulative production of Cu = 600×10^6 t (~2400 yrs of ocean circulation)

Convection to moho controls shape of axial magma chamber


Convection Controls Magma Chamber Shape


Data from Samail Ophiolite Supports Calculated $\delta^{18}O$ Depth Profile


Ophiolite succession and seismic layers of oceanic crust

Dynamic hydrothermal-magma interface explains:

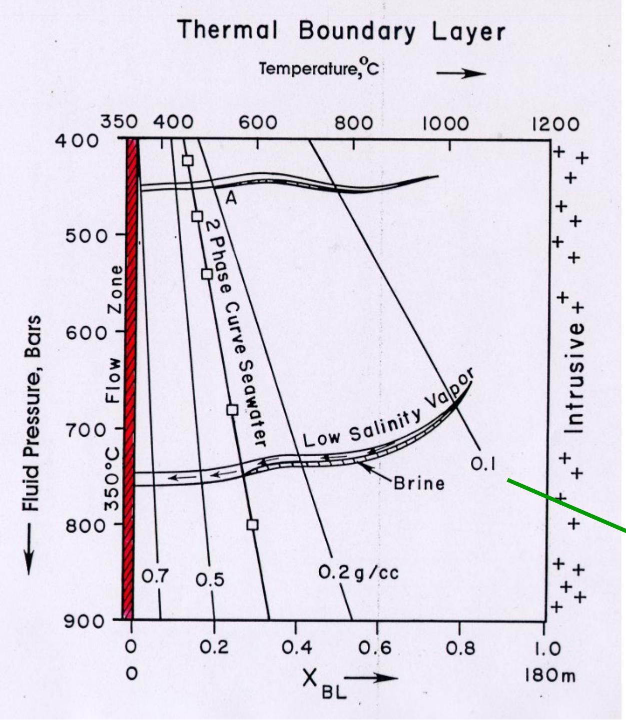
- normal BS[1(vol), 2(heat)] -> megaplume (2-20 d) -> normal
- plume salinity ½ to 2 x seawater
- residence time 150C to discharge <10 yrs[3]
- megaplume discharge > 250[4] x normal

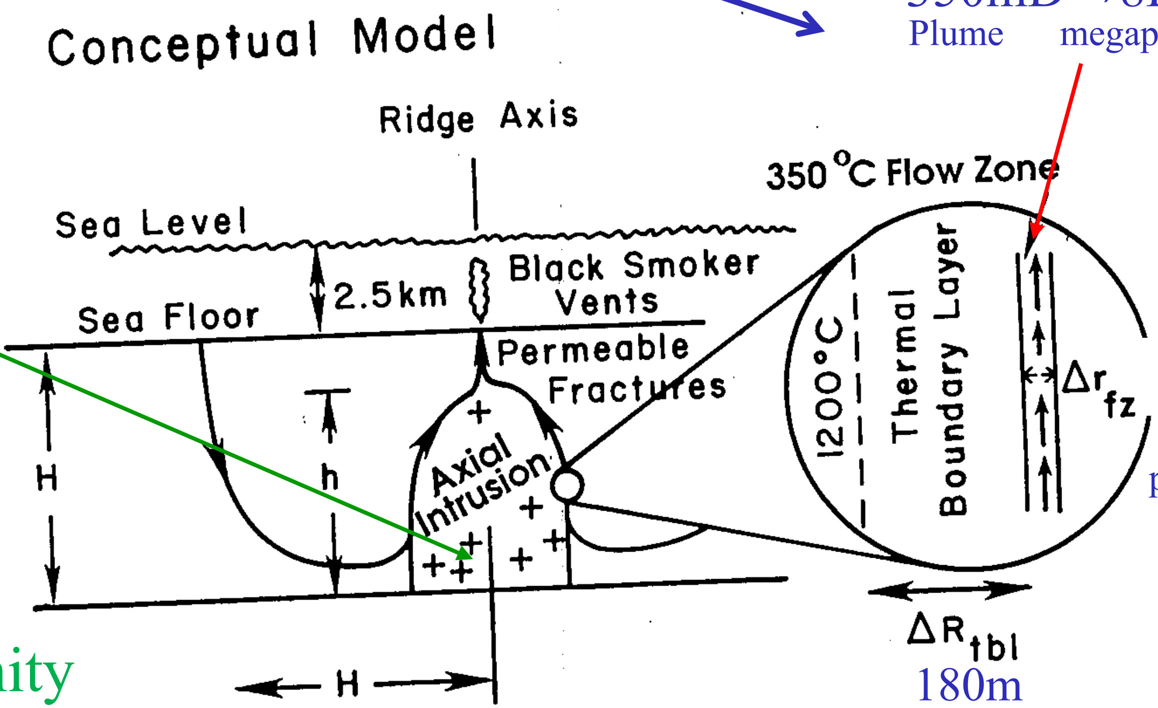
4 equations give system dimensions

Very narrow flow channel

350mD→8D

Plume megaplume





3.4m

10% porosity

180m

Cracking into magma changes discharge salinity

Cathles (1993b)

Conclusions

1. Rift-hydrothermal mineralization can be understood at a fundamental level
2. In oceans we can see ore deposits forming, and from this we have and will continue to learn a lot
3. Oceans are a very large unexplored territory and a huge resource for Cu, Zn, Mn and other metals- Jules Vern was right!

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