Introduction to Quantitative Mineral Resource Assessments and Required Deposit Models

Donald A. Singer

Plan

- What & why quantitative resource assessments
- A short history
- The nature of mineral resources
- General modeling
- Descriptive models
- Beginning digital models
- Classification of deposits-digital models
- Grade and tonnage models
- Spatial rules for models
- Sources of errors in grade & tonnage models
- Deposit density models
- Cost models

Why Three-part Assessments and What Are They

Previous USGS form of Assessing Undiscovered Mineral Resources

- Low, moderate, high and unknown potential for occurrence of resources

- After about 1980 4 levels describing certainty

Why Three-part Form of Assessment

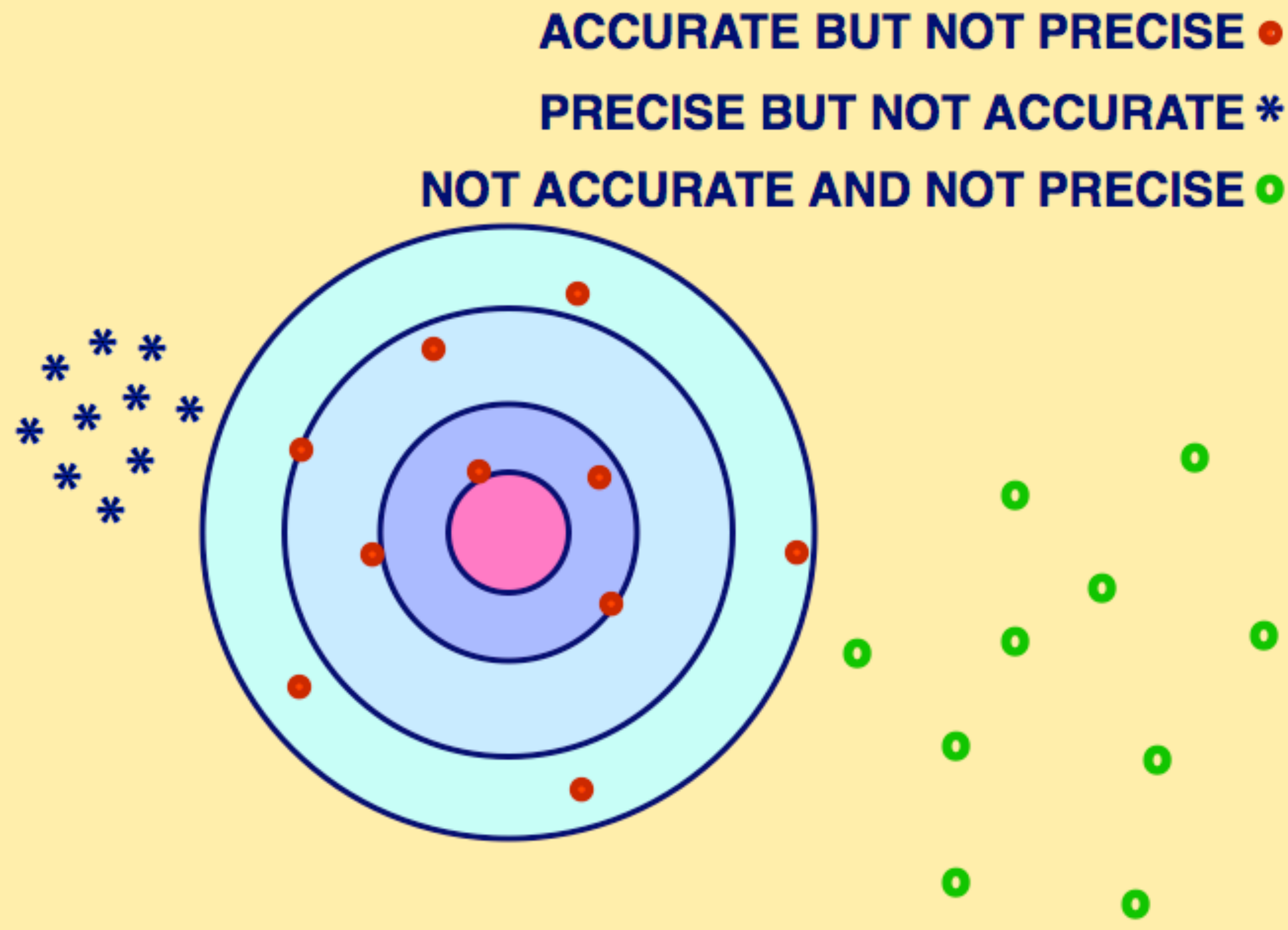
- The kind of assessment recommended here is founded in decision analysis to provide a standard framework for information concerning mineral resources for decisions made under conditions of uncertainty

- Our goal is to provide unbiased information useful to decision-makers

Three-part Assessments:

- Audience is a governmental or industrial policy maker, a manager of exploration, a planner of regional development, or similar decision-maker

- Some of the tools and models presented here will be useful for selection of exploration sites, but that is a side benefit, not the goal



PRECISION AND ACCURACY

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Reducing Biases:

- Design a system to reduce chances of biases

- Provide guidelines

Why Not Just Rank Prospects / Areas?

- Need for financial analysis
- Need for comparison with other land uses
- Need for comparison with distant tracts of land
- Need to know how uncertain the estimates are
- Need for consideration of economic and environmental consequences of possible development

Some Applications of Mineral Resource Assessments:

- To plan and guide exploration programs
- To assist in land use planning
- To plan the location of infrastructure
- To estimate mineral endowment, and
- To identify deposits that present special environmental challenges

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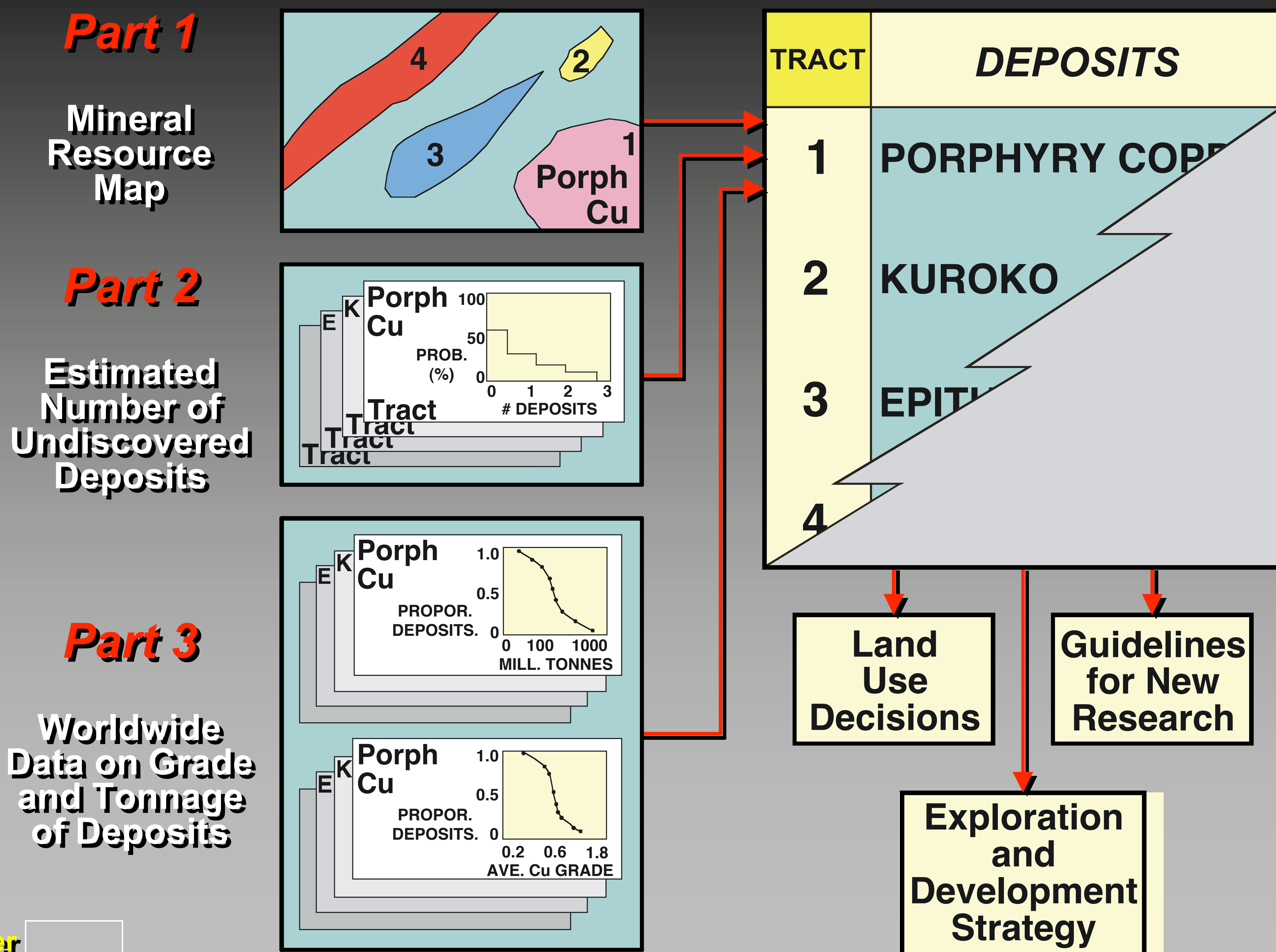
Three-part Resource Assessments

- General locations of undiscovered deposits are delineated from a deposit type's geologic setting
- Frequency distributions of tonnages and grades of well-explored deposits serve as models of grades and tonnages of undiscovered deposits
- Number of undiscovered deposits are estimated probabilistically by type

3-Part Mineral Resource Assessment



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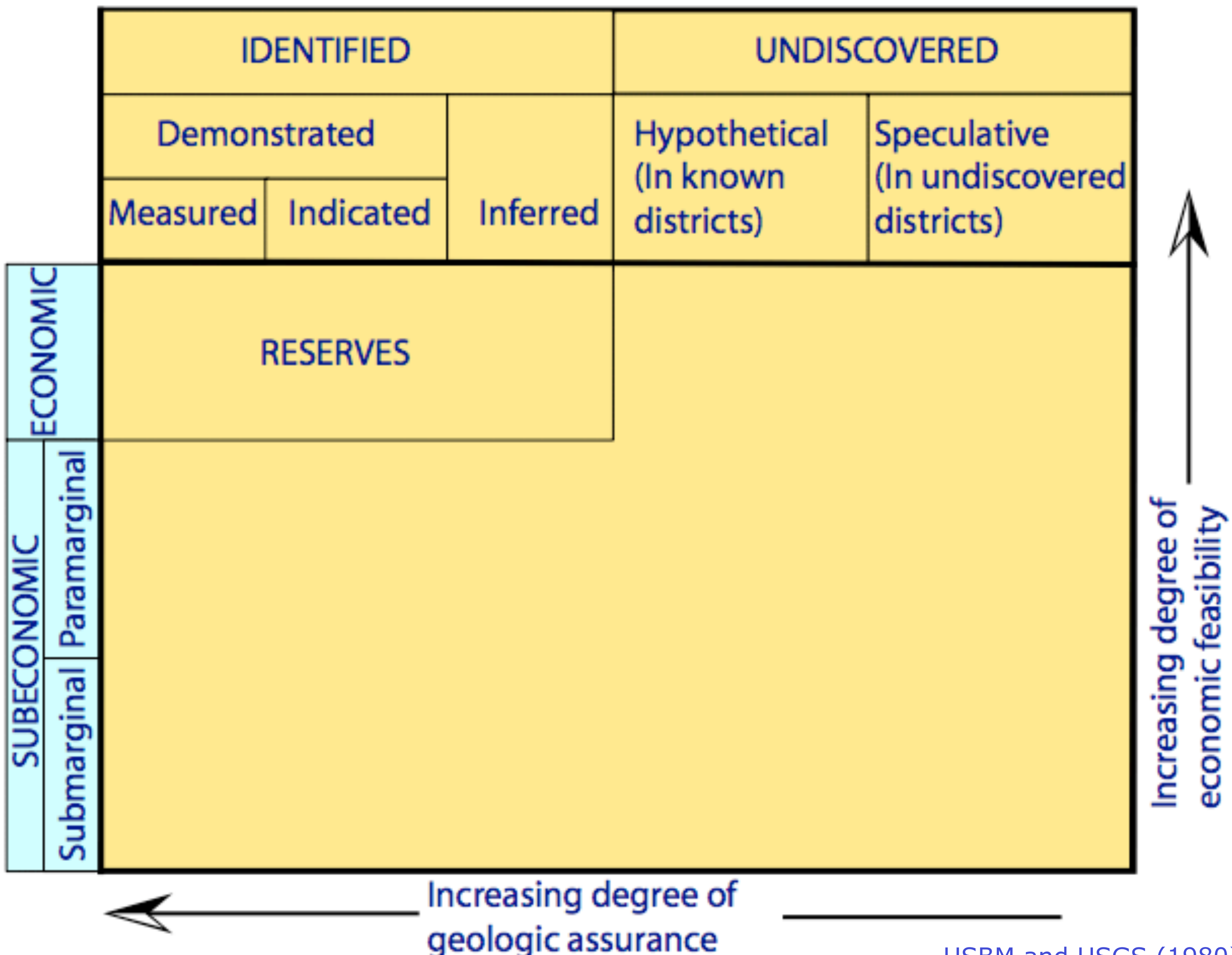
United States Department of the Interior Classification System



USBM and USGS (1980)

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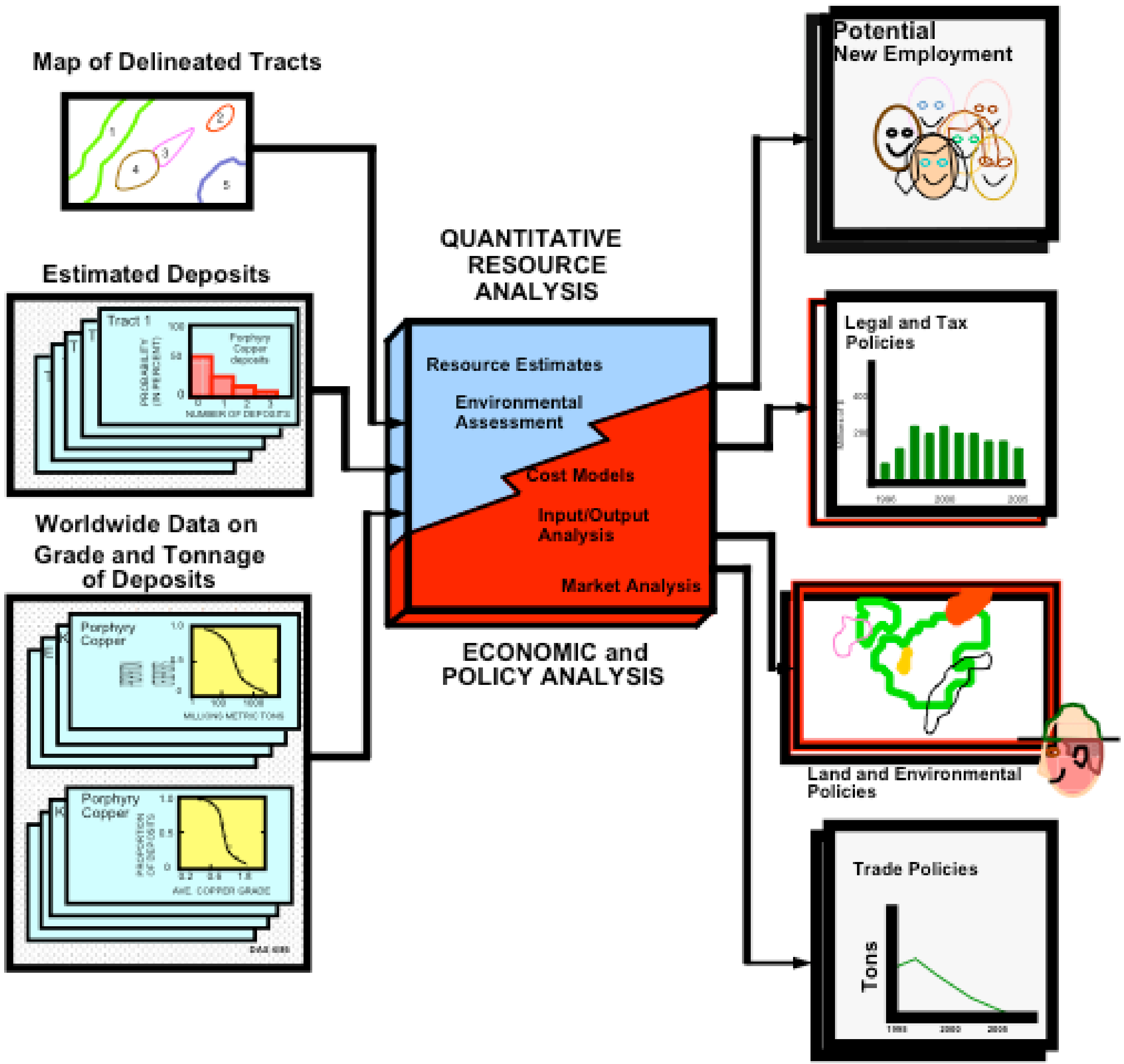

Map of Delineated Tracts
Estimated Deposits
Worldwide Data on Grade and Tonnage of Deposits
QUANTITATIVE RESOURCE ANALYSIS
Resource Estimates
Environmental Assessment
Cost Models
Input/Output Analysis
Market Analysis
ECONOMIC and POLICY ANALYSIS
Potential New Employment
Legal and Tax Policies
Land and Environmental Policies
Trade Policies
Tons

Menzie, 2005

Short History of Three-part Assessments (Where, Who, When)

In the Beginning

- 1957 “Method of appraising economic prospects of mining exploration over large territories—Algerian Sahara case study” by M. Allais
- 1971 Assessment of copper by Kennecott Copper
- 1974 Briefed DOI Office of Management and Budget, on proposed three-part assessment of Alaska.
- 1975 Resources for the Future Conference on Materials Modeling—encouragement by J. Carlson (DoI) & W. Leontief
- Development of three-part by Singer and Menzie with important contributions by Bliss, Orris, Mosier, Root, Cox

Alaska Native Claims Settlement Act (ANSCA)

- Entitled native peoples to select 44 of Alaska's 375 million acres
- Authorized up to 80 million acres of National Interest Lands for inclusion in National Parks, Wildlife Refuges, Wild and Scenic Rivers, and National Forests
- Required Congress to complete land classification by December of 1978
- The Alaska Statehood Act entitled the state to select 102 million acres for its own purposes

Alaska National Interest Lands (1973)

From Singer and Ovenshine (1979)

- In 1974, Congress asked the USGS to assess the mineral resources of the National Interest Lands
- USGS began a series of studies of 1:250,000 scale quadrangles to meet the request
- First 3-part assessments, Nabesna (1975) and Tanacross (1976) published along with a paper on 3-part form (1975)
- By 1976 it was clear that such studies could not be completed within required timeframe because of changes in boundaries and the area of the National Interest Lands

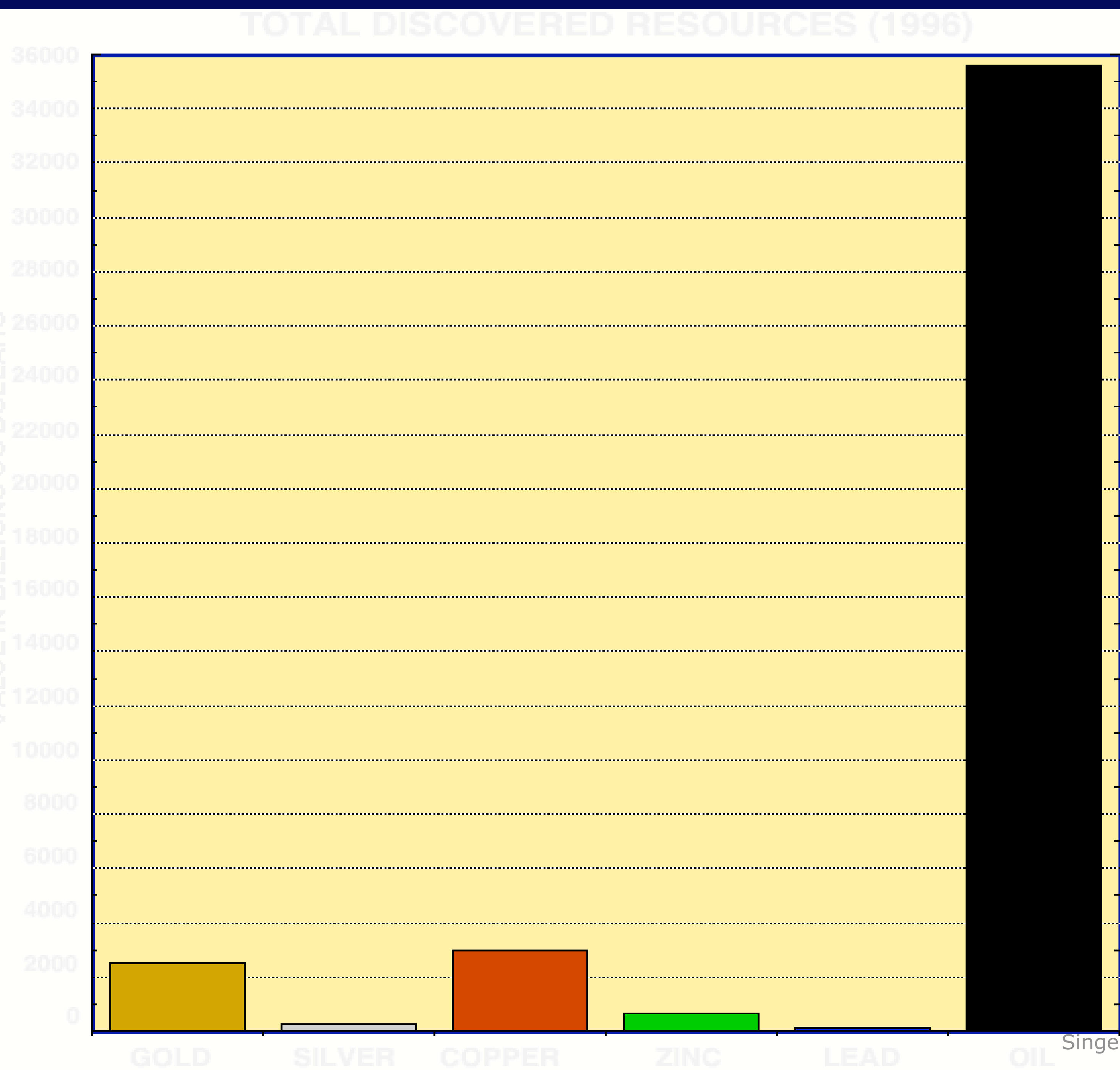
- USGS undertook a 1:1,000,000 scale mineral assessment of Alaska called RAMRAP
- The assessment was divided into 4 regions that covered 80% of the state
- Compilations were made of available geology, mineral occurrences, gravity and aeromagnetic data
- Eleven grade and tonnage models were developed for the 1978 assessments
- The assessment was presented in the 3-Part form where deposit models were available

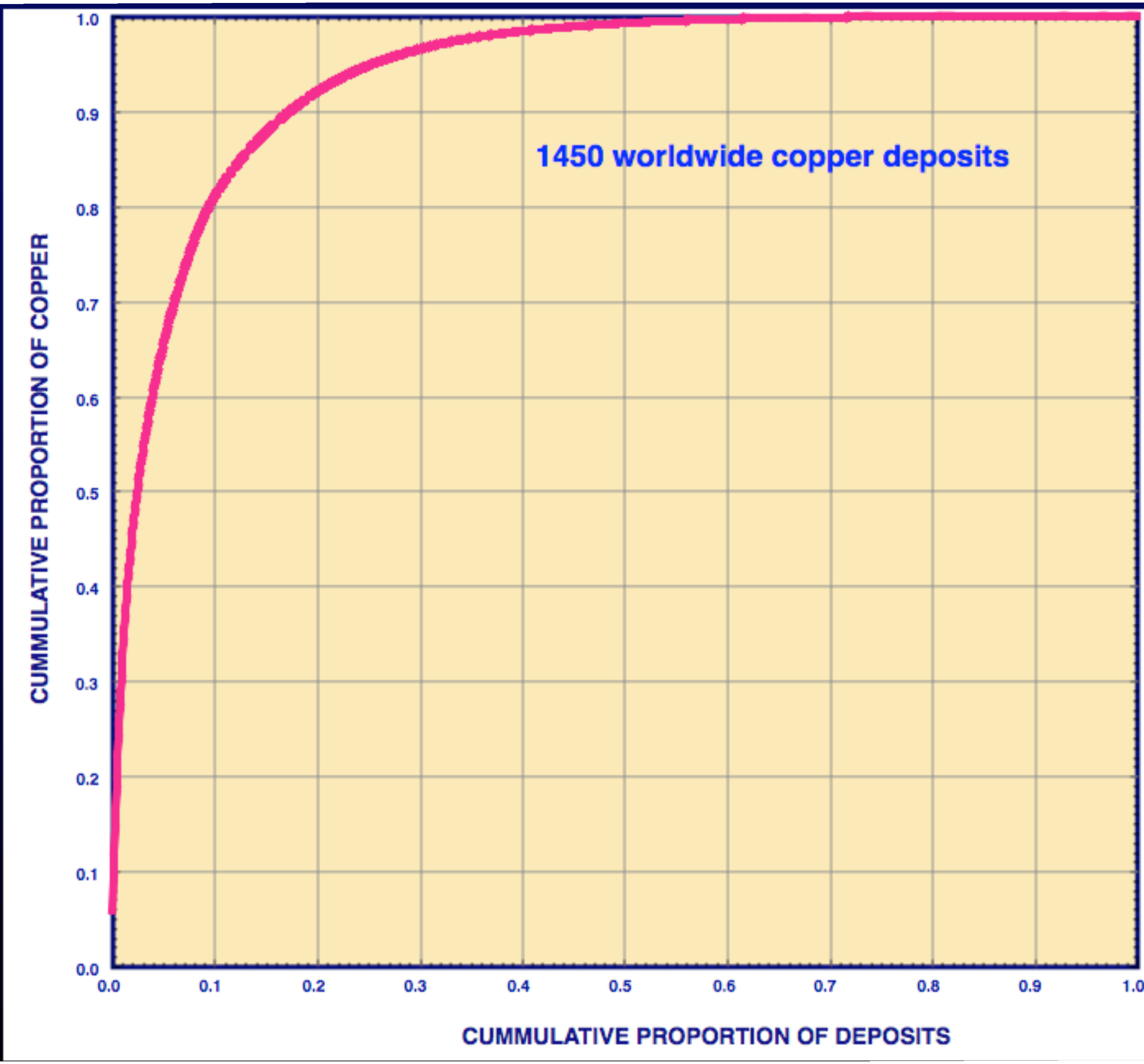
Three-part Assessments

- 7 Alaska 1:250,000 scale quadrangles (1975-81)
- 4 1:1,000,000 sections of Alaska, US (1978)
- 3 US 1:250,000 scale quadrangles (1982-92)
- Colombia 1:1,000,000, descriptive & g-t models pub. (1983-84)
- U.S. Forest wilderness tracts Pacific Mountain System, US (1986)
- Costa Rico 1:500,000 (1987)
- Lode Sn deposits of Seward P. Alaska, US (1989)
- Bolivia (1991)
- Northern Spotted Owl, NW CA, W OR, and W WA, US (1991)
- Kootenai National Forest, US (1992)
- Tongass National Forest, US (1992)
- Nevada, US 1:1,000,000 (1993-96)
- Venezuela (1993)
- Puerto Rico (1993)
- US National assessment 1:1,000,000 (1996-02)
- Bendigo orogenic Au, Victoria, Australia 1:100,000 (2006-07)
- Porphyry Cu, South America 1:1,000,000 (2005-2007)

Nature of Mineral Resources

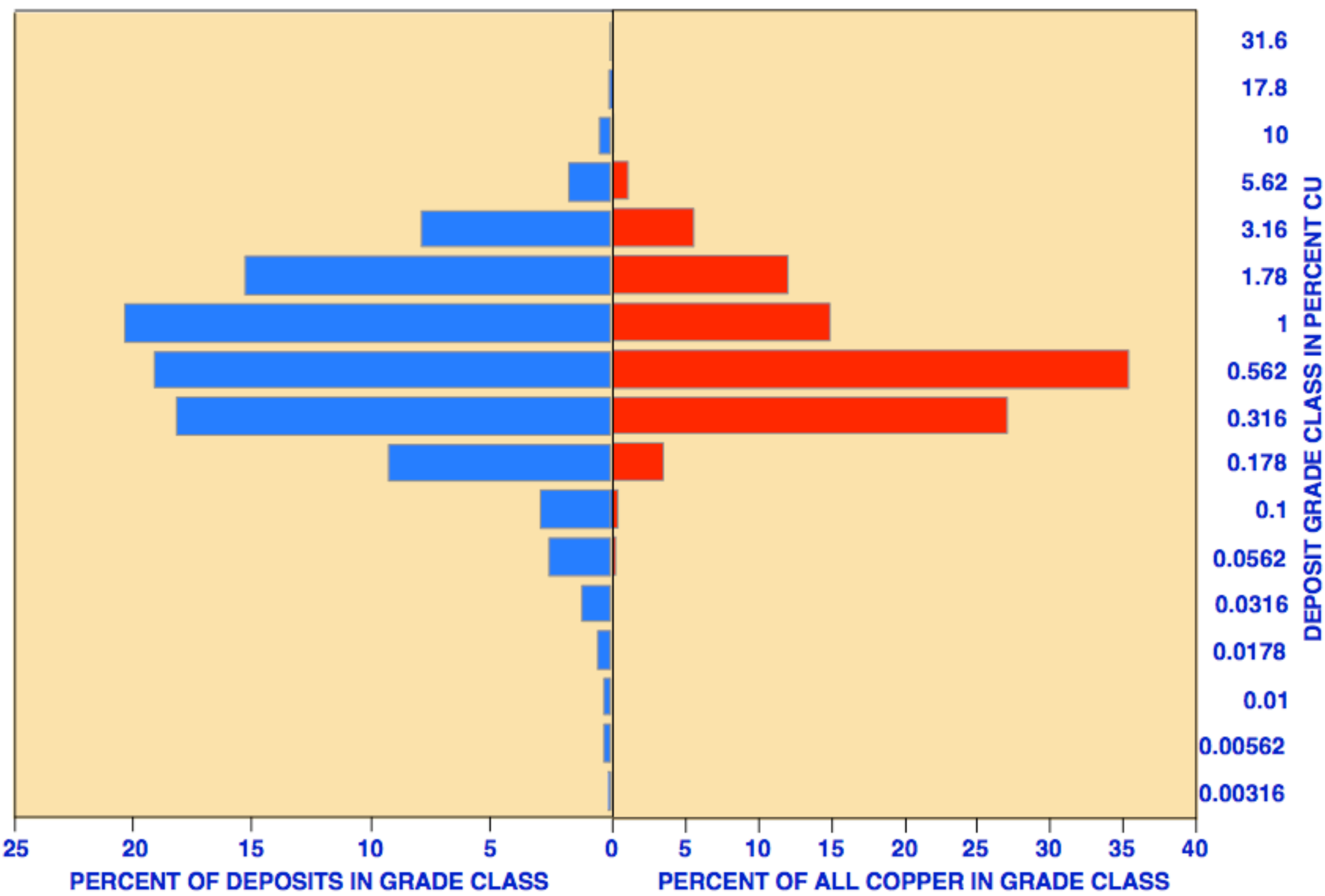
VALUE OF RESOURCES



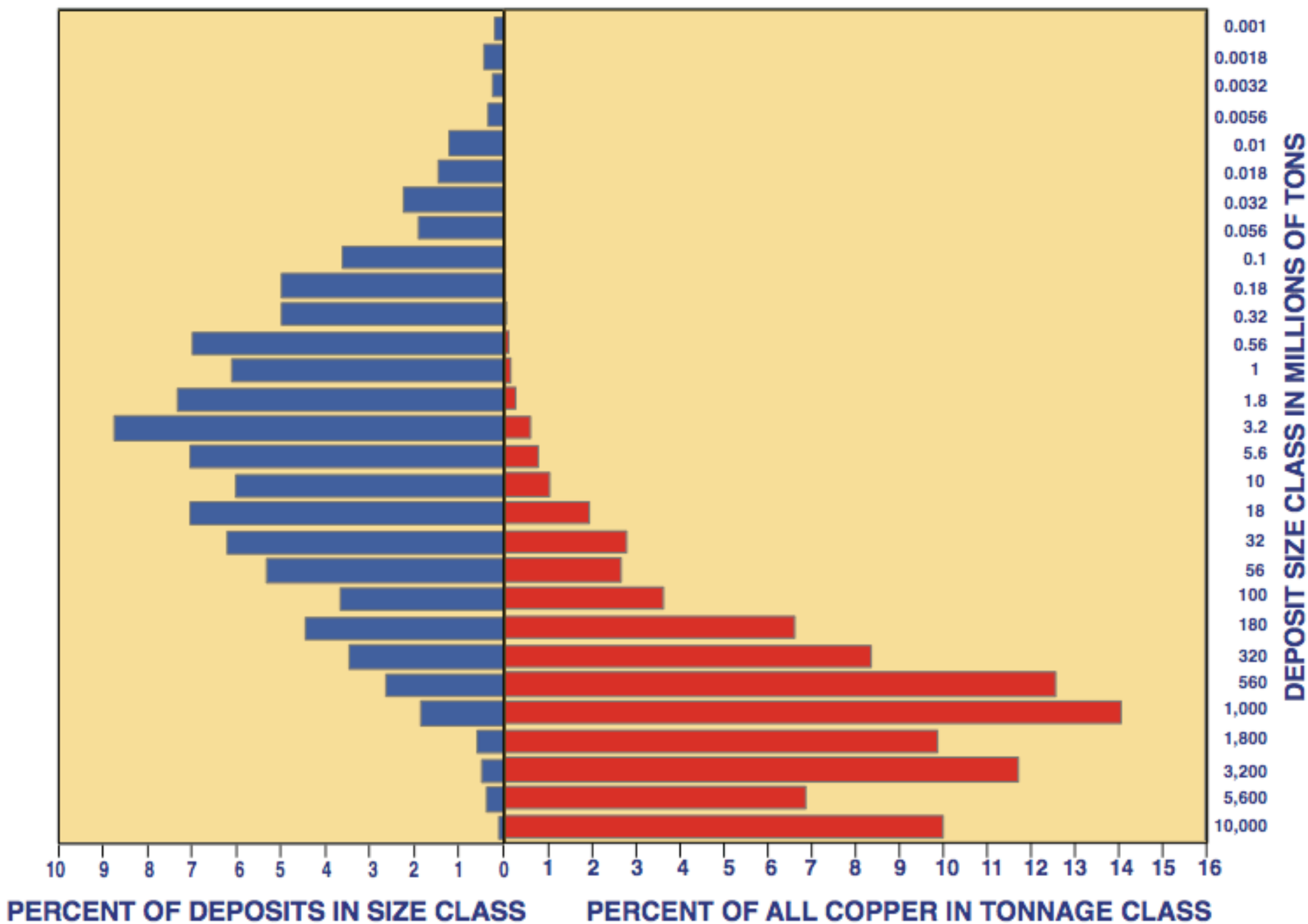


1450 worldwide copper deposits
CUMMULATIVE PROPORTION OF COPPER
CUMMULATIVE PROPORTION OF DEPOSITS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

DAS1007



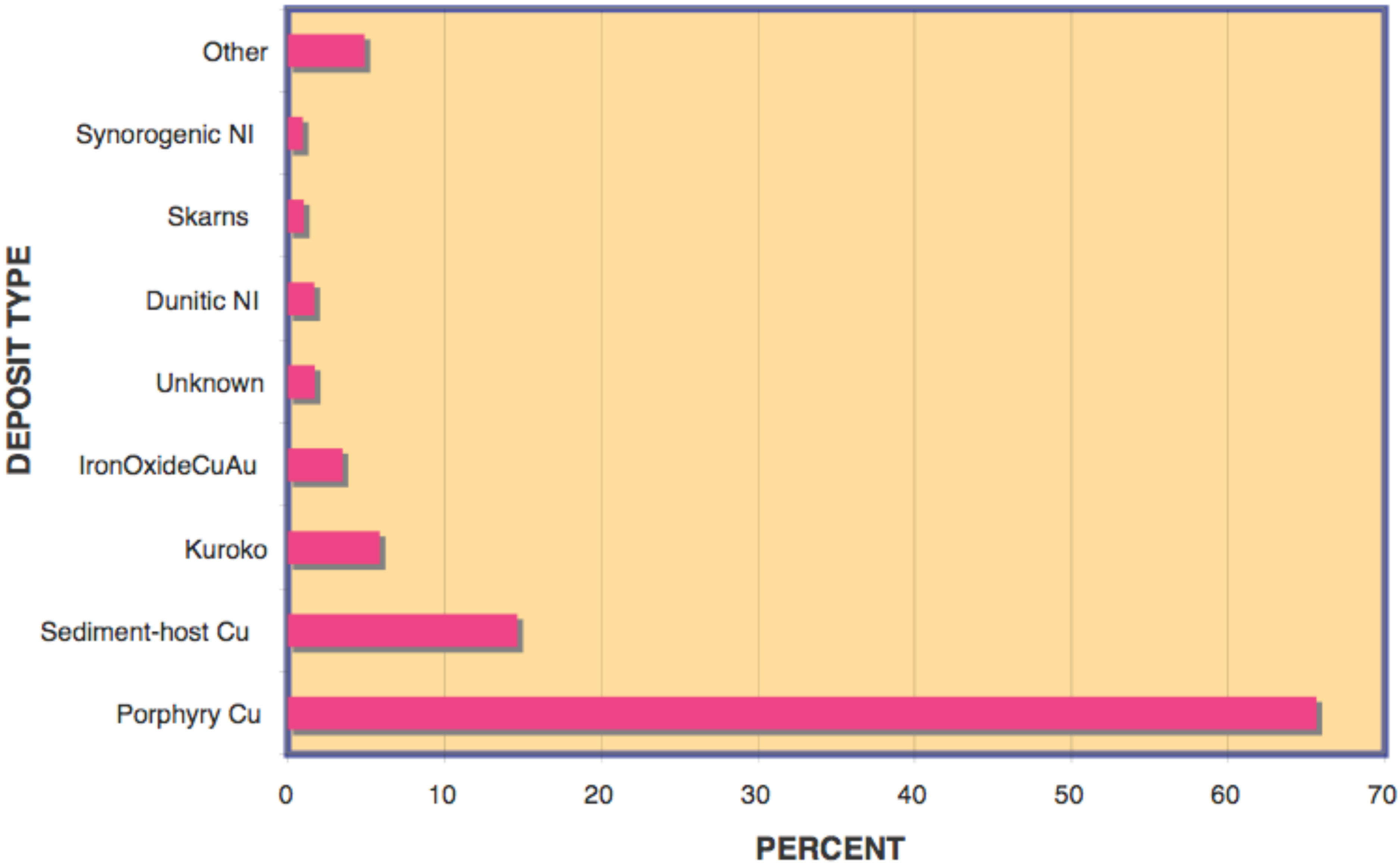
Proportion of copper metal and proportion of deposits by average grade class for 2,045 copper-bearing deposits containing 2,065,000,000 metric tons of copper.



Proportion of copper metal and proportion of deposits by size of deposit for 2045 copper-bearing mineral deposits containing 2,065,000,000 metric tons of copper.

DAS1007

IMPORTANCE OF DEPOSIT TYPE



Percent of all known copper in each type of deposit.

DAS1007

General Modeling Information

Mineral Deposit Models Are Used to Reduce Uncertainty About:

- General locations of resources
- Grades and tonnages of deposits
- Number of deposits
- Value of resources

Singer

Compilations of Mineral Deposit Models Designed For QRA

Cox, D.P., ed., 1983, USGS—INGEOMINAS mineral resource assessment of Colombia: Ore deposit models: USGS Open–File Report83–423, 89 p

Singer, D.A., and Mosier, D.L., eds., 1983, Mineral deposit grade–tonnage models: USGS Open–File Report 83–623, 100 p

Cox, D.P., ed., 1983, USGS—INGEOMINAS mineral resource assessment of Colombia: Additional ore deposit models: USGS Open–File Report 83–901, p. 25

Singer, D.A., and Mosier, D.L., eds., 1983, Mineral deposit grade–tonnage models—II: USGS Open–File Report 83–902, 101 p.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: USGS Bulletin 1693, 379 p.

Cox, D.P., Singer, D.A., and Rodriguez, E.A., eds., 1987, Modelos de yacimientos minerales: USGS Open–File Report 87–486, 514 p. (in spanish)

Mosier, D.L., and Page, N.J, 1988, Descriptive and grade–tonnage models of volcanogenic manganese deposits in oceanic environments––a modification: USGS Bulletin 1811, 28 p.

Anom., translator, Cox, D.P., and Singer, D.A., eds., 1990, Mineral deposit models: USGS Bulletin 1693, 378 p. (in Chinese)

Orris, G.J., and Bliss, J.D., eds., 1991, Some industrial mineral deposit models–descriptive deposit models: USGS Open–File Report 91–11A, 73 p.

Orris, G.J., and Bliss, J.D., eds., 1992, Industrial mineral deposit models: Grade and tonnage deposit: USGS Open–File Report 92–437, 84 p.

Bliss, J.D., ed., 1992, Developments in mineral deposit modeling: USGS Bulletin 2004, 168 p.

Rogers, M.C., et.al., 1995,Descriptive mineral deposit models of metallic and industrial deposit types and related mineral potential assessment criteria: Ontario GS Open-File Report 5916, 241p.

Types of Mineral Deposit Models:

- Descriptive models,
- Grade and tonnage models,
- Density or Spatial models,
- Cost models, and
- Geoenvironmental models

General Comments About Deposit Models[1]

- **A model is a way in which the human thought process can be amplified.**

- **The way to describe a model is first by thinking about what it is for, about its function, not the list of items that make up its structure.**

- **What is surely needed as a minimum is an information system that will help the policy makers to make their decisions.**

[1] Churchman, C. West, 1968, The Systems Approach, Dell Publishing Co., N.Y., 243p.

Mineral Deposit Models Are Important in Quantitative Resource Assessments Because:

- Grades and tonnages of most types are significantly different
- Types occur in different settings identifiable from geologic maps
- Only form allowing economic analysis
- Strong reducer of variance in places and in amounts of resources

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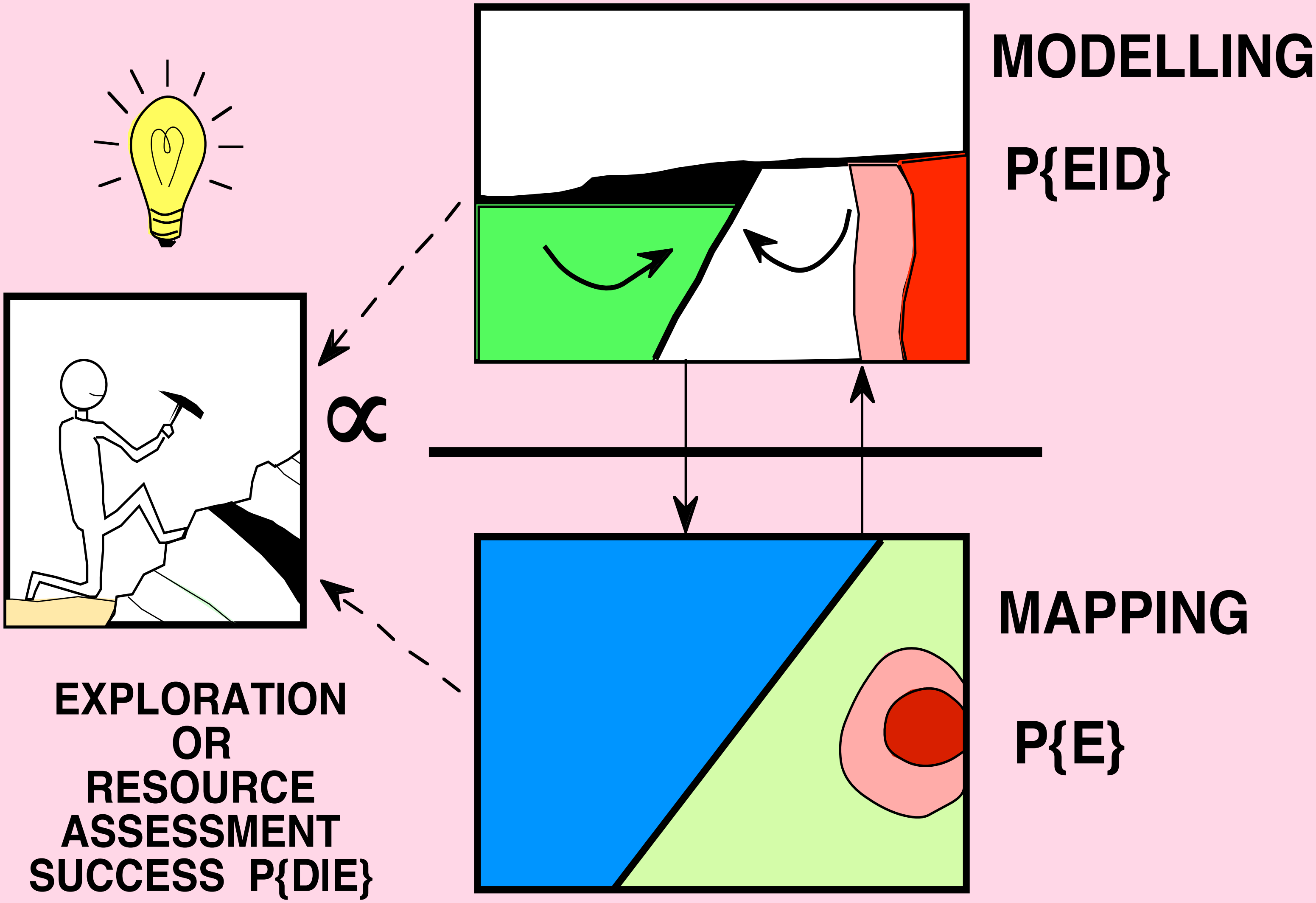
What Is a Mineral Deposit Model?

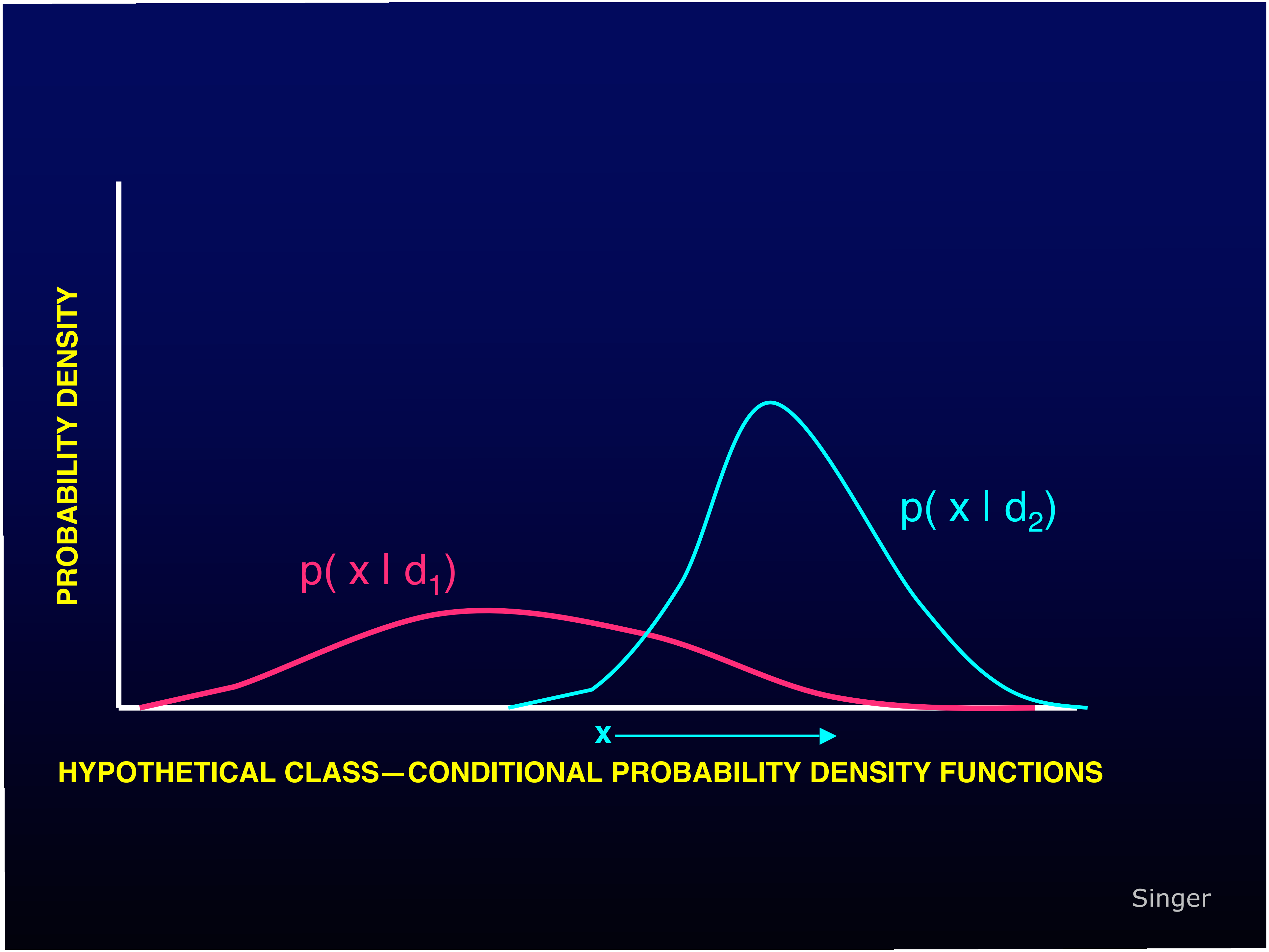
A mineral deposit model is a systematically arranged body of information that describes some or all of the essential characteristics of a particular feature or phenomenon; it presents an idealized condition within which essential elements may be distinguished and from which extraneous elements may be recognized and excluded

(Barton, 1993)



$$P(D \mid E) = P(E \mid D)\, P(D) \,/\, (P(E \mid D)\, P(D) + P(E \mid \bar{D})\, P(\bar{D}))$$

SINGER


PROBABILITY DENSITY
p(x l d$_1$)
p(x l d$_2$)
x
HYPOTHETICAL CLASS—CONDITIONAL PROBABILITY DENSITY FUNCTIONS
Singer

Necessary and Sufficient

- **NECESSARY = If evidence is false (does not exist) then probability of deposit decreases**

$$P(\bar{E}|D) \,/\, P(\bar{E}|\bar{D}) \ll 1.0$$

- **ESSENTIAL MEANS:** $P(D|\bar{E}) = 0.0$

- **SUFFICIENT = If evidence is true (does exist) then probability of deposit increases**

$$P(E|D) \,/\, P(E|\bar{D}) \gg 1.0$$

- **DISCRIMINATORY could mean either necessary or sufficient**

Descriptive Models

Descriptive Model

- GEOLOGICAL ENVIRONMENT
  - Rock types, Textures, Age range
  - Depositional environment, Tectonic setting, Associated deposits
- DEPOSIT DESCRIPTION
  - Mineralogy, Texture/structure, Alteration, Ore Controls, Weathering, Geochemical Signature, Diagram

There Are Many Compilations Of Mineral Deposit Models :

- Anom., ed., 1998, Exploration models for major Australian mineral deposit types
- Ekstrand, et al., eds., 1995, Geology of Canadian mineral deposit types
- Roberts., and Sheahan, eds., 1988, Ore deposit models
- Rongfu, Pei, ed., 1995, Mineral deposits models of China
- Sheahan, and Cherry, eds., 1993, Ore deposit models, volume II

Some Are Designed For Quantitative Resource Assessments:

- Bliss, ed., 1992, Developments in mineral deposit modeling
- Cox, and Singer, eds., 1986, Mineral deposit models

Descriptive Mineral Deposit Models in Three-part Assessments

- Focus on observations
- Only use theories of origin to suggest what to observe
- Observations must be available at scale of assessments

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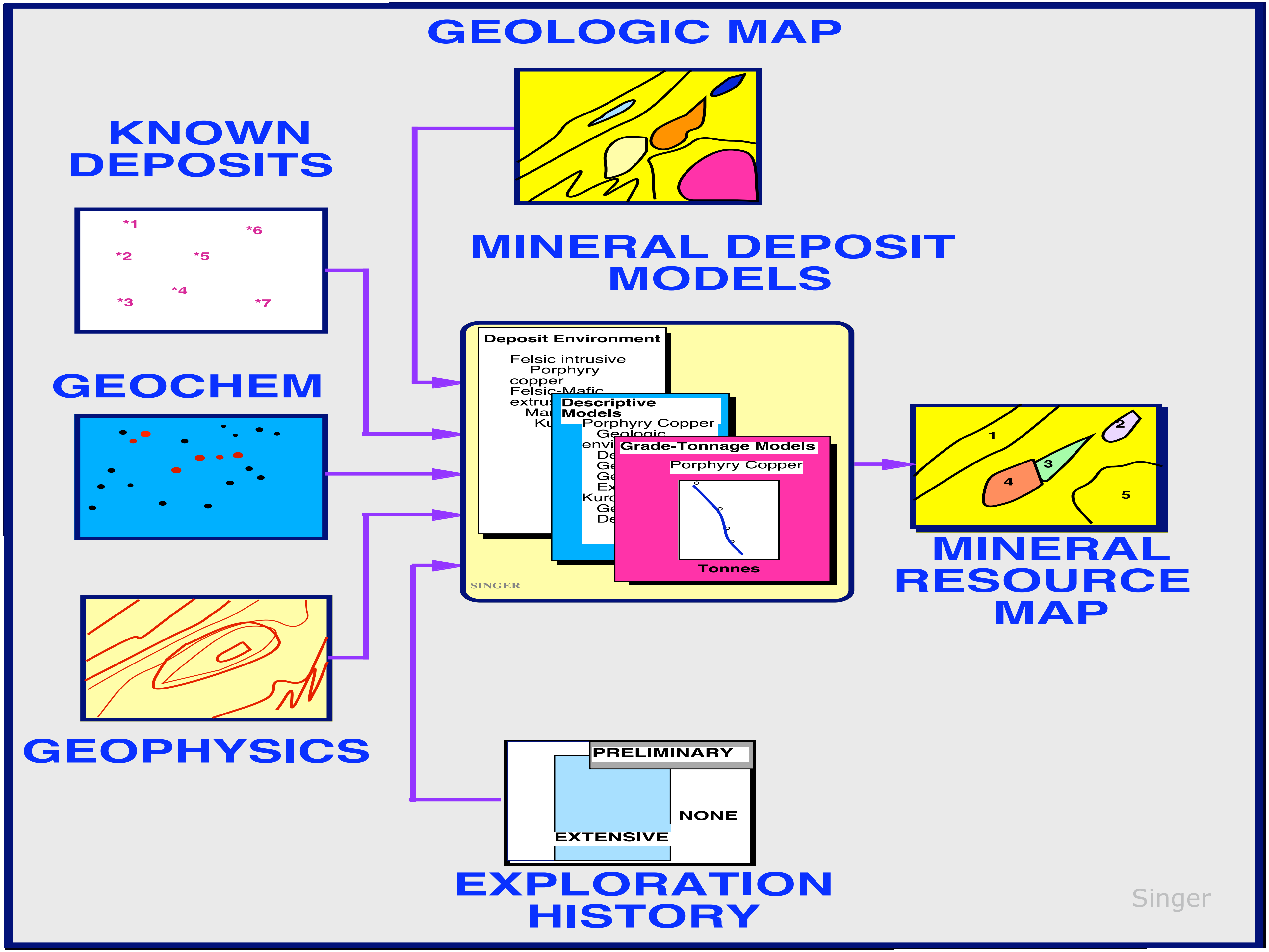

GEOLOGIC MAP
KNOWN DEPOSITS
*1
*6
*2
*5
*4
*3
*7
GEOCHEM
GEOPHYSICS
MINERAL DEPOSIT MODELS
Deposit Environment
Felsic intrusive
Porphyry
copper
Descriptive Models
Porphyry Copper
Grade-Tonnage Models
Porphyry Copper
Tonnes
SINGER
MINERAL RESOURCE MAP
1
2
3
4
5
PRELIMINARY
NONE
EXTENSIVE
EXPLORATION HISTORY
Singer

Building a Model

Desirable to define and use the same set of rules for all deposits in the model

These same set of rules apply to all of the undiscovered deposits that are estimated

DESCRIPTIVE MODEL OF PORPHYRY Cu-Au MODEL 20c

By Dennis P. Cox

DESCRIPTION:

Stockwork veinlets of chalcopyrite, bornite, and magnetite in porphyritic intrusions and coeval volcanic rocks. Ratio of Au (ppm) to Mo (percent) is greater than 30 (see fig. 77).

GENERAL REFERENCES:

Sillitoe, R.H.,1979, Some thoughts on gold-rich porphyry copper deposits: Mineralium Deposita, v. 14, p. 161-174.

Cox, D.P., and Singer, D.A., 1992, Distribution of gold in porphyry copper deposits, in DeYoung, J.H., and Hammerstrom, J.M. eds., Contributions to commodity research: U.S. Geological Survey Bulletin 1877, p. C1-C14.

EXAMPLES:

Dos Pobres, USAZ	(Langton and Williams, 1982)
Copper Mountain, CNBC	(Fahrni and others, 1976)
Tanama, PTRC	(Cox, 1985)

Cox, 1986

Geological Environment

- **Rock Types** Tonalite to monzogranite; dacite, andesite flows and tuffs coeval with intrusive rocks. Also syenite, monzonite, and coeval high-K, low-Ti volcanic rocks (shoshonites).
- **Textures** Intrusive rocks are porphyritic with fine- to medium-grained aplitic groundmass.
- **Age Range** Cretaceous to Quaternary.
- **Depositional Environment** In porphyry intruding coeval volcanic rocks. Both involved and in large-scale breccia. Porphyry bodies may be dikes. Evidence for volcanic center; 1-2 km depth of emplacement.
- **Tectonic Setting(s)** Island-arc volcanic setting, especially waning stage of volcanic cycle. Also continental margin rift-related volcanism.
- **Associated Deposit Types** Porphyry Cu-Mo; gold placers.

Cox, 1986

Deposit Description

- **Mineralogy** Chalcopyrite ± bornite; traces of native gold, electrum, sylvanite, and hessite. Quartz + K-feldspar + biotite + magnetite + chlorite + actinolite + anhydrite. Pyrite + sericite + clay minerals + calcite may occur in late-stage veinlets.

- **Texture/Structure** Veinlets and disseminations.

- **Alteration** Quartz ± magnetite ± biotite (chlorite) ± K-feldspar ± actinolite, ± anhydrite in interior of system. Outer propylitic zone. Late quartz + pyrite + white mica ± clay may overprint early feldspar-stable alteration.

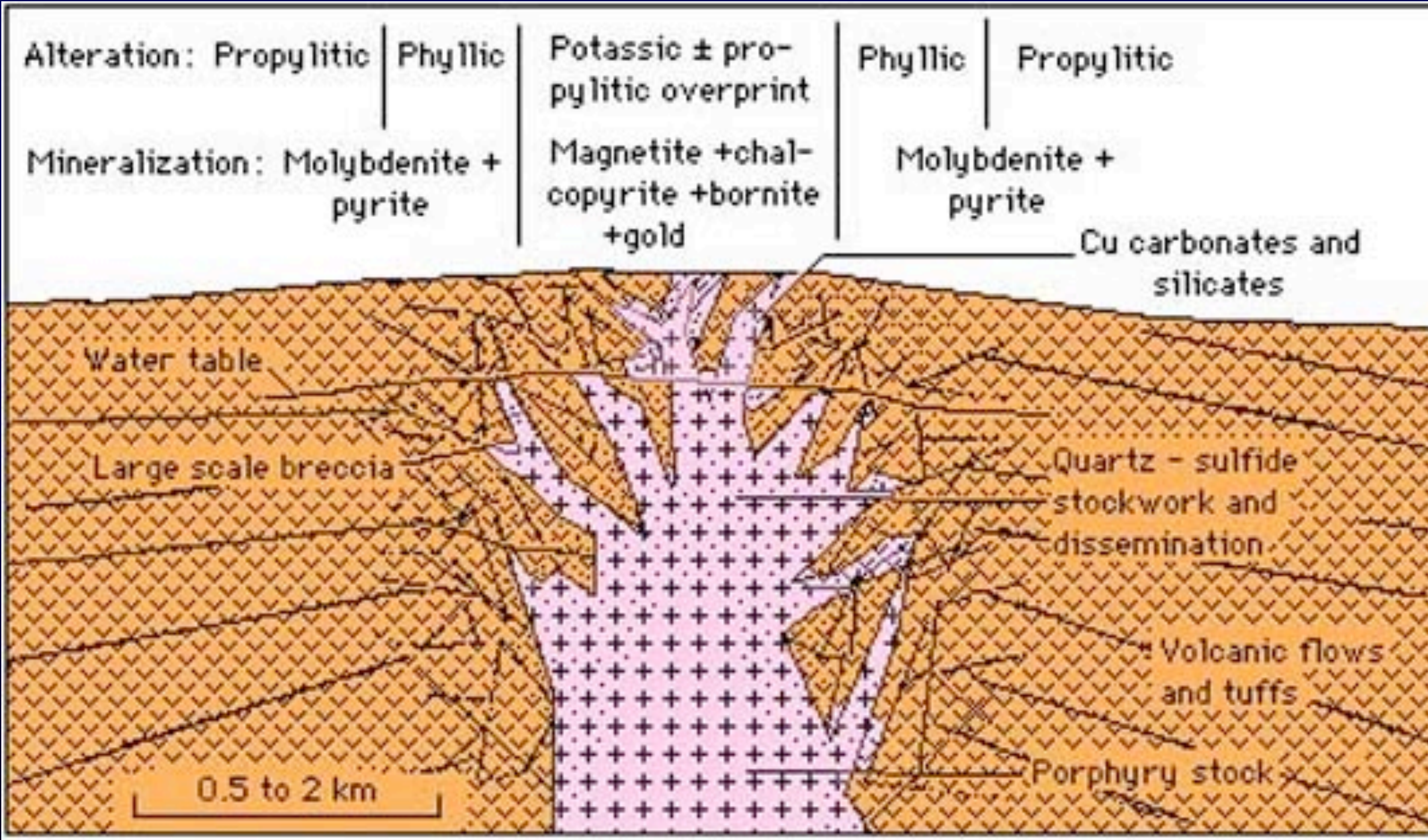
- **Ore Controls** Veinlets and fractures of quartz, sulfides, K-feldspar magnetite, biotite, or chlorite are closely spaced. Ore zone has a bell shape centered on the volcanic-intrusive center. Highest grade ore is commonly at the level at which the stock divides into branches.

- **Weathering** Surface iron staining may be weak or absent if pyrite content is low in protore. Copper silicates and carbonates. Residual soils contain anomalous amounts of rutile.

- **Geochemical Signature** Central Cu, Au, Ag; peripheral Mo. Peripheral Pb, Zn, Mn anomalies may be present if late sericite pyrite alteration is strong. Au (ppm):Mo (percent) >30 in ore zone. Au enriched in residual soil over ore body. System may have magnetic high over intrusion surrounded by magnetic low over pyrite halo.

Cox, 1986

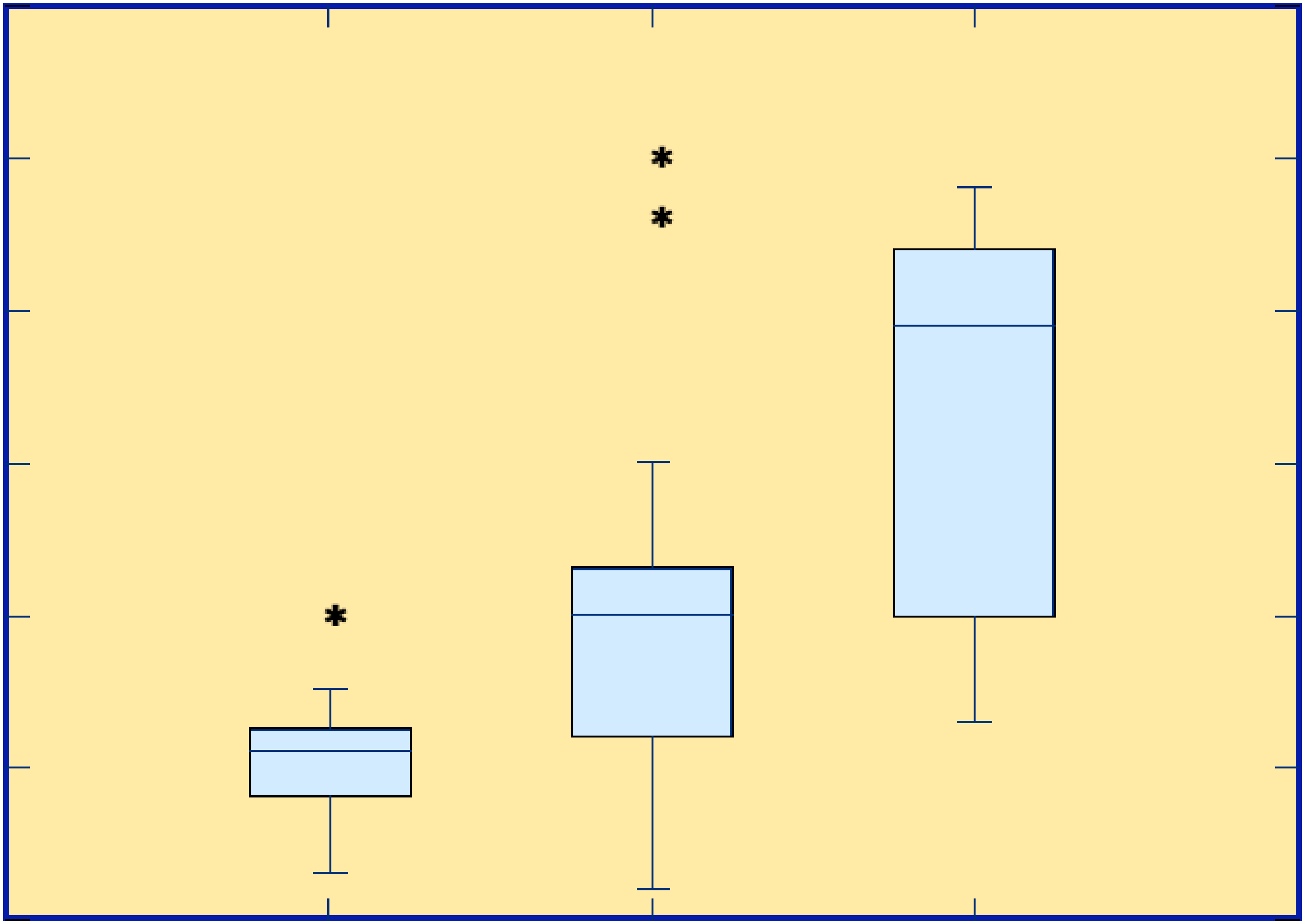
PORPHYRY Cu-Au DIAGRAM



PORPHYRY Cu-Au

Cox, 1986

DEPTH OF EMPLACEMENT OF SUBTYPES OF PORPHYRY COPPER DEPOSITS



Model 24c
DESCRIPTIVE MODEL OF VOLCANOGENIC Mn
By Randolph A. Koski

DESCRIPTION Lenses and stratiform bodies of manganese oxide, carbonate, and silicate in volcanicsedimentary sequences. Genesis related to volcanic (volcanogenic) processes.

GEOLOGICAL ENVIRONMENT

Rock Types Chert, shale, graywacke, tuff, basalt; chert, jasper, basalt (ophiolite); basalt, andesite, rhyolite (island-arc); basalt, limestone; conglomerate, sandstone, tuff, gypsum.

Age Range Cambrian to Pliocene.

Depositional Environment Sea-floor hot spring, generally deep water; some shallow water marine; some may be enclosed basin.

Tectonic Setting(s) Oceanic ridge, marginal basin, island arc, young rifted basin; all can be considered eugeosynclinal

Associated Deposit Types Kuroko massive sulfide deposits.

DESCRIPTIVE MODEL OF CYPRUS-TYPE VOLCANOGENIC MANGANESE.

MODEL 24 c-4

By Dan L. Mosier and Norman J Page

DESCRIPTION Lenticular bodies of umber (manganiferous Fe-rich sedimentary rock) overlying pillow-basalt flows at the base of a sedimentary sequence. Genesis related to volcanogenic processes.

GEOLOGIC ENVIRONMENT

Rock Types Umber, silt, grit, conglomerate, radiolarian chert, pillow basalt, red jasper, chalk, and marl; tholeiitic volcanic rocks.

Textures Basalt shows pillow structures and brecciation.

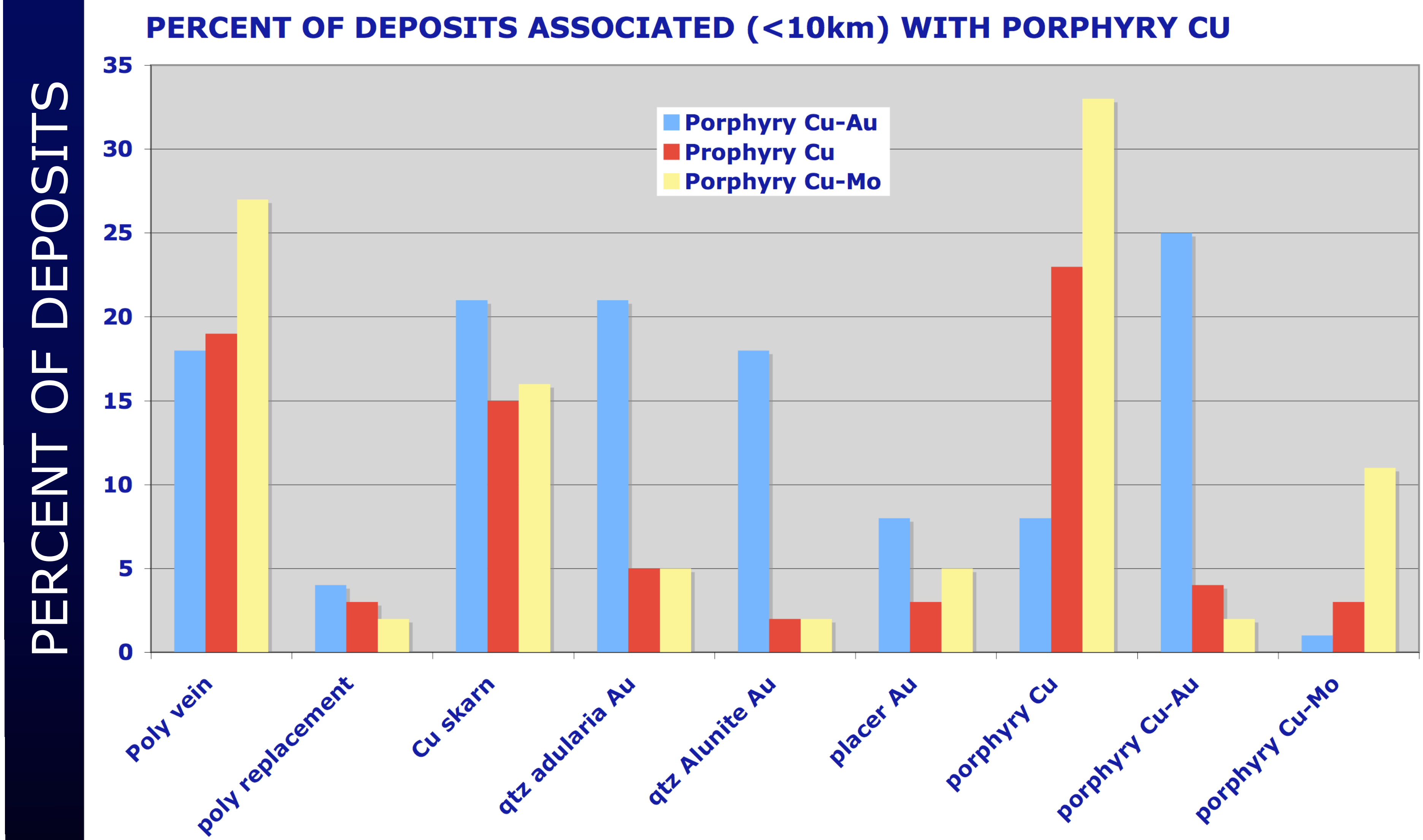
Age Range Late Cretaceous.

Depositional Environment Deep to shallow marine basin near a continental margin.

Tectonic Setting(s) Interarc-basin and midoceanic-ridge settings obducted onto a continental margin.

Associated Deposit Types Cyprus massive sulfide deposits.

Beginning Digital Models



PERCENT OF DEPOSITS ASSOCIATED (<10km) WITH PORPHYRY CU
PERCENT OF DEPOSITS
35
30
25
20
15
10
5
0
Porphyry Cu-Au
Prophyry Cu
Porphyry Cu-Mo
Poly vein
poly replacement
Cu skarn
qtz adularia Au
qtz Alunite Au
placer Au
porphyry Cu
porphyry Cu-Au
porphyry Cu-Mo

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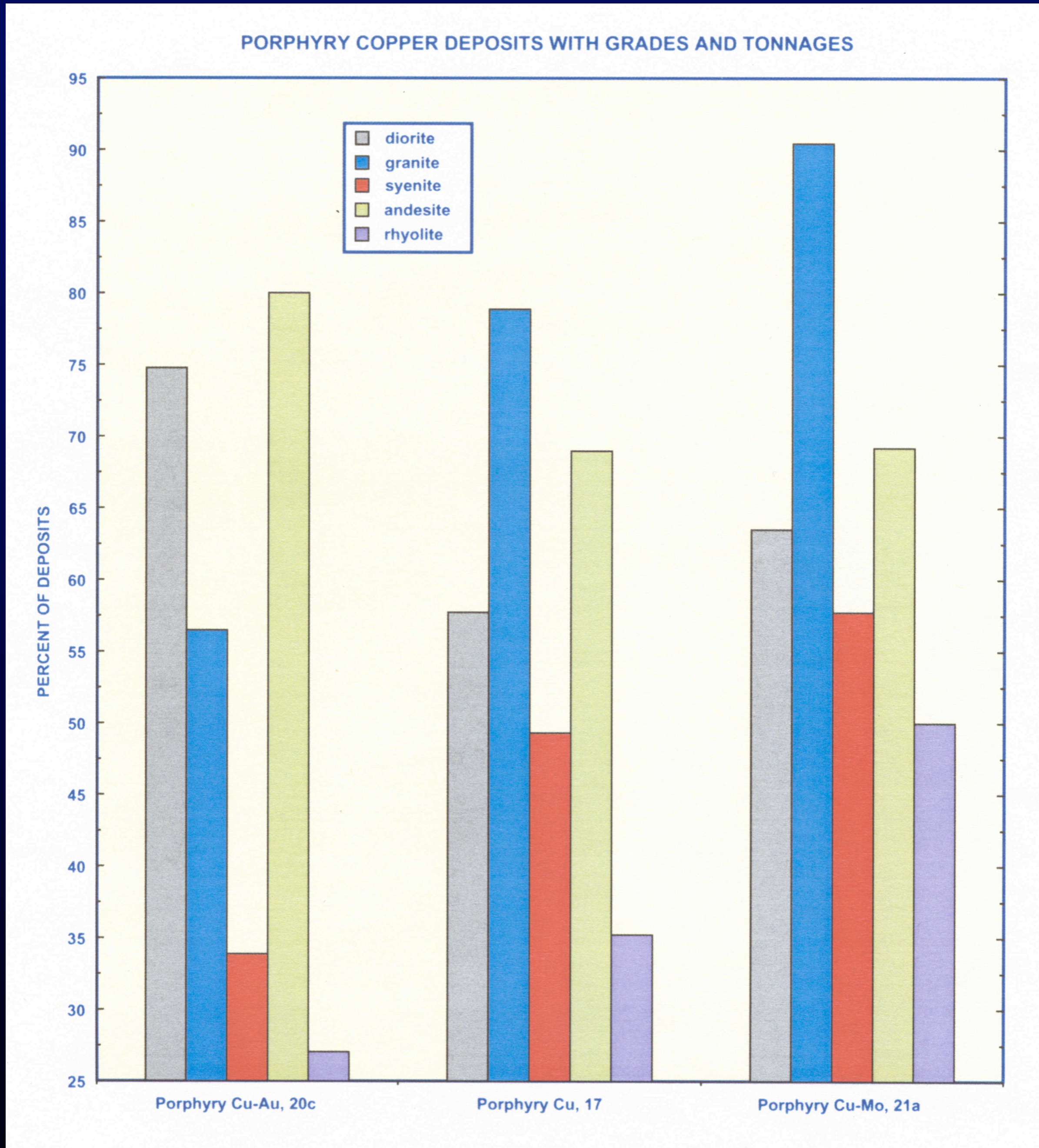
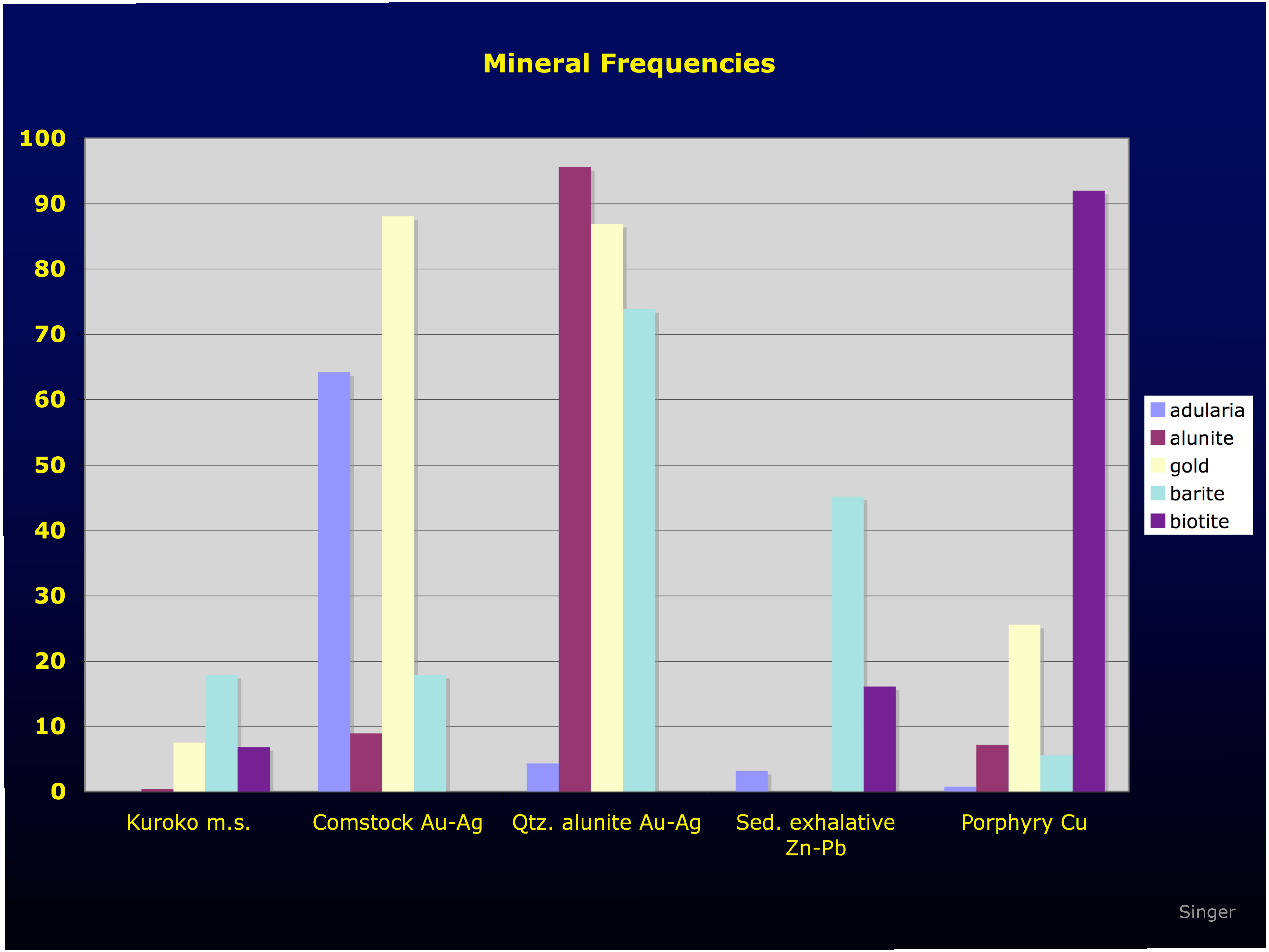


PORPHYRY COPPER DEPOSITS WITH GRADES AND TONNAGES
PERCENT OF DEPOSITS
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
diorite
granite
syenite
andesite
rhyolite
Porphyry Cu-Au, 20c
Porphyry Cu, 17
Porphyry Cu-Mo, 21a

Singer


Mineral Frequencies
100
90
80
70
60
50
40
30
20
10
0
Kuroko m.s.
Comstock Au-Ag
Qtz. alunite Au-Ag
Sed. exhalative Zn-Pb
Porphyry Cu
adularia
alunite
gold
barite
biotite
Singer

Classification of Deposits: Benefits of Digital Models

Probabilistic Neural Network Is a Classifier

- **Estimates probability of unknown sample being from known populations**
- **True probability density estimated from training set**
- **If we know true probability density ($f_i[x]$), prior probability (p_i), and cost of misclassification (c_i), there is a Bayes optimal decision rule:** $p_i c_i f_i[x] > p_j c_j f_j[x]$

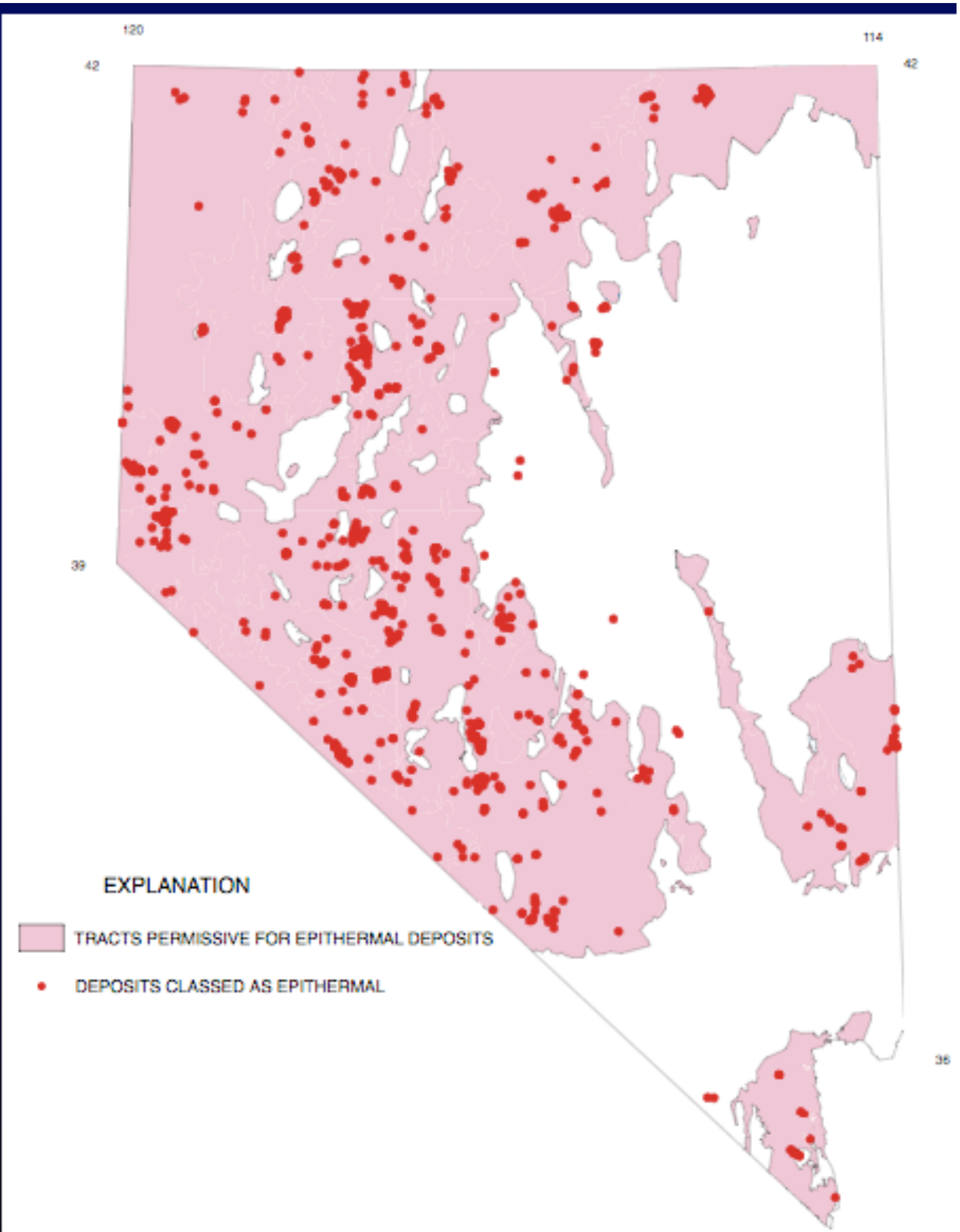
Singer and Kouda, 1997

Classification of Deposits With a Probabilistic Neural Network

- Trained PNN with 1005 deposits to recognize 28 deposit types based on 58 minerals & 6 rock types
- Test A: type–by–type comparison with experts
  53% of 989 deposits in 28 types correctly classed
- Test B: grouped types in expert delineated tracts
  99% of 907 pluton-related deposits correctly classed 98% of 825 epithermal deposits correctly classed

Singer and Kouda, 1997

Occurrences PNN Classed Into Epithermal Group Based on Minerals/Rocks (98% of 825 Correct)



Singer and Kouda, 1997

Benefits of Digital Descriptive Mineral Deposit

- Documented and reproducible
- Do not miss the obvious
- Can be used in classification and prediction

Grade and Tonnage Models

The purpose of grade and tonnage models is to provide unbiased representations of the grades and tonnages of undiscovered mineral deposits in a tract or belt

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Building a Model

Desirable to define and use the same set of rules for all deposits in the model

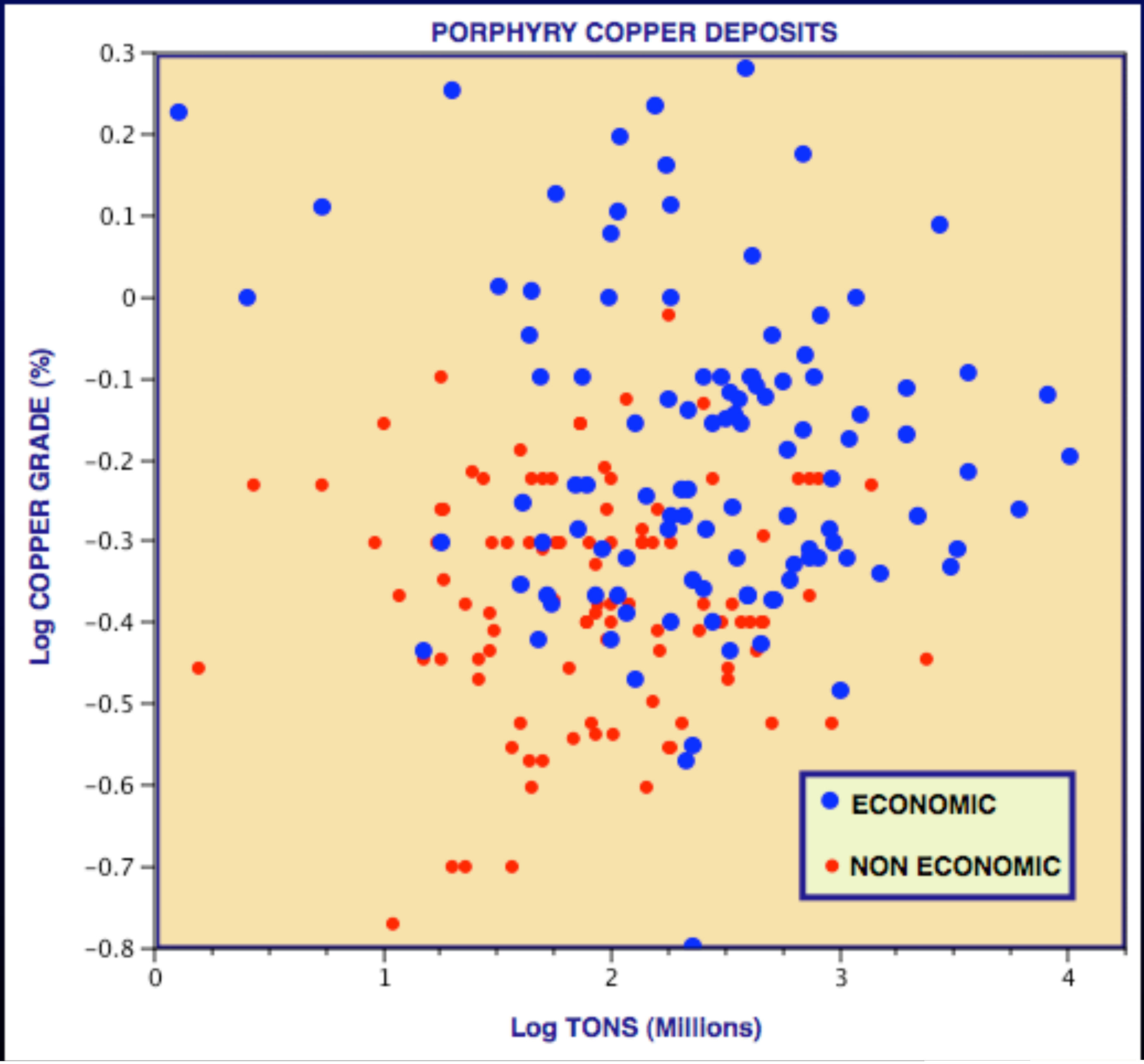
These same set of rules apply to all of the undiscovered deposits that are estimated

Grade Tonnage Models

- Grade and tonnage models used in 3-part assessments represent the premining grade and tonnage of a deposit. This means that current resources at the lowest cutoff grade are added to past production.

- Grade and tonnage models use resource figures to represent the mineralized material in a deposit in order to allow for possibly different technologies and mining costs to be assumed.

Grade and Tonnage Models Contain Uneconomic Deposits and Typically Have Tonnage Independent of Grade



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When Is A New Model Needed?

A new model is required in any situation where there is no existing grade and tonnage model.

A new model is required in any situation where an existing grade and tonnage model can be shown to be a biased model of the undiscovered deposits.

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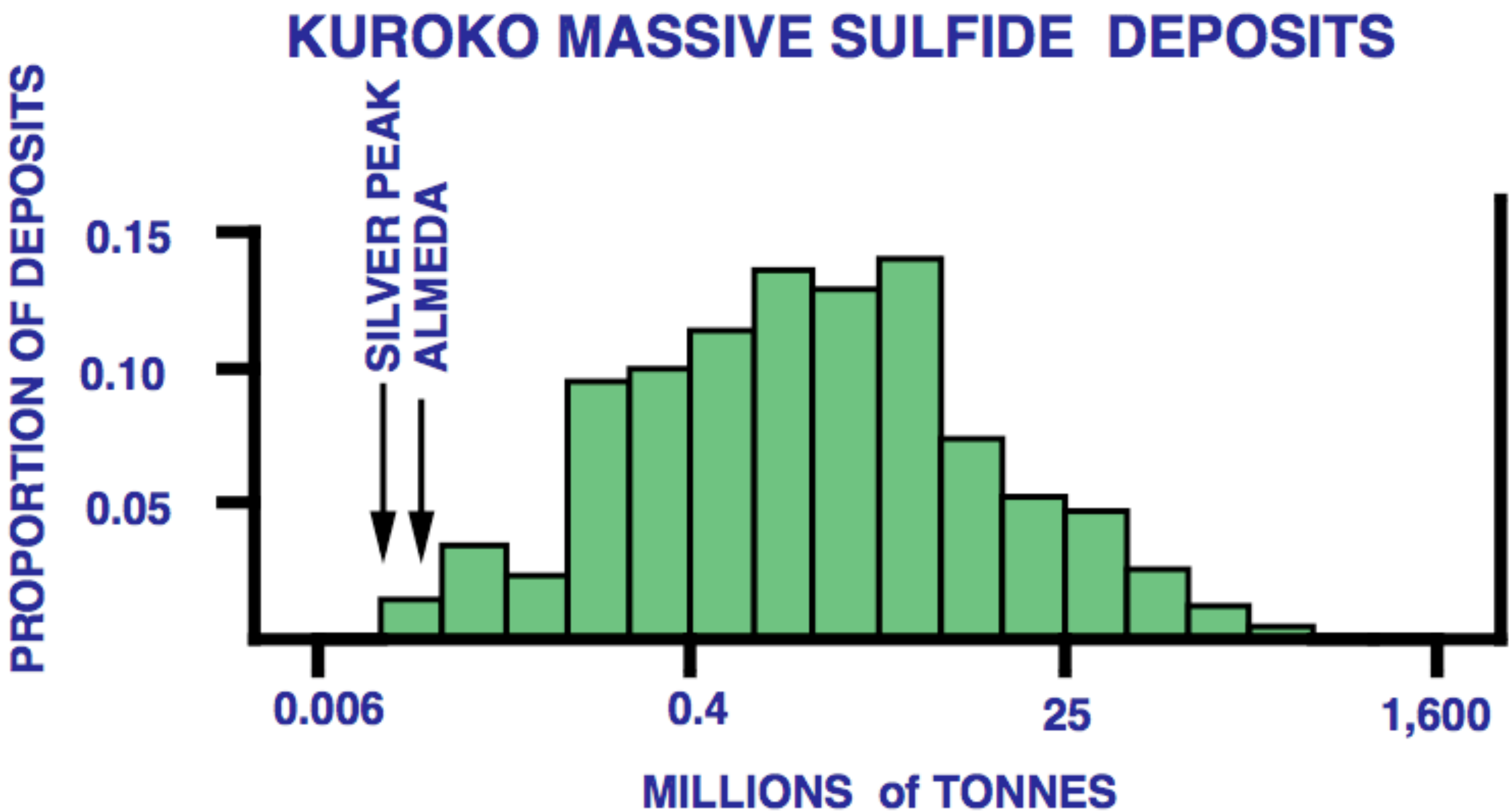
Suggesting Existing Model Not Appropriate (1983, 1993)



Comparison of tonnages of two deposits in Medford OR to the kuroko massive sulfide grade and tonnage model.

Singer

New Model Needed

Two Jurassic kuroko-type massive sulfide deposits were known in a part of southern Oregon where a mineral resource assessment was being prepared. The two previously mined and thoroughly explored deposits were found with a "*t*" test to be significantly lower in tonnage ($p < 0.001$) than the general kuroko grade and tonnage model. Clearly a new grade and tonnage model was needed here.

Singer and others, 1983
Singer, 1993

New Grade and Tonnage Model of Sierran Kuroko Deposits

- This model applies to the descriptive model for kuroko massive sulfide, number 28a
- Only kuroko deposits of Triassic or Jurassic age in North America were used to construct this subset
- These deposits are significantly smaller in tonnage than the worldwide kuroko group
- The reason for the size difference is not known

Spatial Rules for a Deposit Model

Scale Effects on Deposit Definition

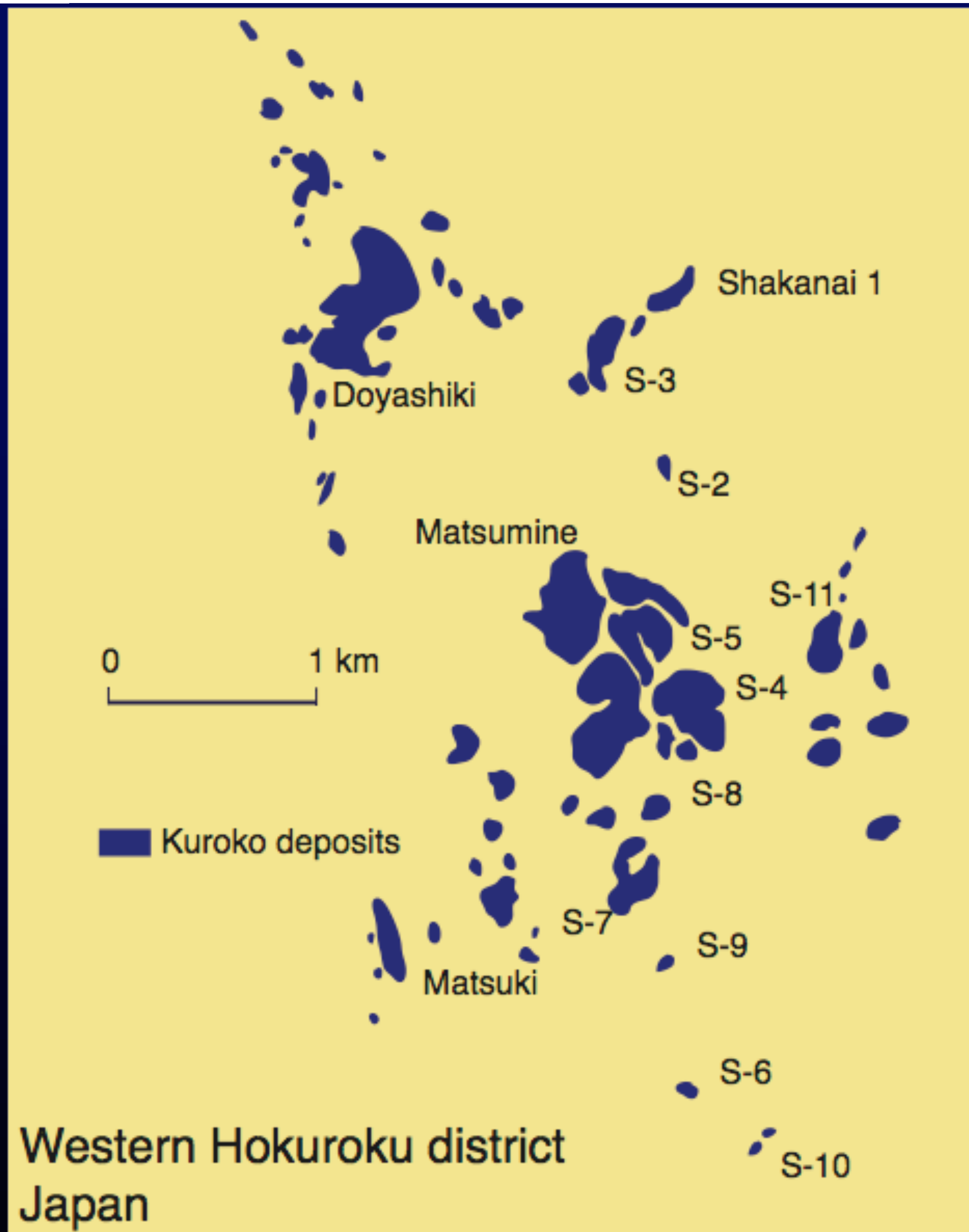
Map scale affects what is called a mineral deposit

For some deposits legal boundaries affect what is reported as a deposit

Spatial Rules

For deposit models, a spatial rule should be used to determine which ore bodies should be combined. For example, ore bodies of both kuroko and Cyprus type massive sulfides were combined into single deposits based on a 500-m rule of adjacency (Mosier and others, 1983)

Kuroko deposits in Eastern Hokuroku Basin



Singer

Ore Deposits in Western Hokuroku Basin (Tanimura et al, 1983)

Deposit Name	Cu%	Zn%	Pb%	Au (ppm)	Ag (ppm)	Tons (m. metric)
Tsutsumizawa	1.13	1.4	0.4			0.411
Doyashiki	2.28	1.3	0.2			8.946
Kamiyama	1.32	10	1.8			0.932
Nanatsudate	2.6	7.8	1			0.677
E. Kannondo	1.15	1.3	0.2			0.105
Oyama 1	1.5	3	0.5			0.06
N. Kannondo	3.02	3	0.5			0.258
Inarizawa	1	6.5	1.2			0.034
Ochiaizawa	2.32	6.5	0.5			0.207
Oishizawa	2.82	2.4	0.4			0.09
Oyama 2	2.7	1.5	0.3			0.1
Matsumine	2.39	3.6	1	0.5	57	30
Shakanai 1	2.3	14.6	3.2	2	270	0.54
Shakanai 2	2.3	12.3	7.6	1.7	260	
Shakanai 3	1.1	10	6.2	0.8	410	0.36
Shakanai 4	1.7	2.9	0.7	0.3	25	3.6
Shakanai 5	1.9	3.4	1			0.43
Shakanai 7	1.3	3.2	0.9			1
Shakanai 8	0.7	1	0.2			2.8
Shakanai 11	1.9	11.8	3.4			
Matsuki	3.74	2	0.8	0.6	55	0.66
Takadate						1.2
Takadate South						

Applying Spatial Rule

- Data on the 23 different "deposits" were updated
- A 500m rule was applied, resulting in only three deposits
- Grade and tonnage models built using spatial rules result in grade and tonnage models that can be consistently used in assessments
- Models constructed in this manner are significantly different than those constructed without such rules

Building a Model

- Construction of grade and tonnage models involves identification of well-explored deposits that are believed to belong to type being modeled

- A descriptive model is commonly prepared, and attributes of each deposit in the group are compared with it to ensure that all are same type

- Data include average grades of each metal or commodity of possible economic interest and associated tonnage based on total production, reserves, and resources at lowest possible cutoff grade

- These data represent an estimate of the endowment of each known deposit so that the final model can represent the endowment of all undiscovered deposits

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Basic Grade and Tonnage Data

- When planning a mine, it is common to calculate tonnage and grade at different cutoff grades. This allows engineers to plan the mine under several scenarios of material costs and commodity prices and for investors to be aware of alternatives.
- The designation reserves applies to material that is well characterized and can be produced at a profit. Resources include reserves and additional material that is too low grade to currently be profitably produced.
- As prices and costs change during mining, reserves of deposit may be updated. Often costs of mining decrease as mining takes place and lower grade material that was not initially thought to be economic to produce will be able to be profitably mined.

Menzie, 2005

How Are Data Displayed in Grade Tonnage Models?

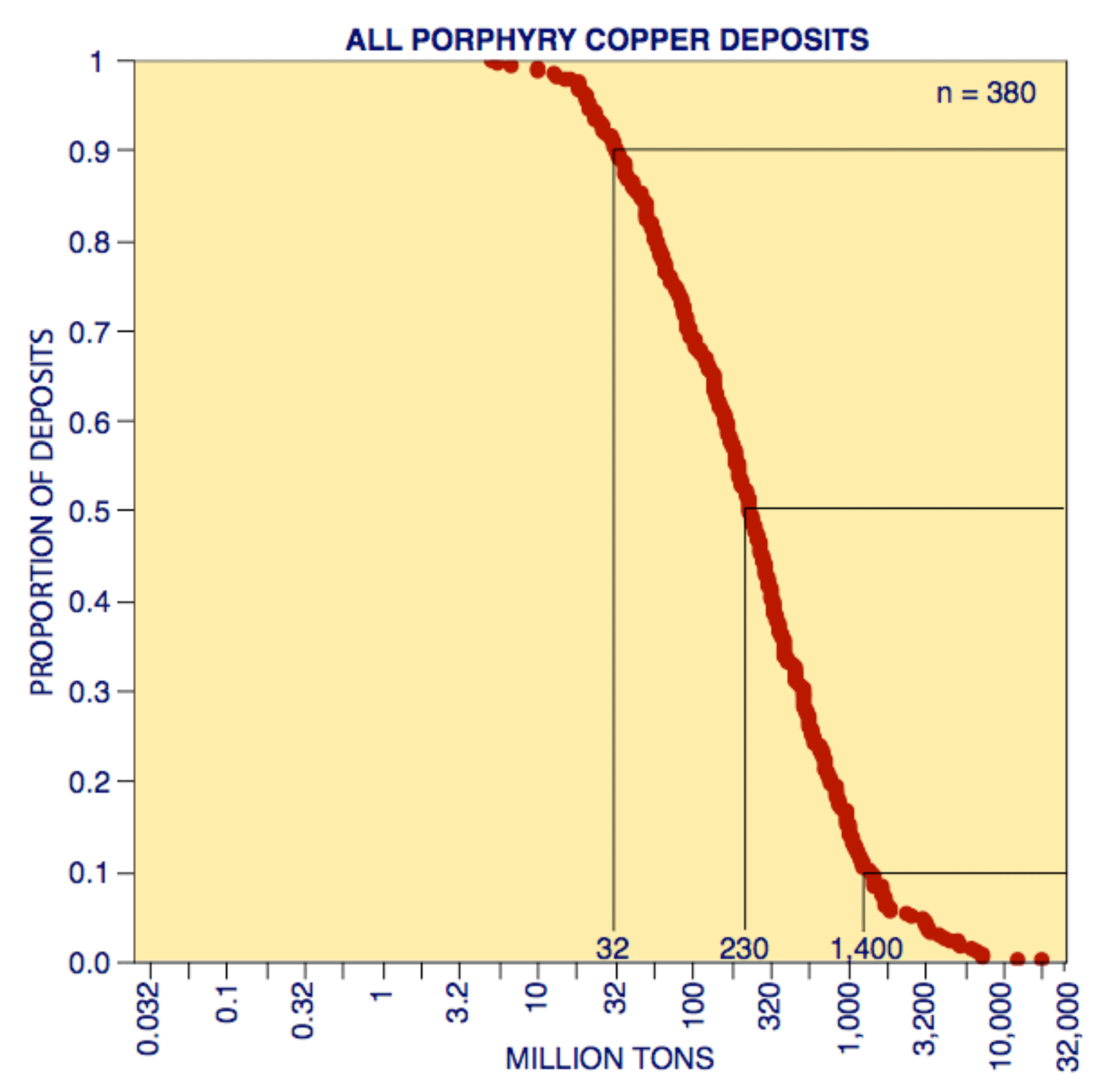
- Grade and tonnage data are usually displayed either as univariate or as bivariate plots.

- In univariate plots the data are sorted from smallest to largest and are plotted against the proportion of the deposits that are as large or larger than each deposit. The median of the data (fiftieth percentile), transformed to logarithms is calculated and ninetieth and tenth percentiles are calculated, using the standard deviation of the data, and a curve is fit to these data. Note that the horizontal scale in the following graphs is a logarithmic scale.

- A univariate plot is made for tonnage and each grade for which a significant proportion of the deposits report grades.

Porphyry Copper G-T Model

Each point represents a deposit, intercepts at the 90th, 50th, and 10th percentile are presented



Singer

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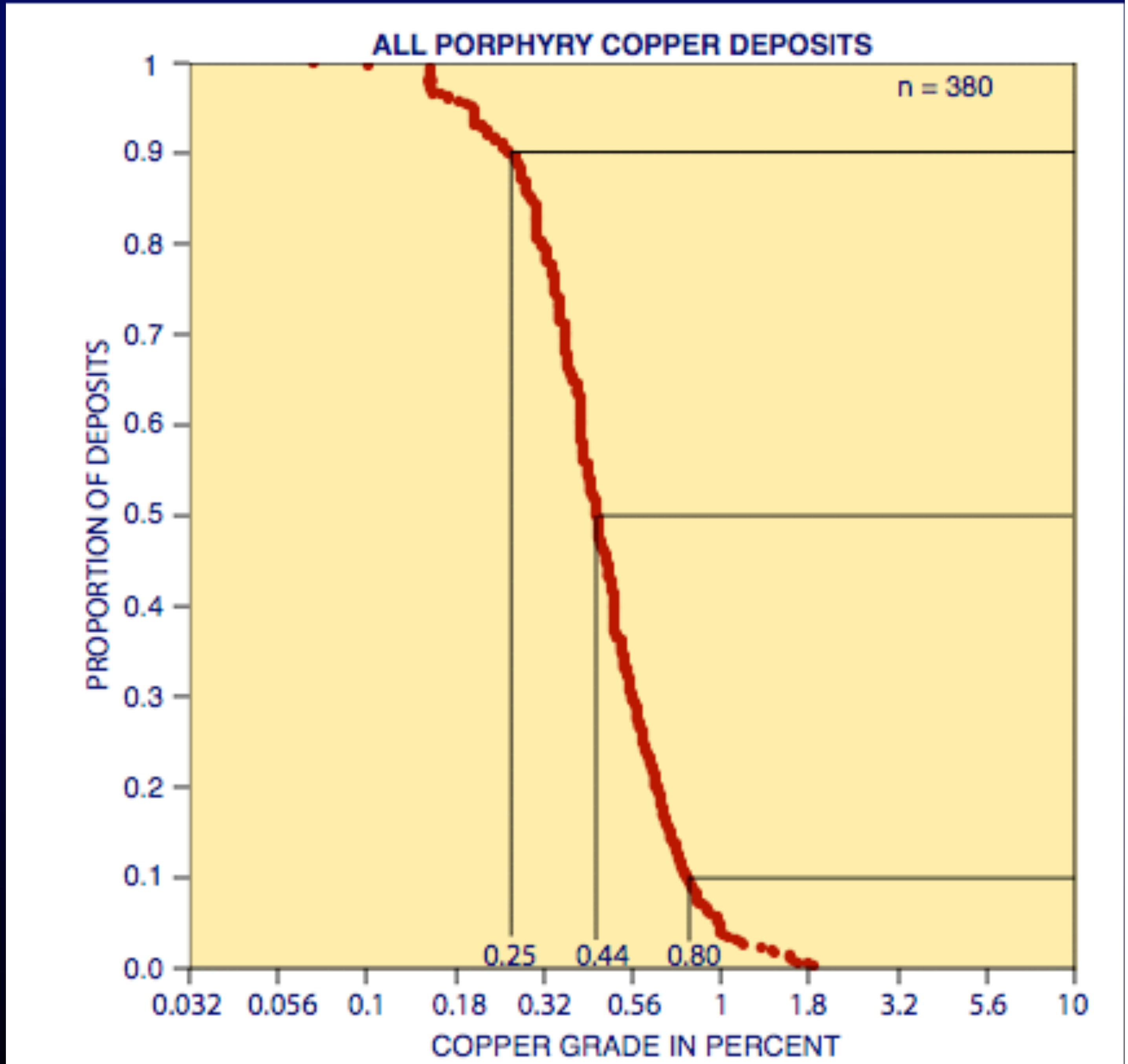

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Porphyry Copper G-T Model

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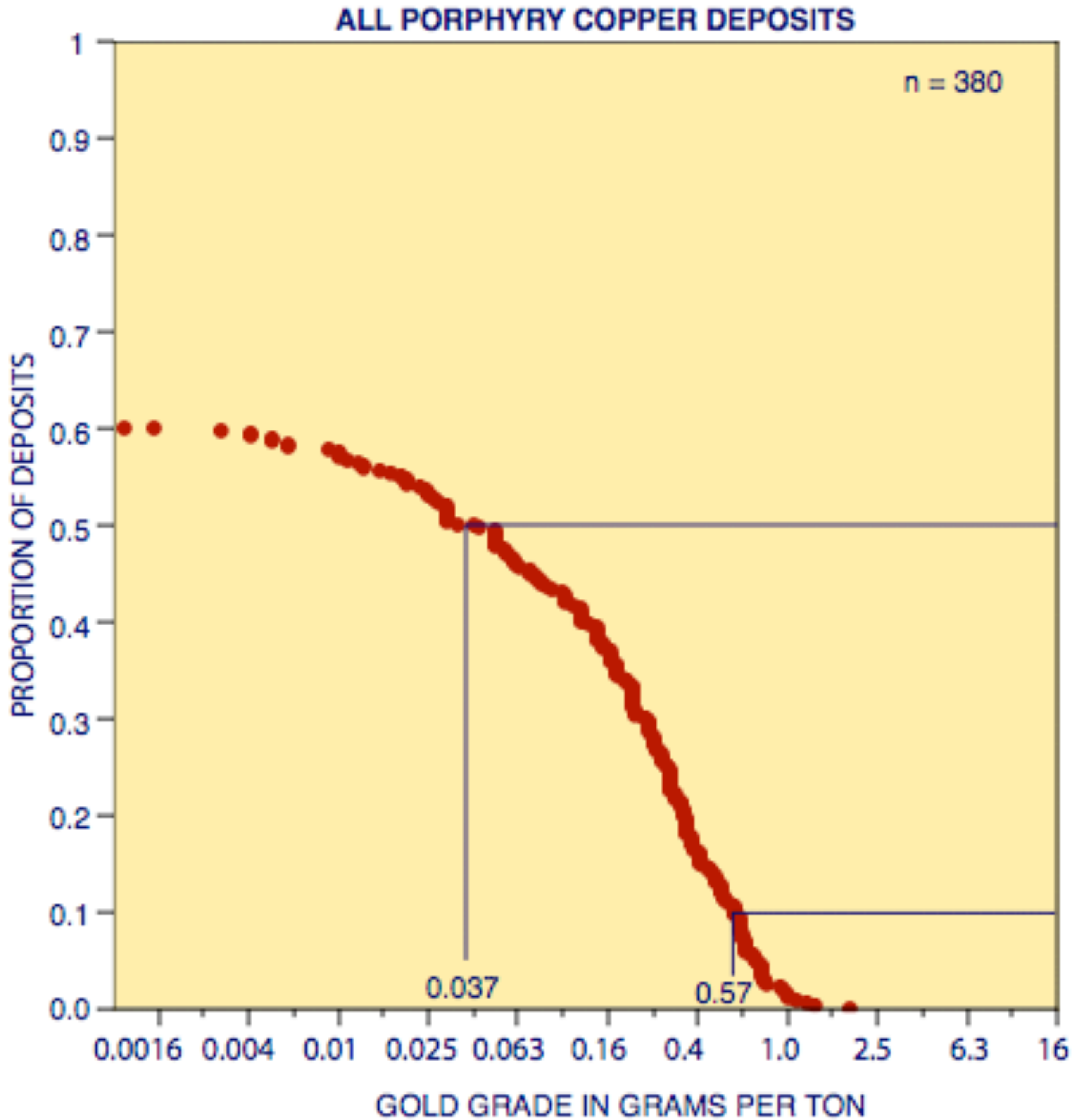

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Bivariate Plots of Grade Tonnage Models

- To compare multiple deposit types with respect to the amount and quality of resources they contain, deposit models may be plotted in grade and tonnage space.

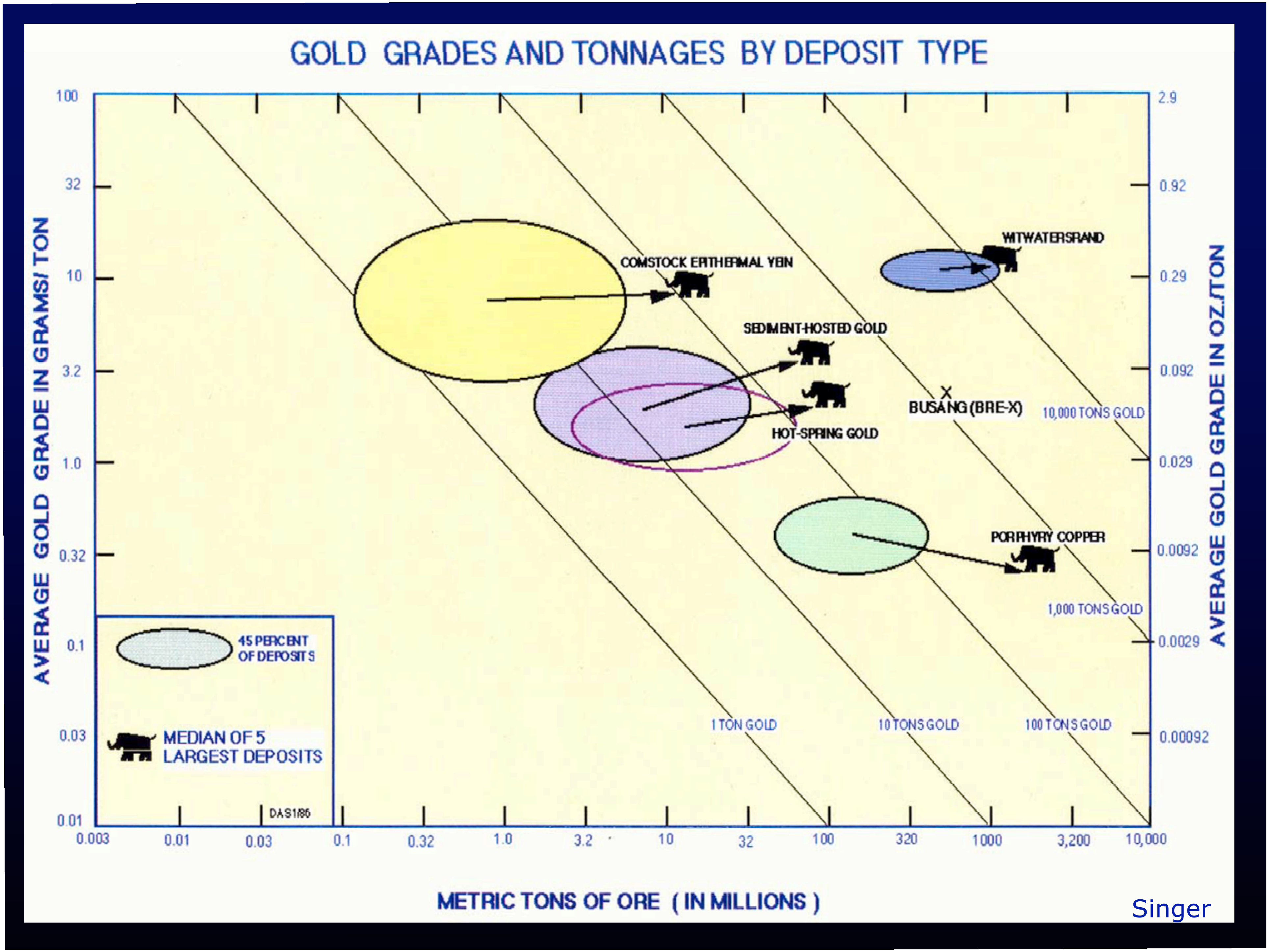
- Because data in grade and tonnage models vary logarithmically plotting all of the deposits in several models may show so much scatter that comparison of central tendencies of the models may be lost. Therefore it is common to plot an ellipse defined by the means of grade and tonnage plus and minus one standard deviation and oriented relative to the correlation of grade and tonnage. Each ellipse contains about 45% of the deposits of each type.

- To show the effect of large deposits, the mean of the five largest deposits (in terms of contained metal) are plotted as an elephant.

Bivariate Plots of Grade Tonnage Models (Continued)

- Notice the diagonal lines in the next slide. These show lines of equal gold content. Points on the line all contain the same amount of gold, however as one moves to the right on the line the grade at each point declines.
- Also notice several of the deposit types. Hot-Spring Au-Ag deposits are quite similar to Comstock Epithermal deposits in terms of their geological characteristics. Hot-Spring Au-Ag deposits are thought to have formed in the upper parts of geothermal systems while Comestock deposits are thought to form slightly deeper in these systems. Also notice the location of the Witwatersrand deposits. These South African deposits have dominated world gold production for almost 100 years.
- Finally, notice the point marked “BreX”. This is the grade and tonnage reported for one of the most famous mining scams in recent years. Notice no deposit types fall anywhere near it. Hmm…

Menzie, 2005


GOLD GRADES AND TONNAGES BY DEPOSIT TYPE
AVERAGE GOLD GRADE IN GRAMS/ TON
AVERAGE GOLD GRADE IN OZ./TON
METRIC TONS OF ORE (IN MILLIONS)
100
32
10
3.2
1.0
0.32
0.1
0.03
0.01
2.9
0.92
0.29
0.092
0.029
0.0092
0.0029
0.00092
0.003
0.01
0.03
0.1
0.32
1.0
3.2
10
32
100
320
1000
3,200
10,000
COMSTOCK EPITHERMAL VEIN
WITWATERSRAND
SEDIMENT-HOSTED GOLD
HOT-SPRING GOLD
BUSANG (BRE-X)
PORPHYRY COPPER
10,000 TONS GOLD
1,000 TONS GOLD
100 TONS GOLD
10 TONS GOLD
1 TON GOLD
45 PERCENT OF DEPOSITS
MEDIAN OF 5 LARGEST DEPOSITS
DAS1/96
Singer

Sources of Errors in Grade and Tonnage Models

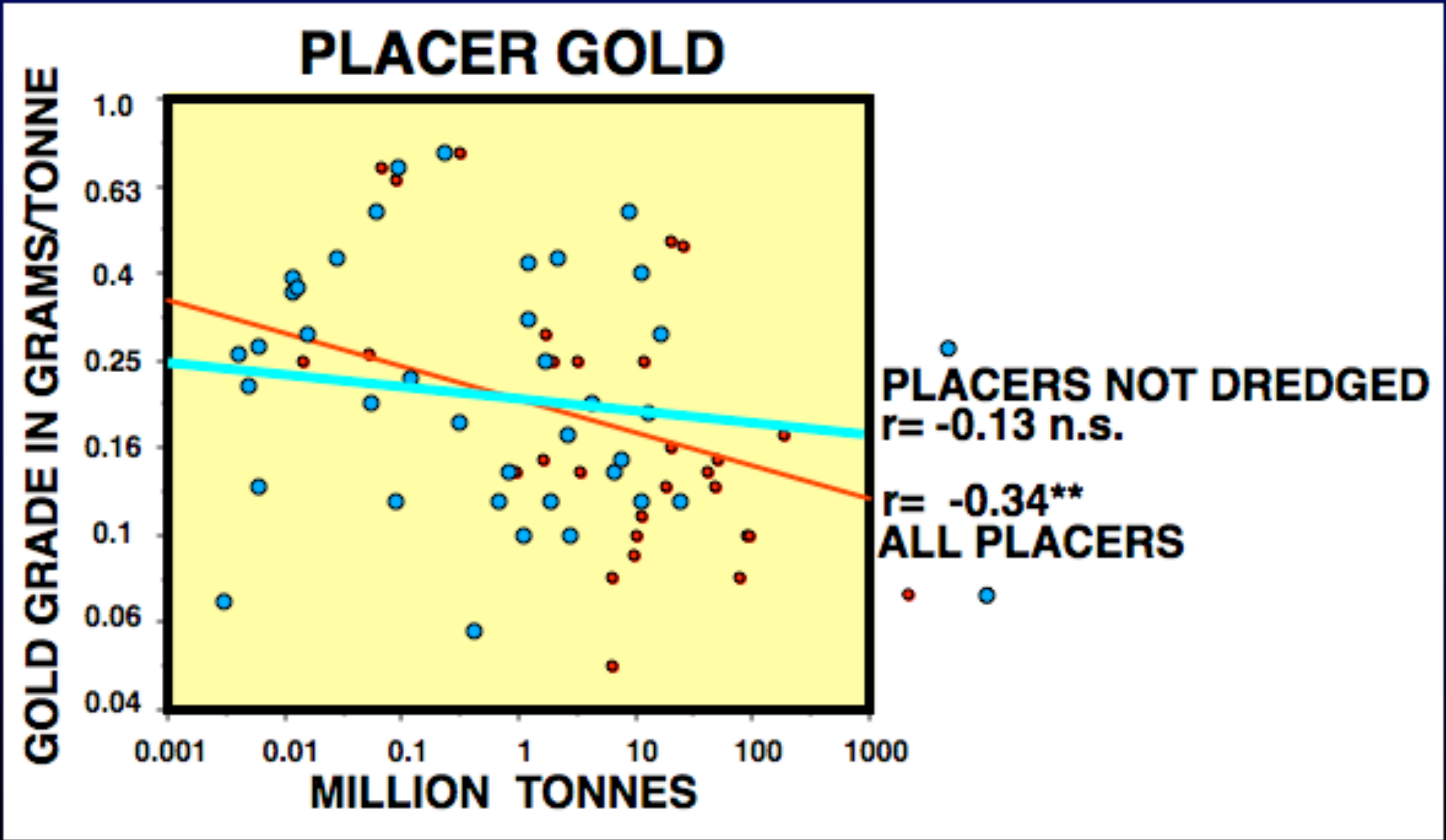
Sources of Errors in Building Models

- Mixed geologic environments
- Poorly known geology
- Data recording errors
- Mixed deposit / district data
- Mixed mining methods
- Incomplete production / resource estimates

Deposit Sampling Units

- Grade and tonnage data are available to varying degrees for districts, deposits, mines, and shafts.
- In many cases old production data are available for some deposits and recent resource estimates are available for other deposits.
- Probably the most common error in constructing grade and tonnage models is mixing old production data from some deposits with resource data from other deposits.
- It is extremely important that all of the data used in the model represent the same sampling unit because mixing data from deposits and districts or old production and recent resource estimates usually produces bimodal or at least non-lognormal frequencies and may introduce correlations among the variables that are artifacts of the mixed sampling units.

Mixing Mining Methods Can Induce Correlations



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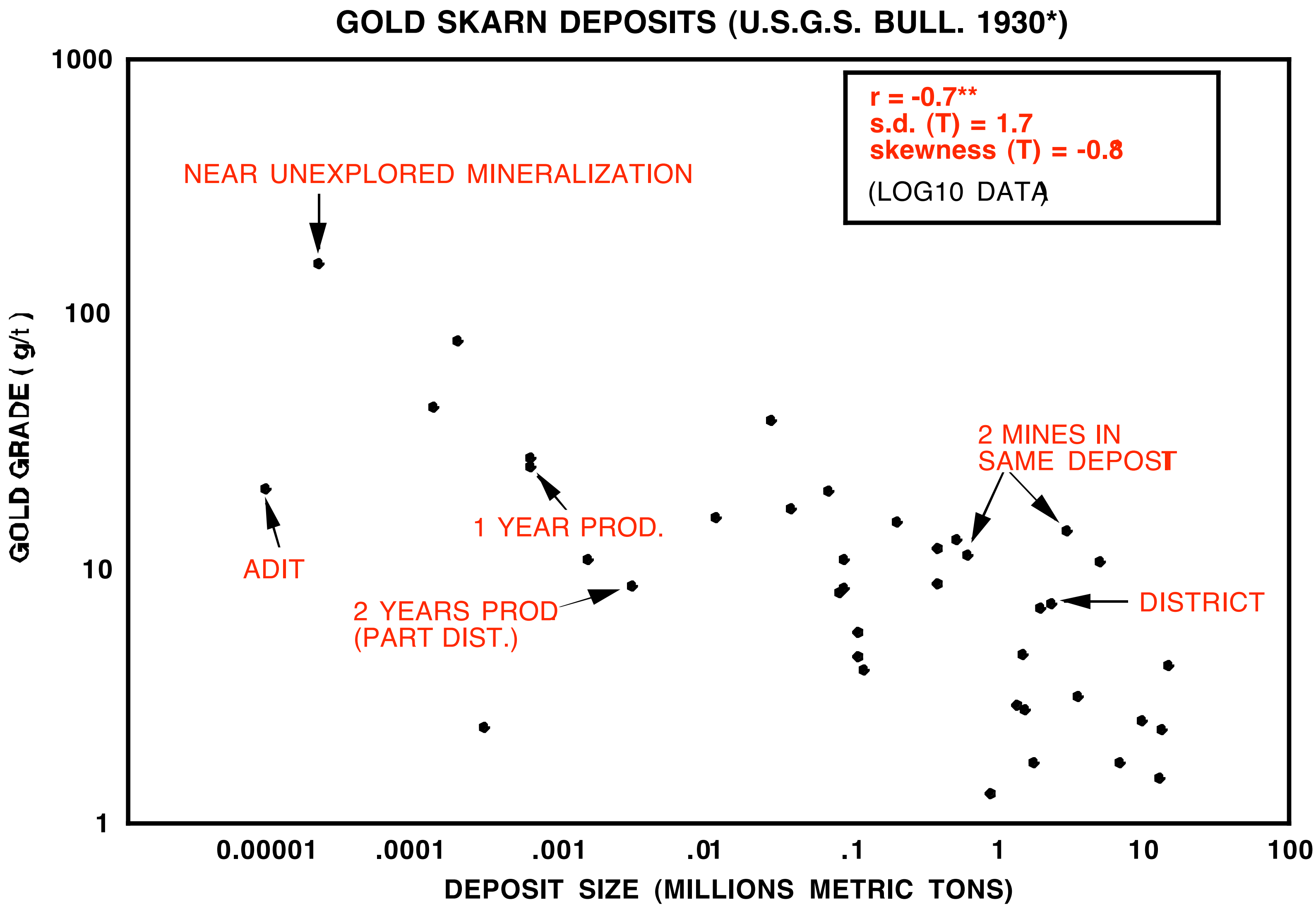
Purpose of Plots and Statistics Is to Discover If the Data Contain Multiple Populations or Outliers

- Based on our experience with a large number of models, deviations from lognormality, outliers, or subgroups are all cause for reexamination of the data.
- Also suggestive of problems are large standard deviations for tonnage, such as those greater than 1.0, and a significant correlation between tonnage and grade.
- If any of these conditions exist, the data should be checked for correctness of data entry, data reporting errors, mixed sampling units, and lastly, correctness of the geologic reasoning that led to the classification of the individual deposits.
- If subgroups of data exist, one or more geologic attribute of the subgroups probably will be different which suggests that the descriptive model may need reexamination.



*Theodore et al., 1991, Gold-Bearing Skarns: U. S. G. S. Bulletin 1930, 61p.

Singer

Undiscovered Deposits Are From the Same Probability Density Function As the Grade and Tonnage Model

Thus: 5% of gold skarns will be from 2 mines on the same deposit, 2.5% will be from adits, 2.5% from incompletely explored deposits, etc.--Forever!

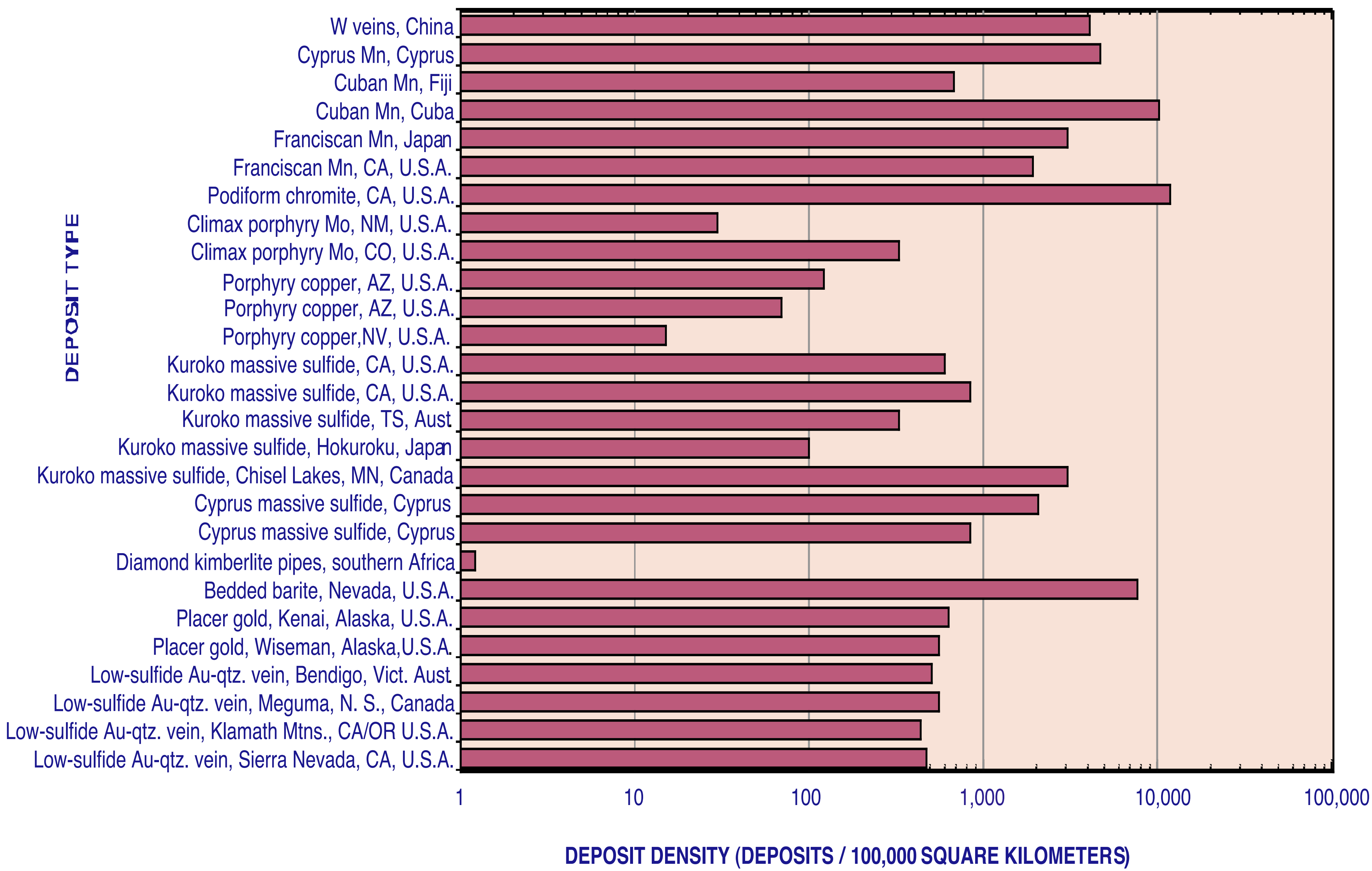
Constructing Grade and Tonnage and Descriptive Models is an *Iterative* Process

Mineral Deposit Density Models

Deposit Density Models

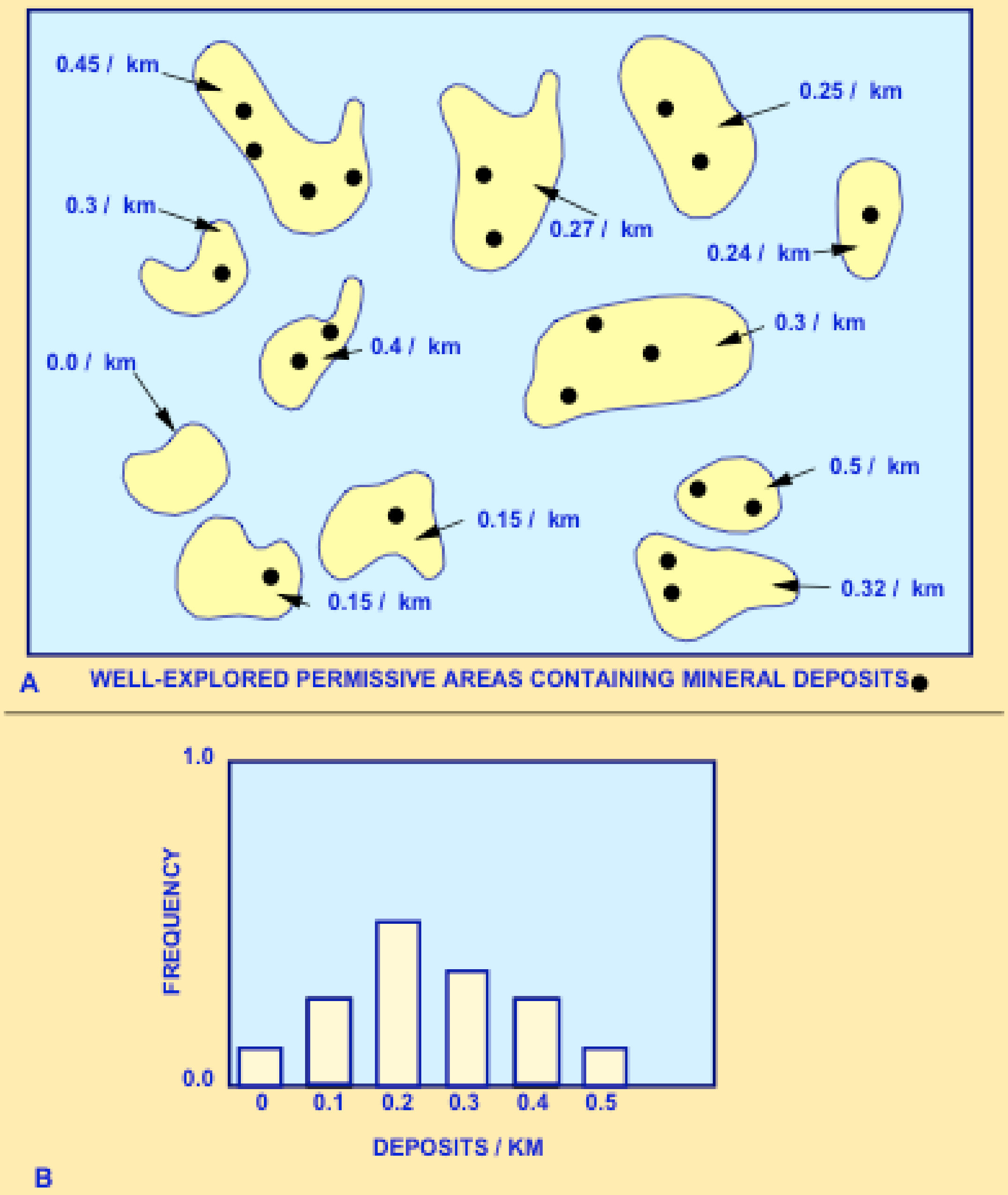
A robust method to estimate of the number of undiscovered deposits is a form of mineral deposit model wherein numbers of deposits per unit area from well-explored regions are counted and the resulting frequency distribution is either used directly for an estimate or indirectly as a guideline in some other method.

MINERAL DEPOSIT DENSITY



Numbers of deposits per unit area by deposit type from well-explored regions as reported in Singer and others (2001) .

DAS404



Example of known deposits in permissive area (A), and histogram of derived deposit densities (B)

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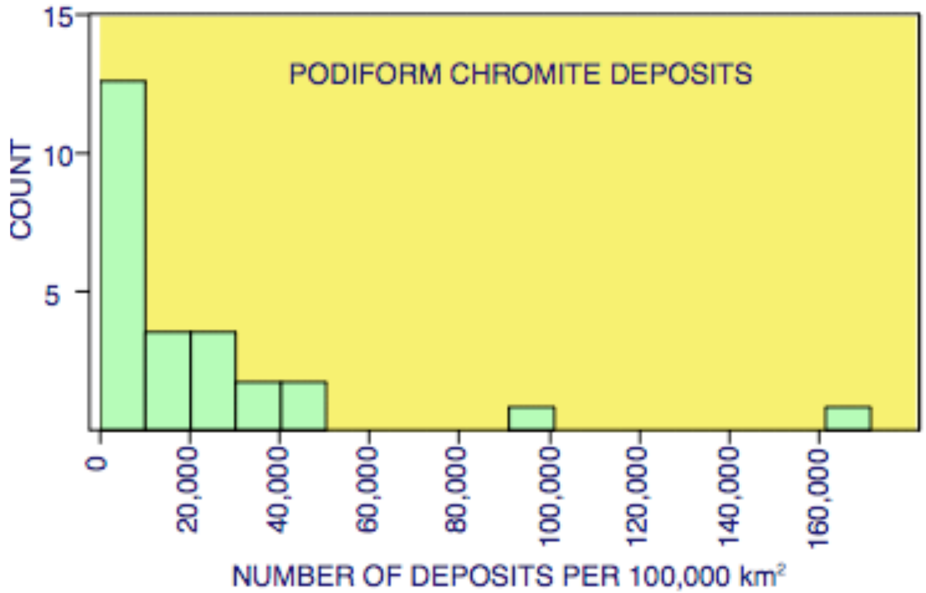
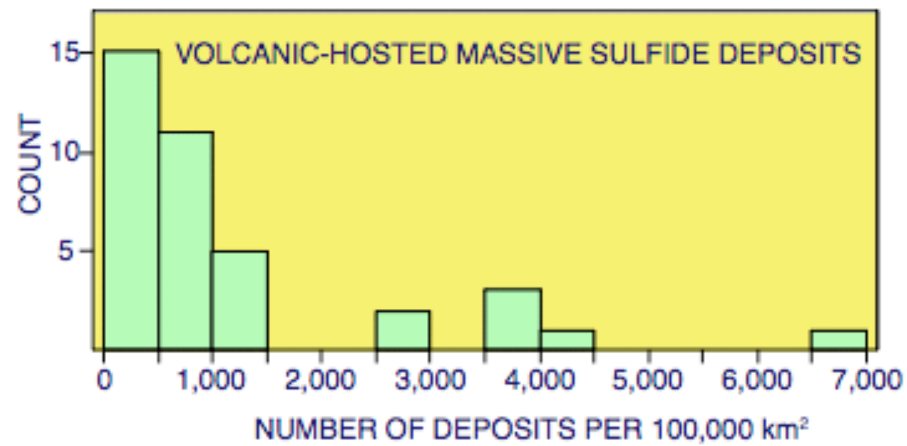
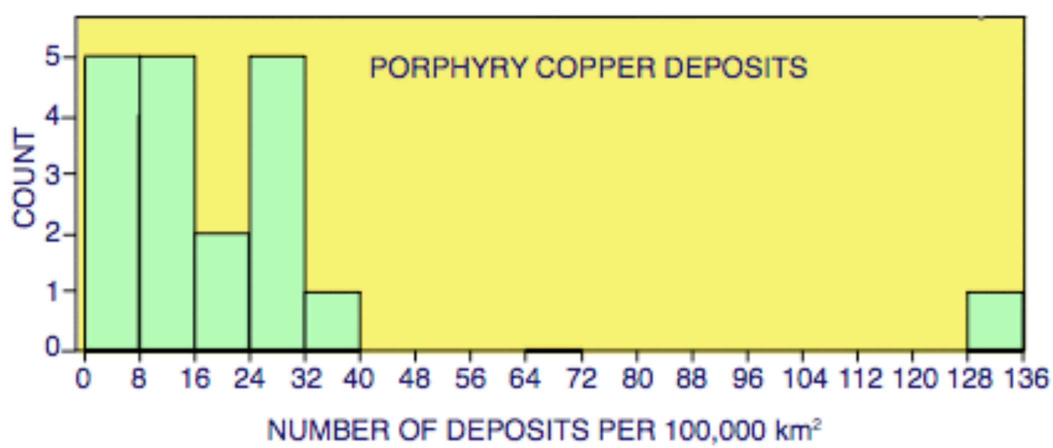
DENSITY HISTOGRAMS OF MINERAL DEPOSITS







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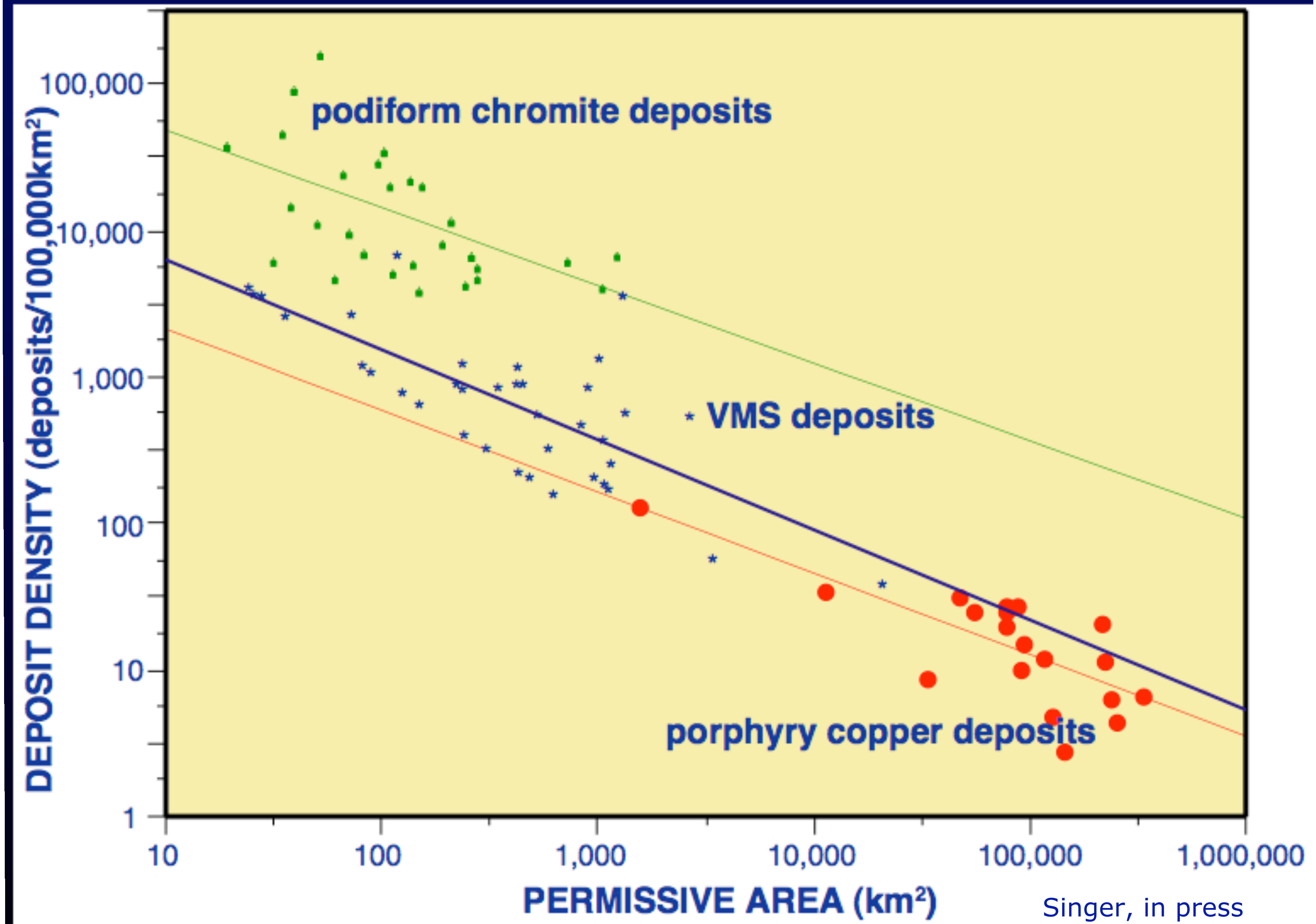
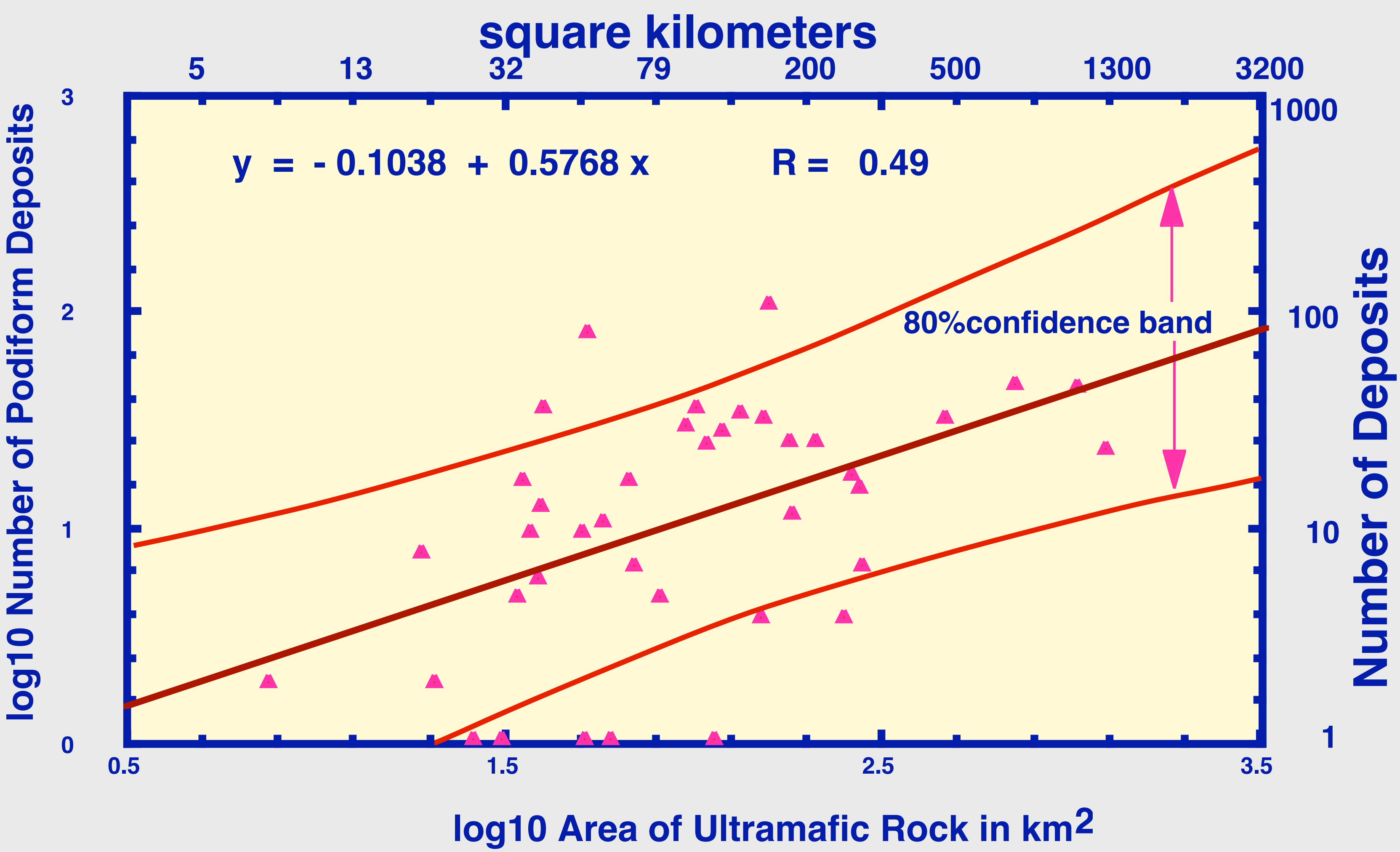


Singer, in press

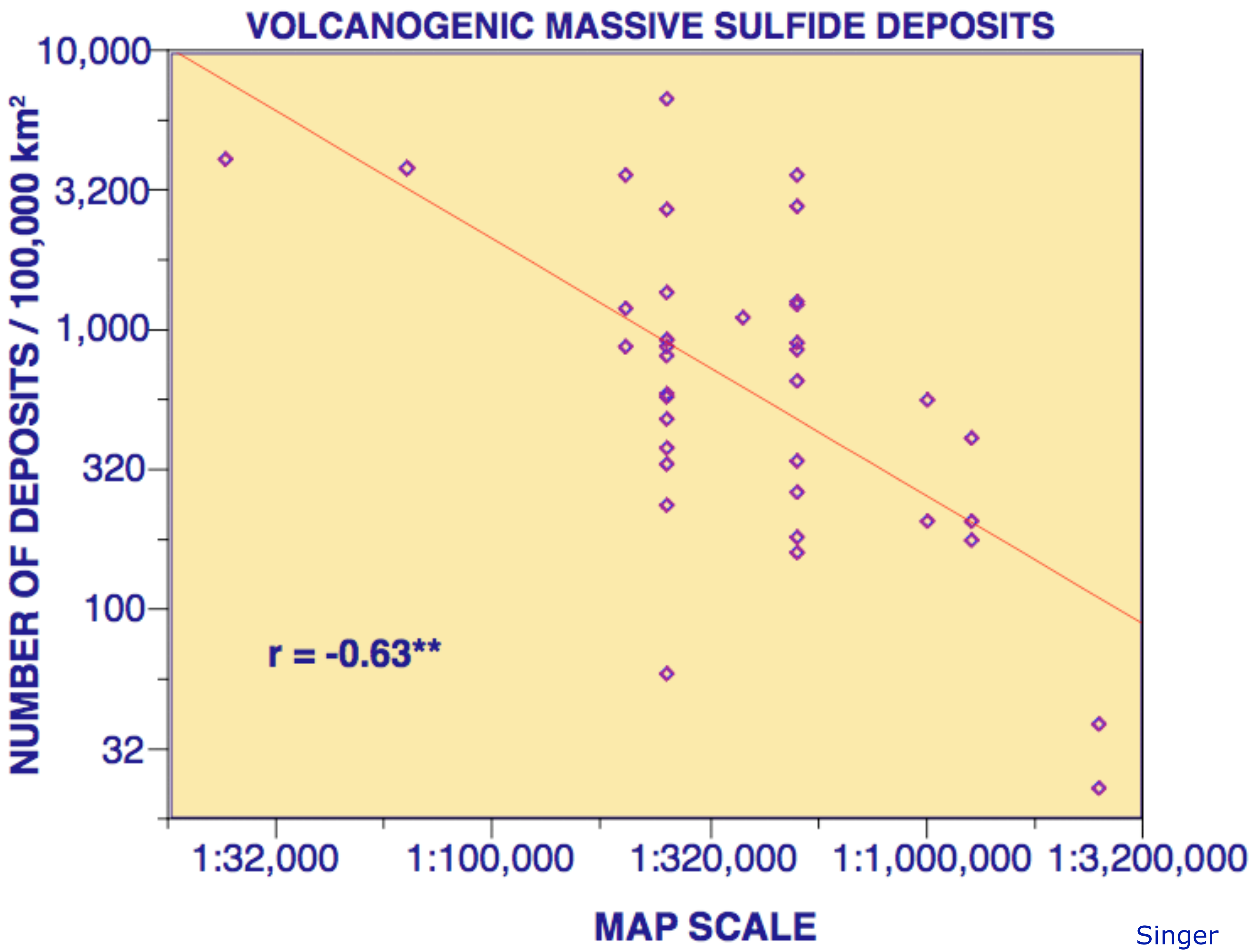
Using the Density–area Relationship–an Example

- The linear regression line and 80 percent confidence limits to the regression estimates are provided in the next plot. Estimates of the number of podiform chromite deposits can be made from the plot by using the logarithm of ultramafic rock area on the X axis projected to the lower confidence limit for the 90 percent estimate of number of deposits, to the regression line for the 50 percent estimate, and to the upper confidence limit for the 10 percent estimate.



Number Podiform Chromite Deposits vs. Area of Ultramafic Rock

Singer, D.A., 1994, Conditional estimates of the number of podiform chromite deposits: Nonrenewable Resources, v. 3, no.3, p. 200-204.


VOLCANOGENIC MASSIVE SULFIDE DEPOSITS
NUMBER OF DEPOSITS / 100,000 km²
10,000
3,200
1,000
320
100
32
r = -0.63**
1:32,000
1:100,000
1:320,000
1:1,000,000
1:3,200,000
MAP SCALE
Singer

Cost Models

Why Consider Economics?

- Many of deposits used in grade and tonnage models were or will be non-economic
- Few nonacademic problems related to mineral resources are resolved by knowing amounts of metal that exist
- Mineral policy issues and problems typically revolve around the effects of minerals that might be economically extracted
- This is true if the problem concerns exploring or developing minerals, values of alternative uses of the land, or environmental consequences of minerals development

A decision-maker needs to be keenly aware both of the expected outcome and of the probabilities of other outcomes

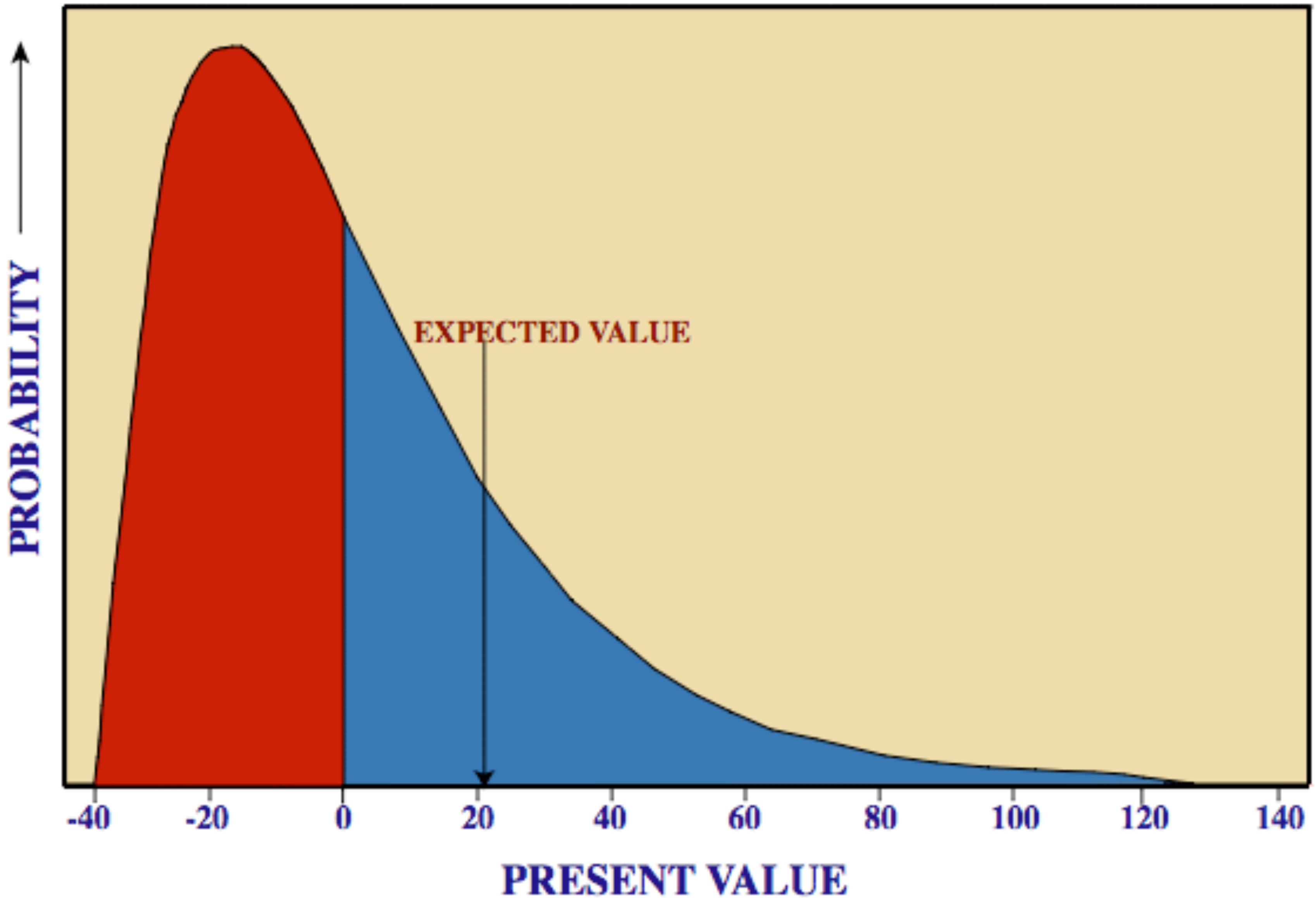
Example

- In a 1956 study, M. Allais reported that a 20 billion francs exploration investment in the Algerian Sahara would result in:

- 70 billion francs expected profit, but

- There was a 65% chance of losing money

Example of Present Value Distributions



Singer

Cost Models

- Models of capital and operating costs required to build and operate a mine and mill, and infrastructure that supports them

- Models do not estimate costs of preproduction exploration, permitting, environmental studies, taxes, corporate overhead, site reclamation, concentrate transportation, or smelter and refinery charges

Cost Models

- These cost models can be used to calculate the proportion of resources that might be economically produced at stated conditions. These cost models were initially developed by the U.S. Bureau of Mines (Camm, 1991, 1994) to assist in mineral resource assessments, but they can also be used in the early stages of a mineral exploration program. They do not require the detailed design of full cost models. They can be applied to a number of types of deposits and can be adjusted for changes in the location of the deposit or changes in prices. The models are capable of generating cost estimates at a level of uncertainty that is common to prefeasability studies.

- The engineering-based models should be statistically tested against modern mining costs to determine if they are still appropriate.

Cost Models

- Daily capacity is the key variable in these models
- Mine life is calculated from capacity
- Capital and operating costs are a function of capacity
- The equations vary with mining and milling methods

Cost Models

The models utilize a rule of thumb, Taylor's rule (Taylor, 1985), to relate mine life to deposit tonnage. Taylor's rule states that:

$$L = 0.2(rt)^{.25} \tag{1}$$

where L is mine life in years and rt is the deposit tonnage.

For some deposits types mining occurs at a faster rate than predicted by Taylor's rule. In such cases, Camm's simplified models must be modified or new cost models developed.

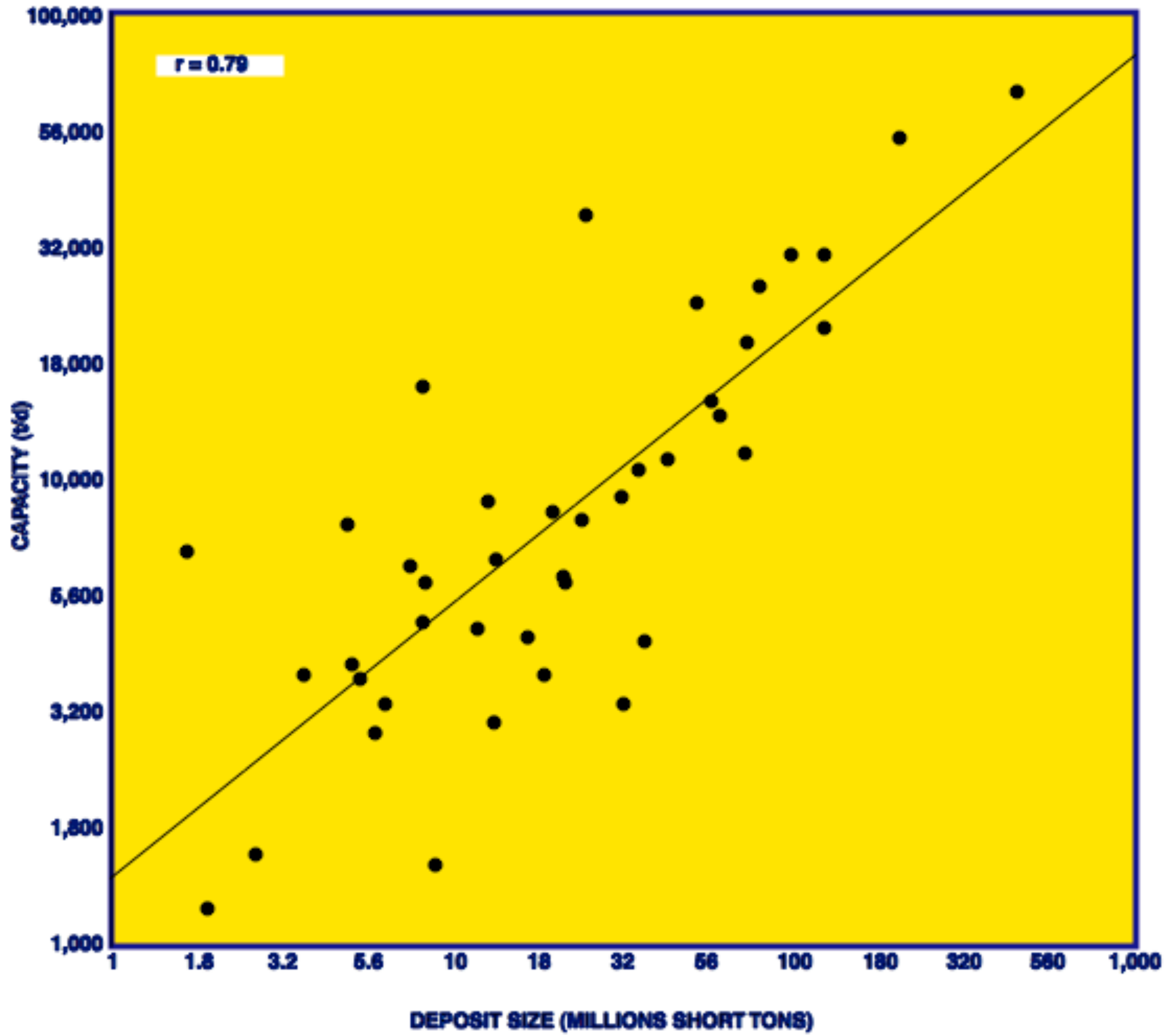


Figure 1--Relationship between mine capacity and size (tons of ore) of economic U. S. open-pit gold-silver mines.

Cost Models

The general form of the cost models is:

$$Y = A(X)^B \tag{2}$$

where: Y is the cost estimate, X is the daily capacity of the mine or mill, and A and B are constants. The capacity of the mine or mill may vary depending upon the tonnage of material being mined or milled and the rate at which the facility is operated.

Menzie, 2005

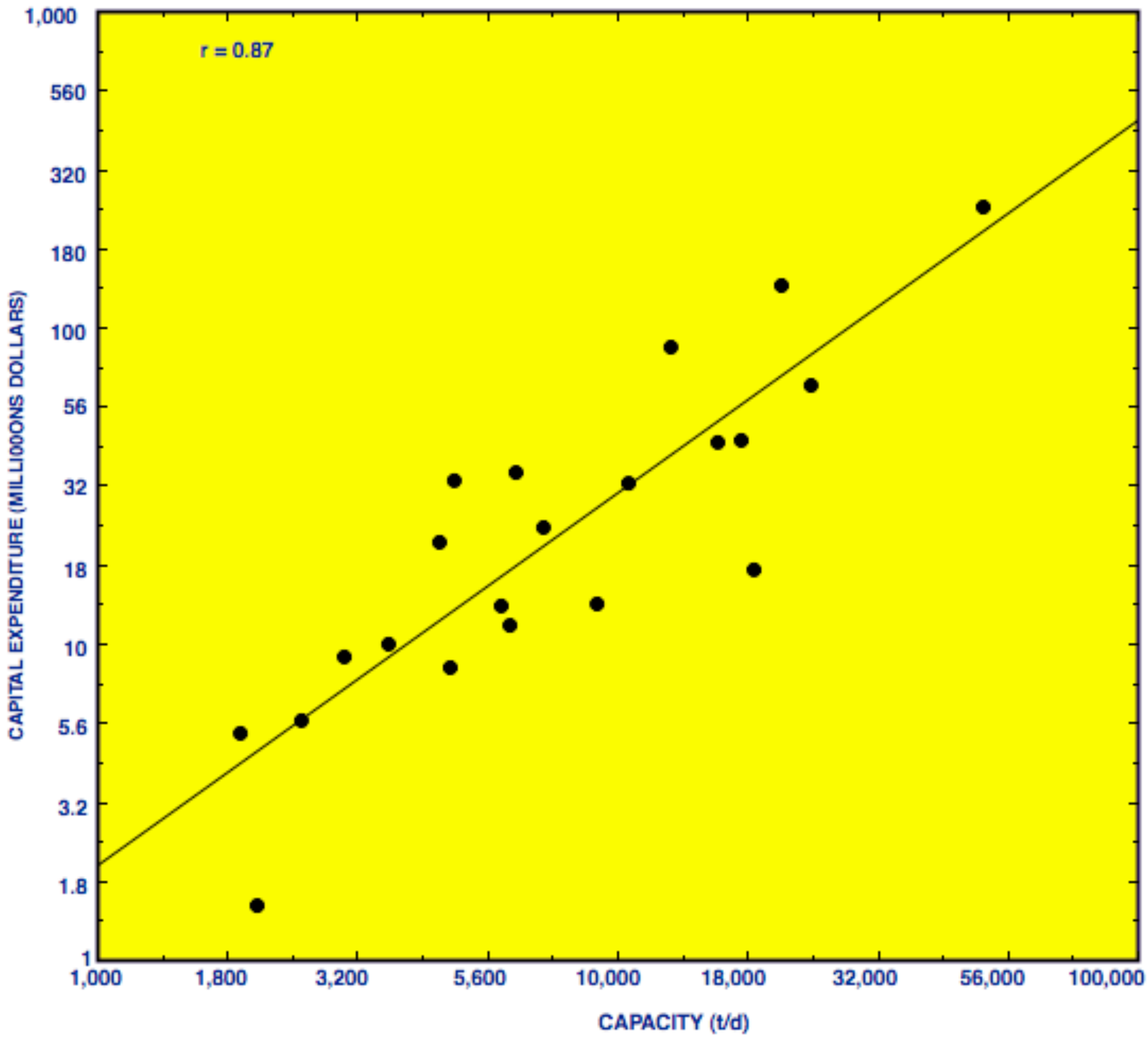


Figure 2--Relationship between capital expenditure and mine capacity of economic U. S. open-pit, heap-leach gold-silver deposits.

Cost Models

The general capacity equation is:

$$X = T / (dpy * L) \text{ or } (T)^{0.75} / (dpy * 0.2)$$

where: X is the daily capacity, dpy is operating days per year, L is the life of the mine and ,T is the tonnage of the mine or mill. The capacity of the mine or mill commonly is further adjusted to account for mine or mill specific factors.

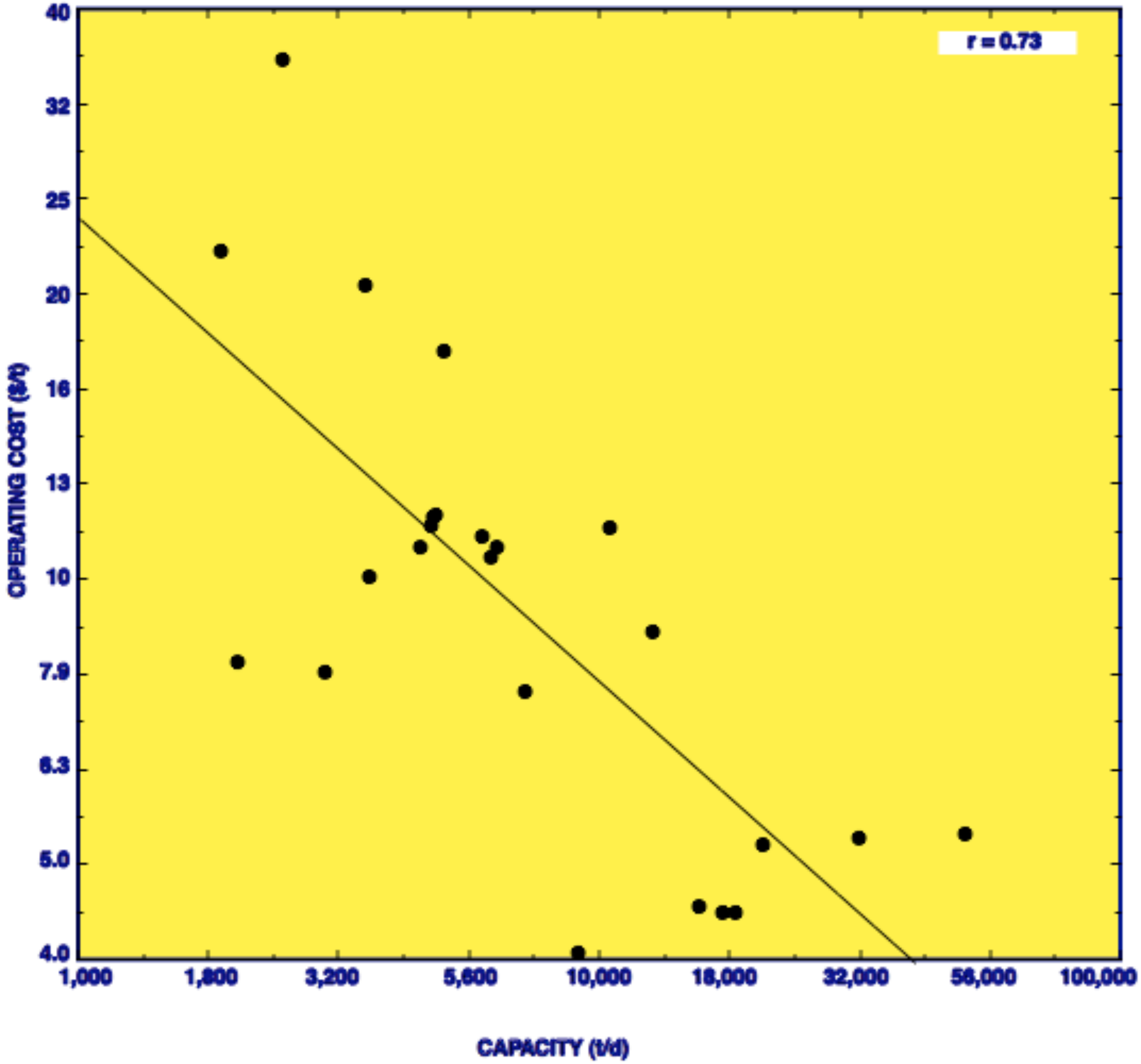
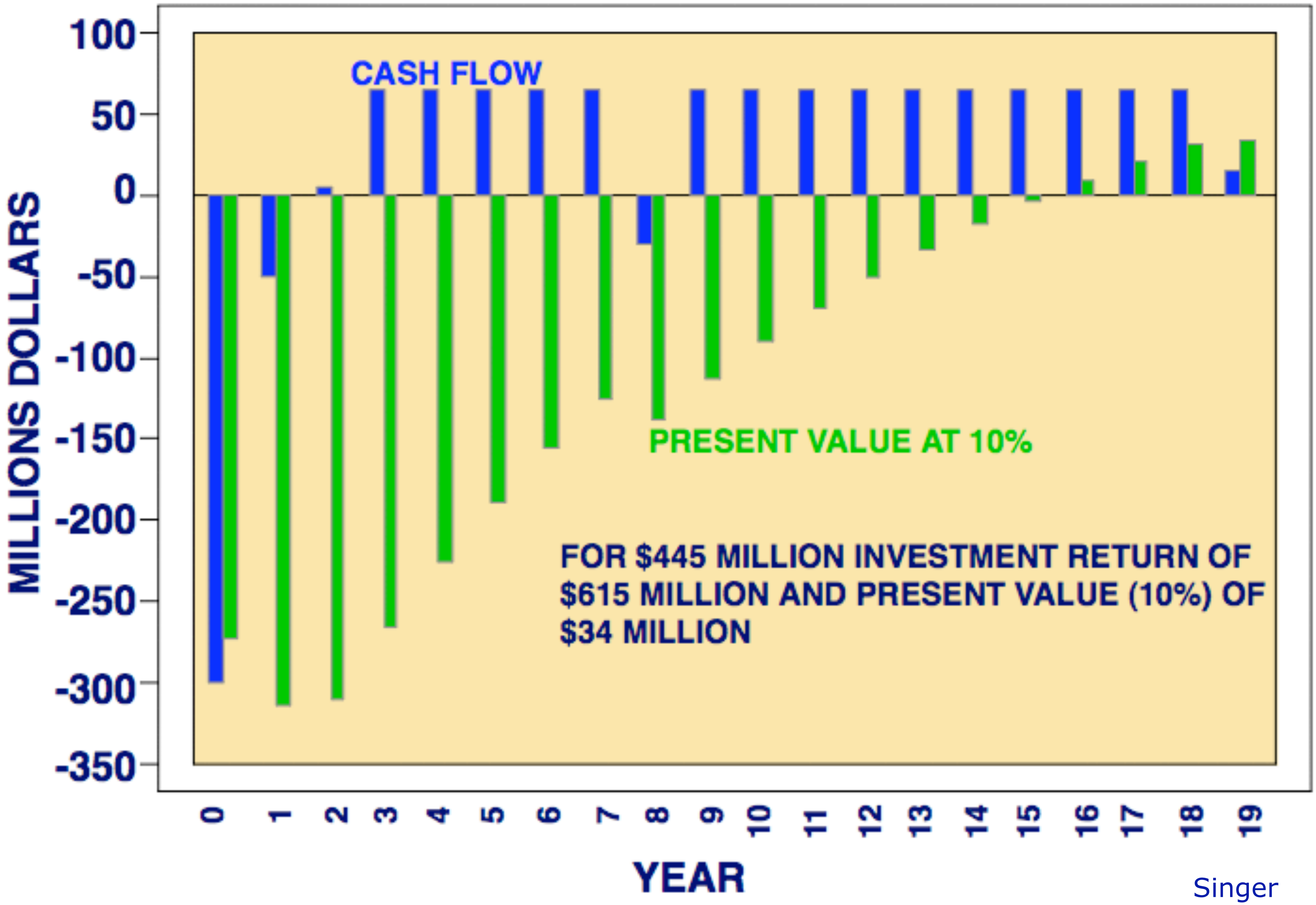


Figure 3--Relationship between operating costs and mine capacity of economic U. S. open-pit, heap-leach gold-silver deposits.

Cost Models

- To evaluate the economics of a deposit the cash flows must be brought together at a common point in time
- All cash values are discounted to the start time using the cost of capital as a discount rate
- For our analyses, we bring capital costs to the present and assume a constant production rate

Possible Cash Flow of a Mine



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Integration

- The life of the mine estimate is then used with the value of production per year with an acceptable rate of return in a standard present-value equation to estimate a deposit's present-value of production

- The present-value of production minus the estimated capital expenditure for the deposit is the present-value of the deposit

- If the deposit's present-value is positive, the filter is predicting that the mine is profitable. Negative present-values predict economic failure at the assumed metal prices and rate of return

Integration

For a tonnage, the dividing (or break even) line between economic and uneconomic is estimated by adding estimated operating cost to capital expenditure divided by capacity times operating days per year times the present value of a dollar for the mine life. That is:

BE = TOC + MOC / (dpy X_{ml} PV)

where BE is the break-even value ($/t), TOC is total operating cost ($/t), MOC is the total capital expenditure ($), dpy is the number of operating days per year, X_{mll} is the mill capacity (t/d), and PV is the present-value of one dollar at the selected rate of return for the life of the mine in years. The break-even value could be viewed as the grade (expressed in $/ton) at which the specific deposit and mining method are just economic.

To account for variability and uncertainty in the inputs to these estimates, we have taken 0.7 and 1.3 of this break-even value to estimate boundaries for uneconomic, marginal, and economic deposits

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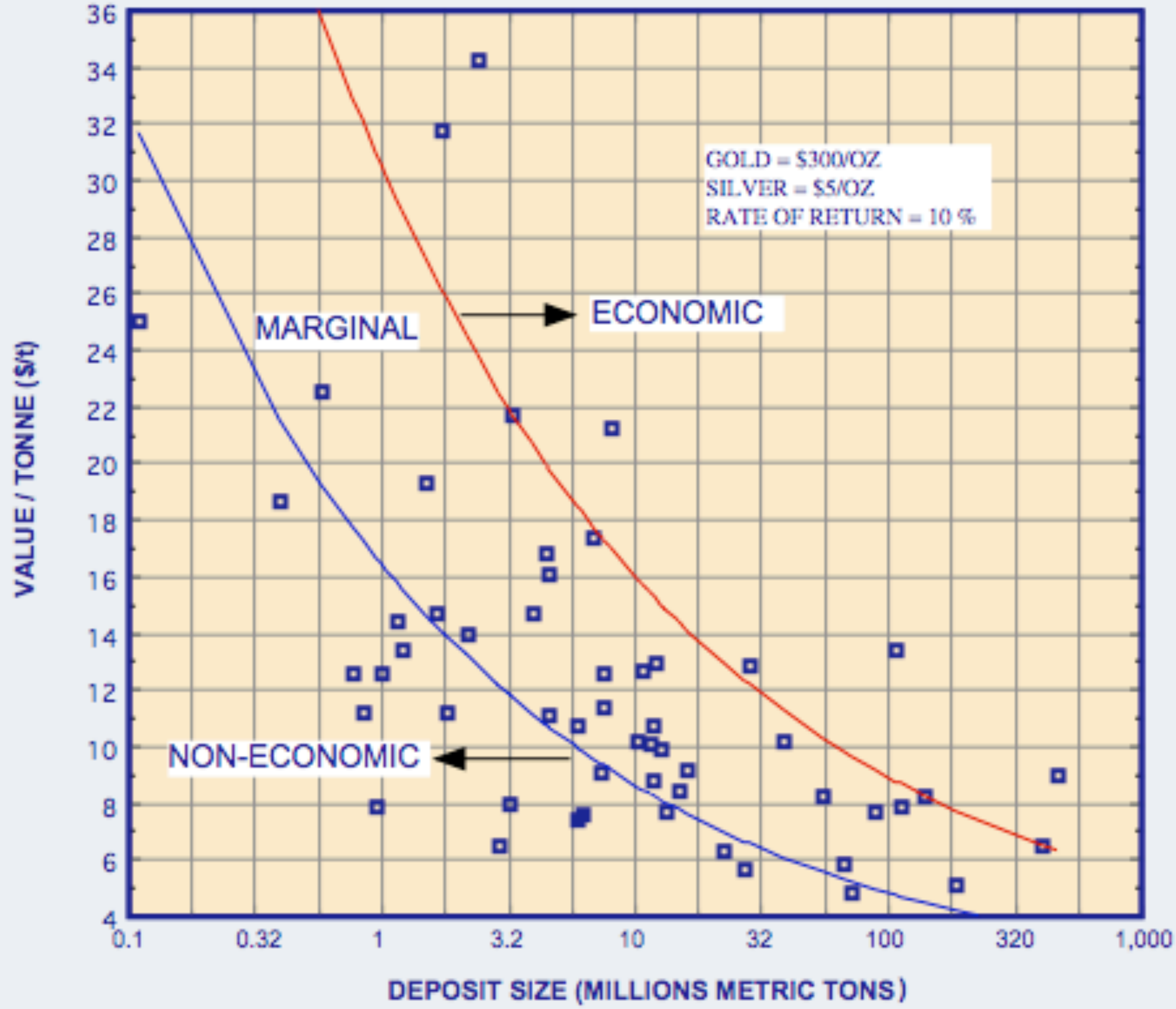
An Economic Filter



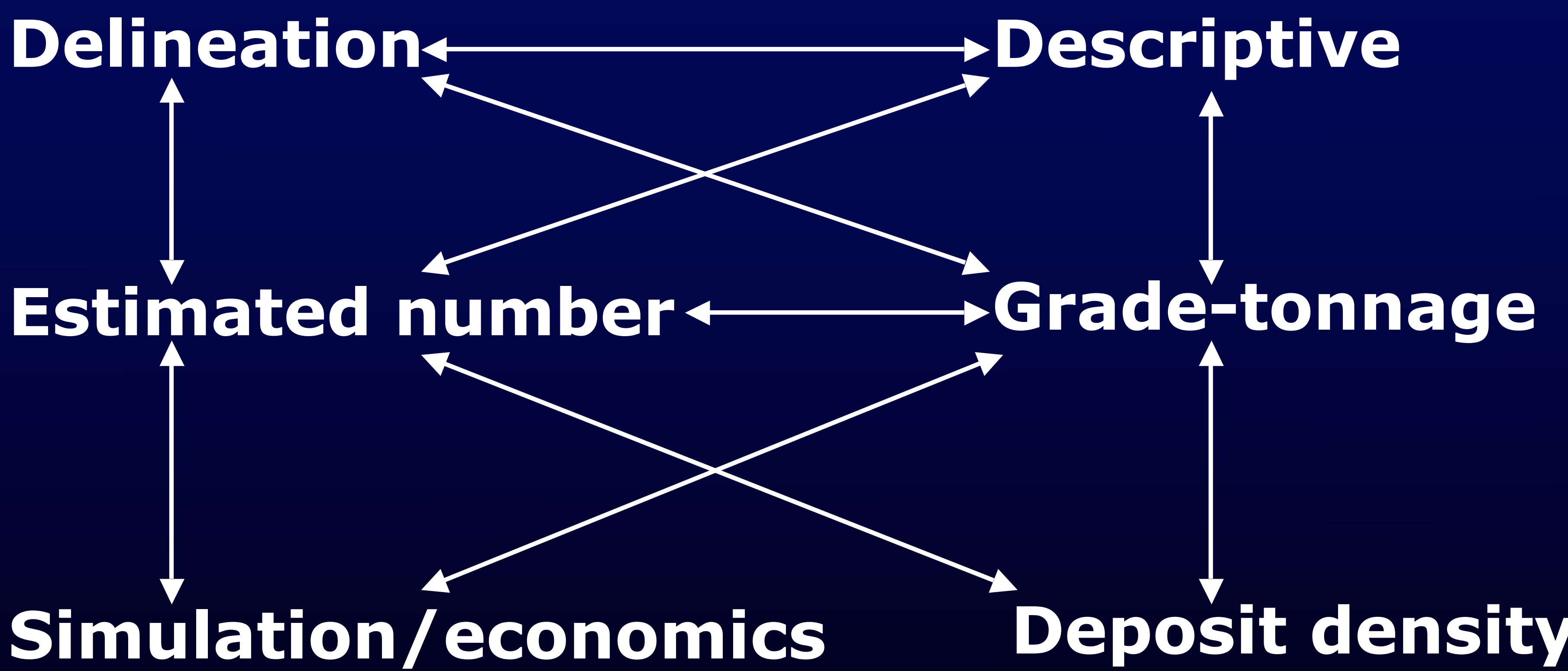
Relationship between value per ton and deposit size (tons of ore) for some U.S. open pit, heap-leach gold-silver deposits

Singer

Cost Models

Although not all costs are included and the estimates are rough, these models serve to discriminate clearly uneconomic from clearly economic deposits at an early assessment stage

Preventing Biased Quantitative Resource Assessments Requires Consistency



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Summary

The kind of assessment recommended here is founded in decision analysis to provide a framework for unbiased information concerning mineral resources for decisions made under conditions of uncertainty

Mineral deposit models are are key to delineation, estimation of numbers of deposits, their sizes and qualities, and their values