Predicting the Global Distribution of Arsenic Pollution in Groundwater

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PURPOSE

To show how:

ii. The distribution of arsenic pollution can be explained by four geochemical mechanisms that operate in specific climatic and tectonic-geomorphic settings, *and*

iii. presently unrecognised occurrences can be predicted.

Structure

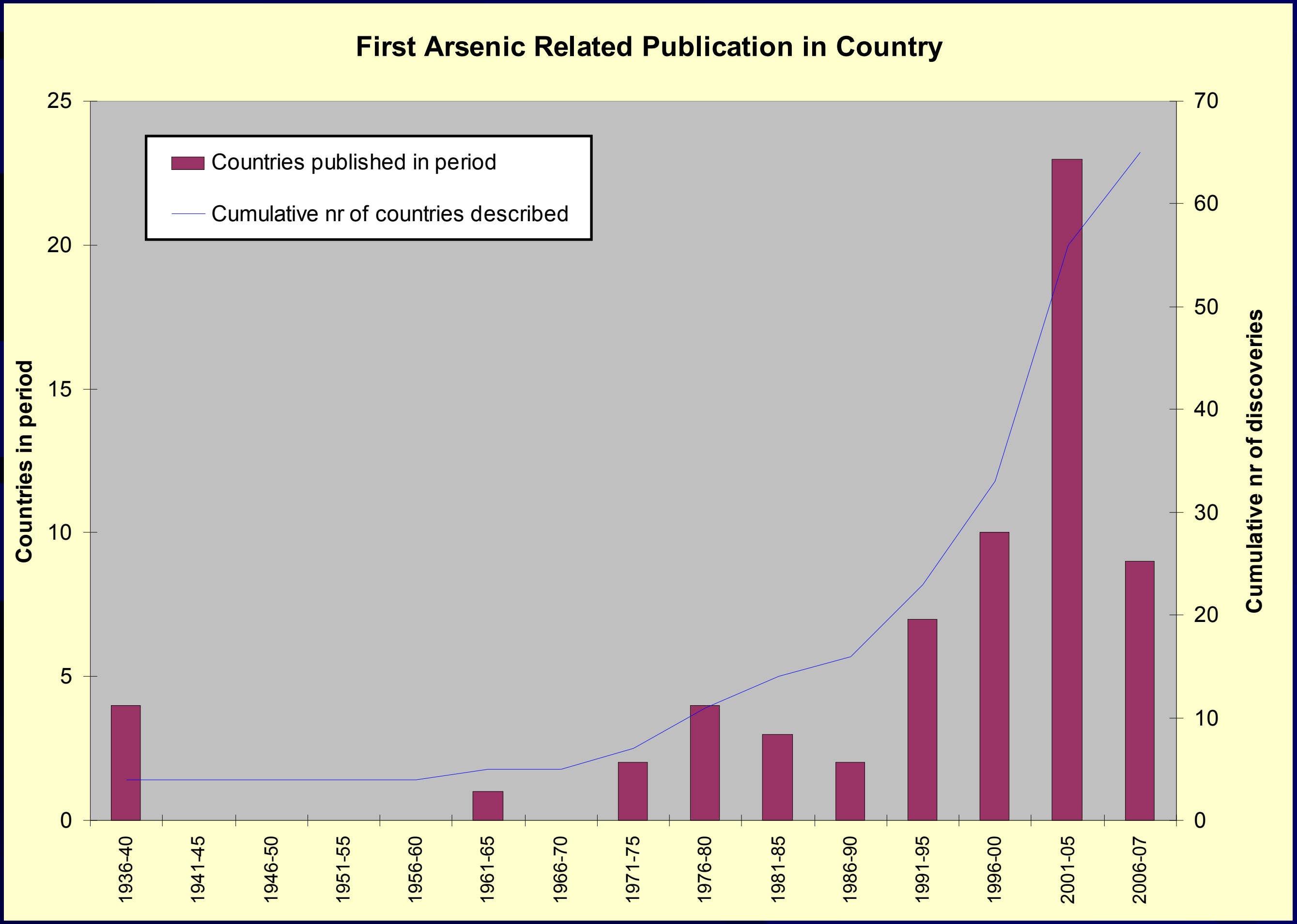
1. Extent of arsenic pollution
2. Four mechanisms of arsenic pollution, and their relation to climate and geology.
3. Generalise where and how arsenic pollution occurs, and where it is absent.
4. The nature of contaminated and uncontaminated river basins.
5. Predict where else arsenic pollution may, and may not, be found.

History of Discovery of Natural Arsenic Pollution

- Germany, 1885; Poland, 1898
- **1920's** Cordoba, **Argentina** (HACRE)
- 1930's Canada, New Zealand
- 1950's Region-II, **Chile**
- 1960's **Taiwan** (BFD)
- 1969, USA: "*no current threat to public health*"[1]
- 1975 & 1983, **India**
- 1993/5, **Bangladesh**
- 1997 onwards – many discoveries
- BUT how complete is the present mapping of arsenic?

1. cited by Ferguson and Gavis (1972)

First Publication on Arsenic Pollution by Country

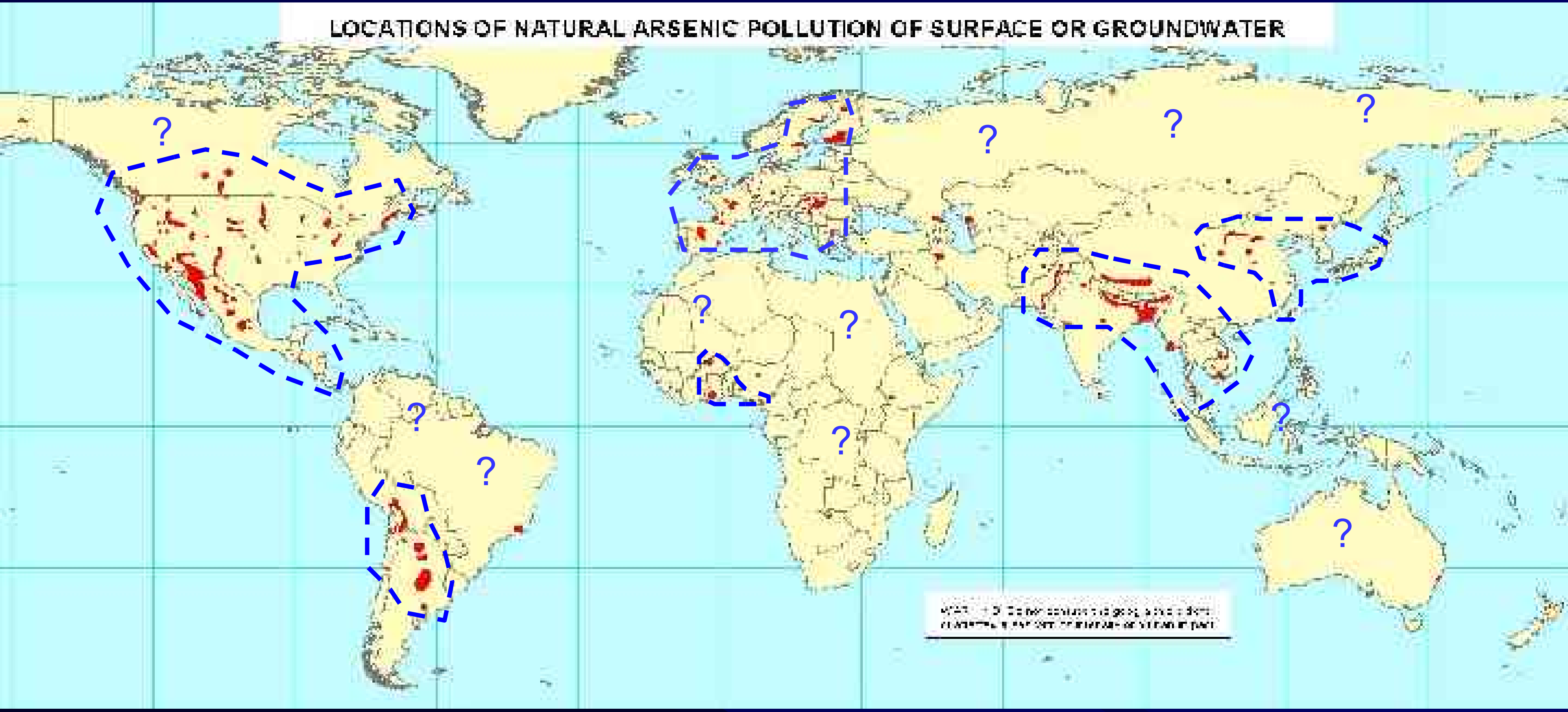


Extent and Severity of Arsenic Pollution

- >230 occurrences:
  - 70 countries
  - 6 continents + oceans
- At peak exposure:
  - 57M drinking >50 ppb
  - 137M drinking >10 ppb

Peak Exposure (millions)		
Country	>50 ppb	>10 ppb
Bangladesh	27	50
India	11	30
China	5.6	15
USA	3.0	30
Myanmar	2.5(?)	?
Pakistan	2.0	5.0
Argentina	2.0	?
Vietnam	1.5	?
Nepal	0.5	2.5
Mexico	0.4	2.0

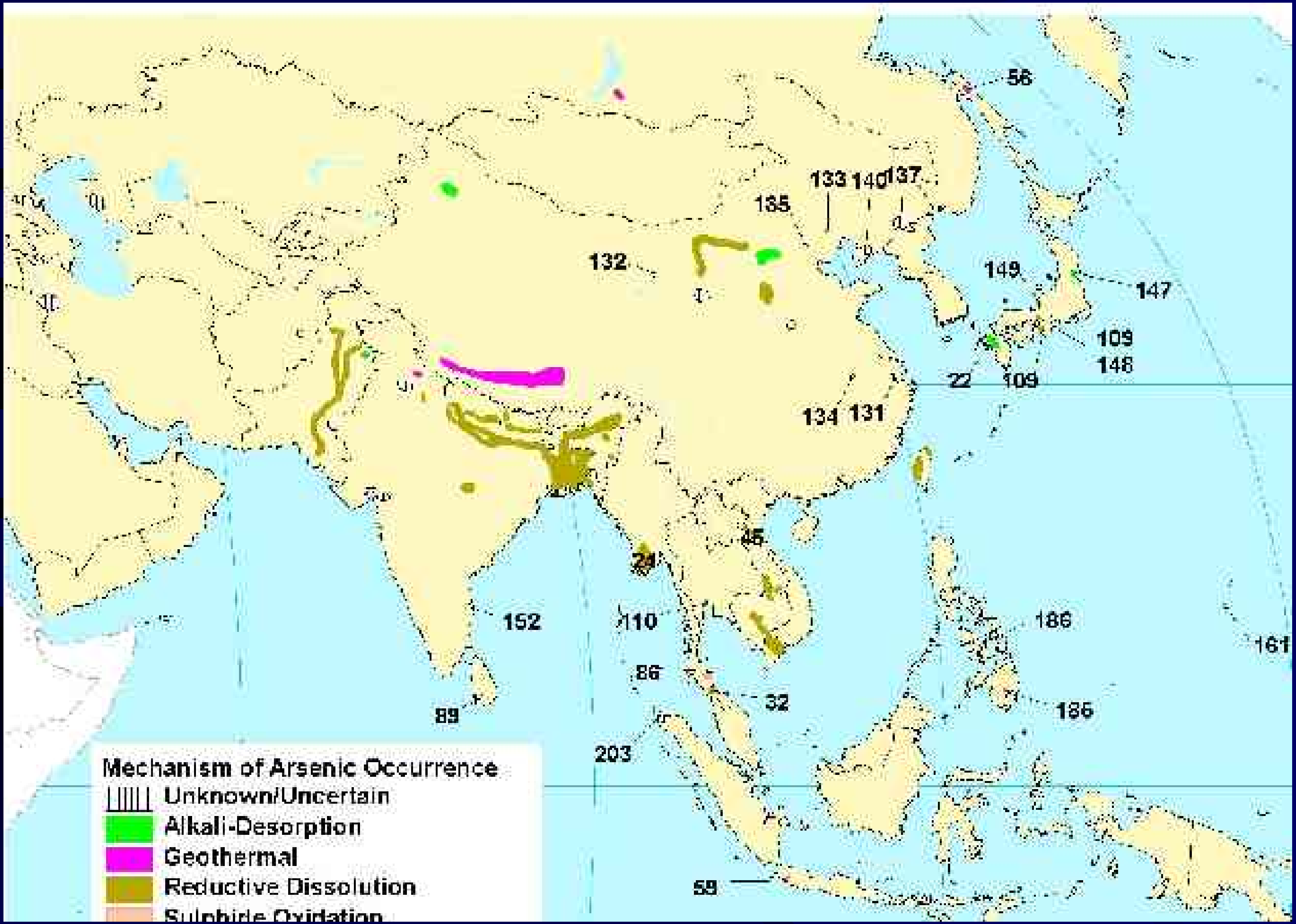
Known Extent of Contamination



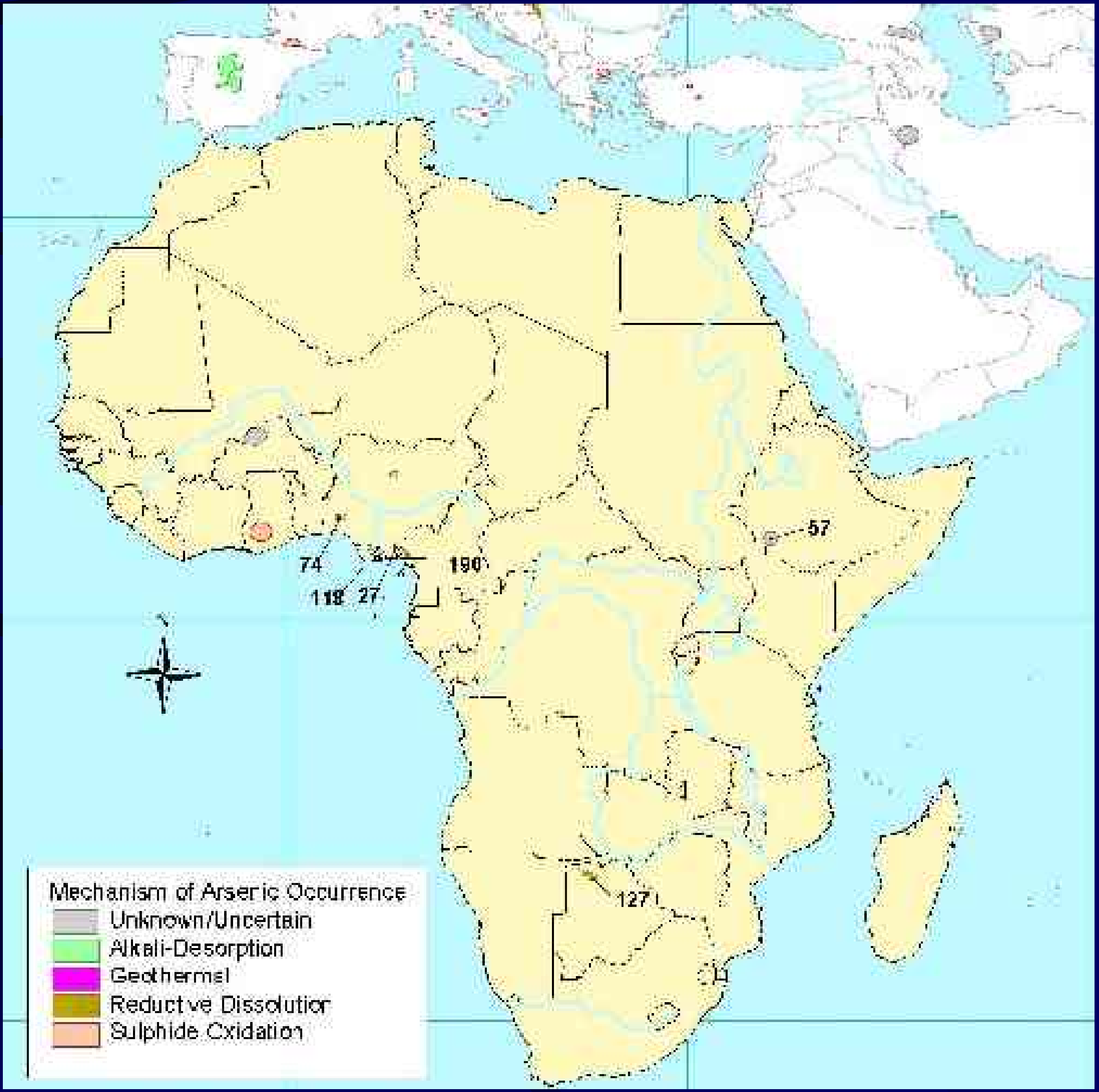
Four Mobilisation Mechanisms

1. **Reductive-Dissolution** (RD) produces near-neutral reducing (NNR) waters: anoxic; pH≈7; **high** Fe, Mn, NH_4, HCO_3; **low** SO_4,NO_3
2. **Alkali-Desorption** (AD) produces alkali-oxic (AO) waters: oxic (DO, NO_3), pH≥8, low Fe
3. **Sulphide Oxidation** (SO) produces acid-sulphate (AS) waters: oxic, pH<<7, high SO_4
4. **Geothermal** (GT) waters: high T, Cl
5. **± Evaporative-concentration**

Arsenic contamination in Asia

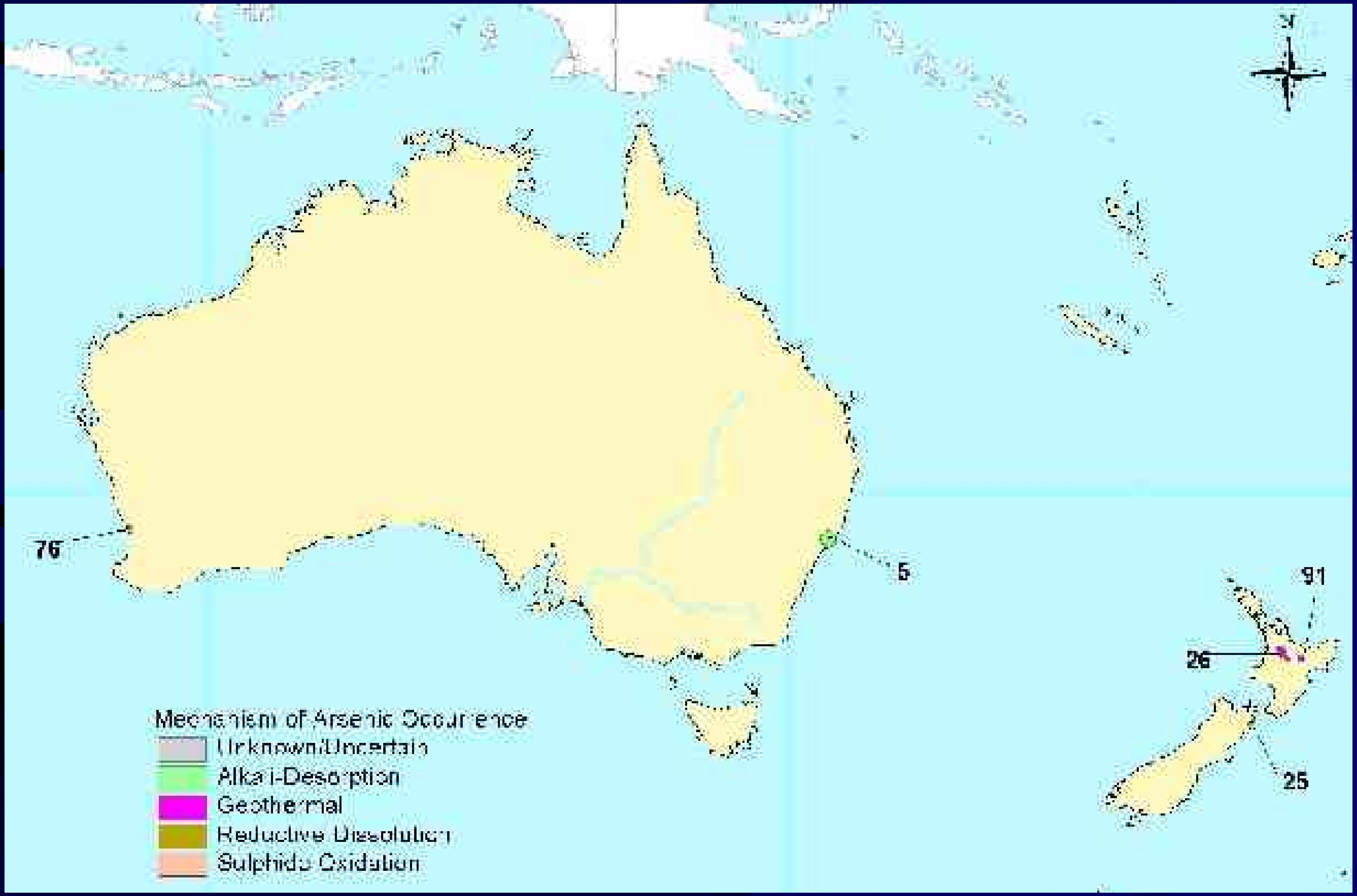


Africa

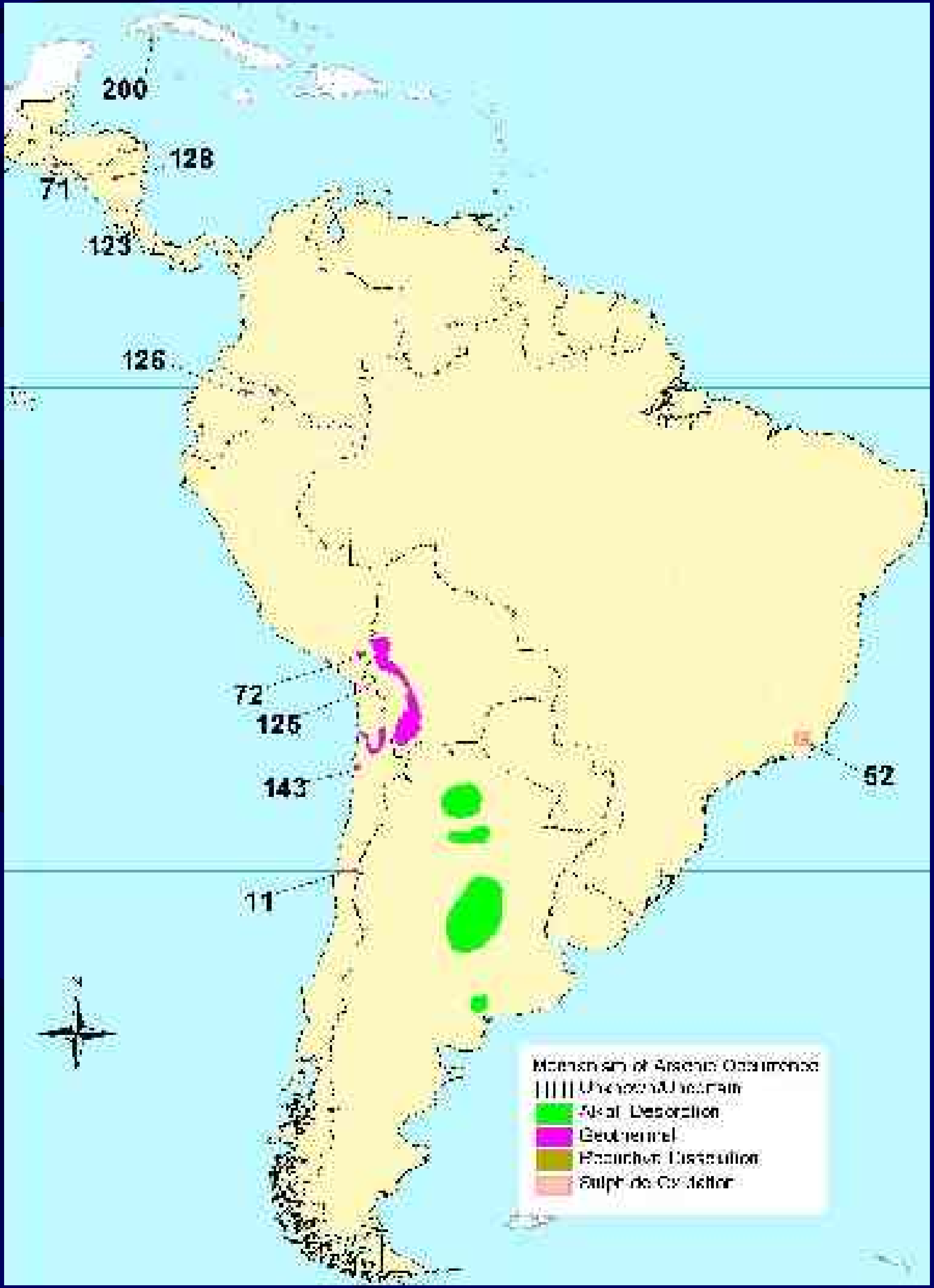


74
118
27
190
57
127
Mechanism of Arsenic Occurrence
Unknown/Uncertain
Alkali-Desorption
Geothermal
Reductive Dissolution
Sulphide Oxidation

Australasia

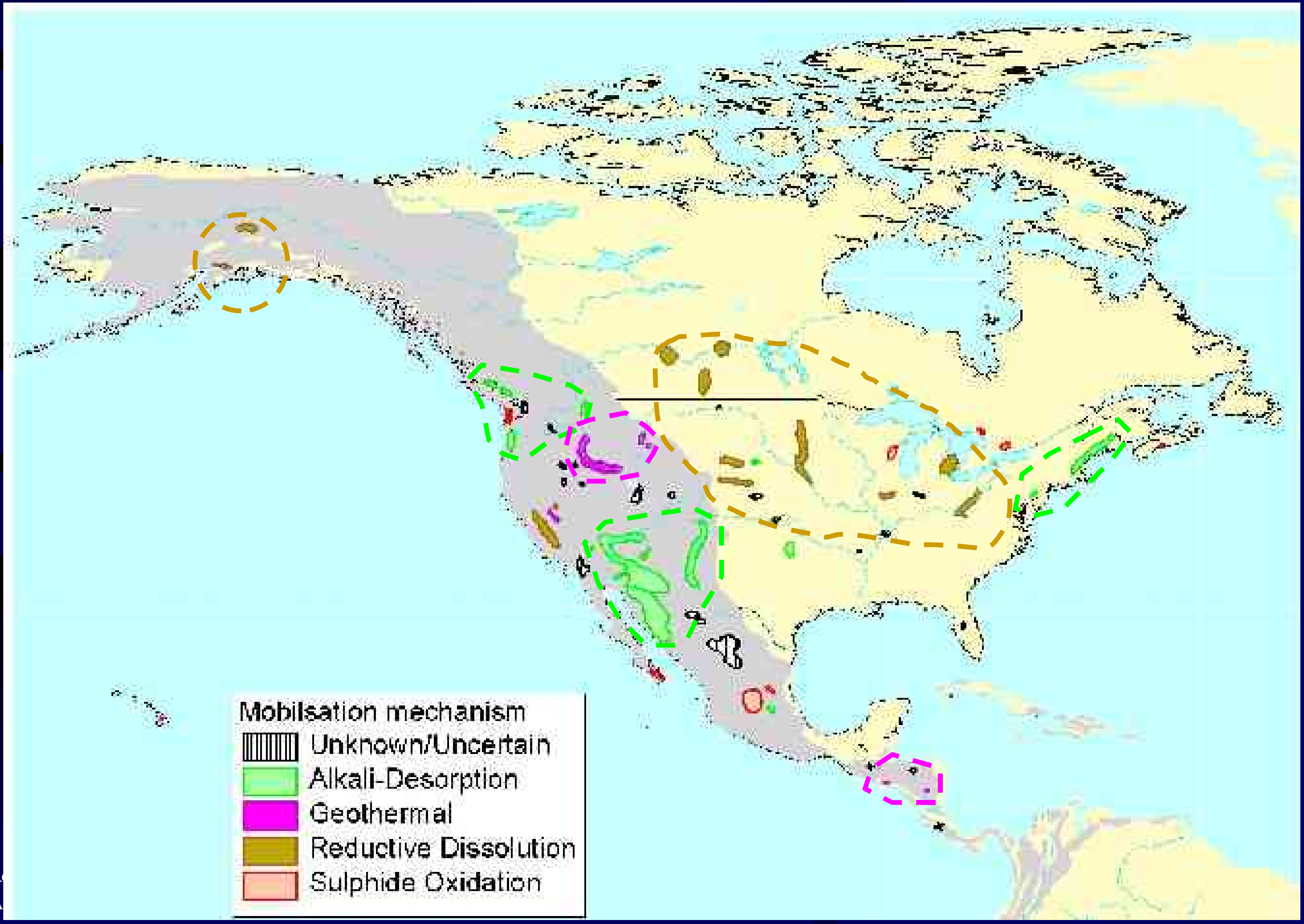


South America

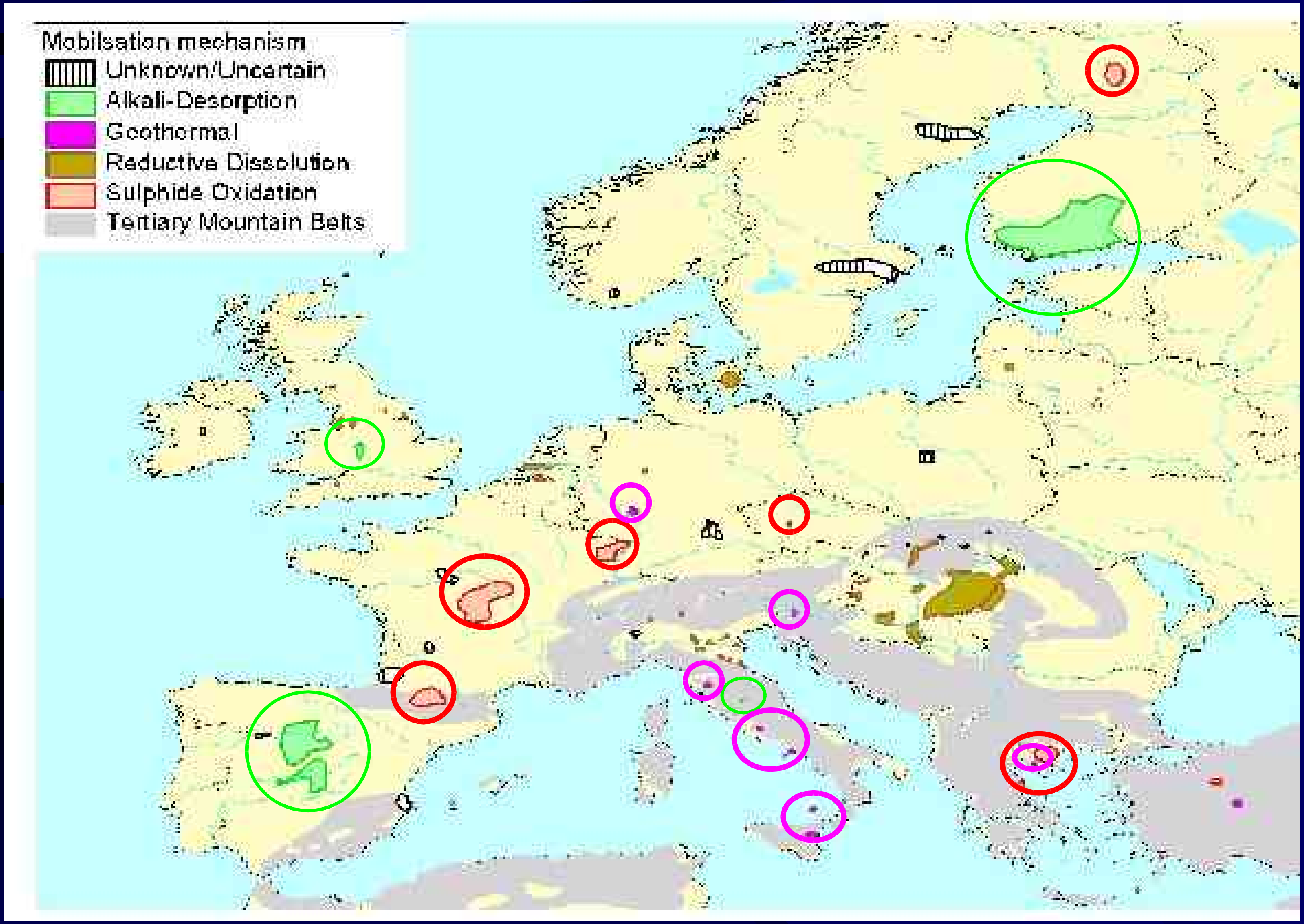


Royal Geographical Society
Annual International Conference 2007

North and Central America



Europe

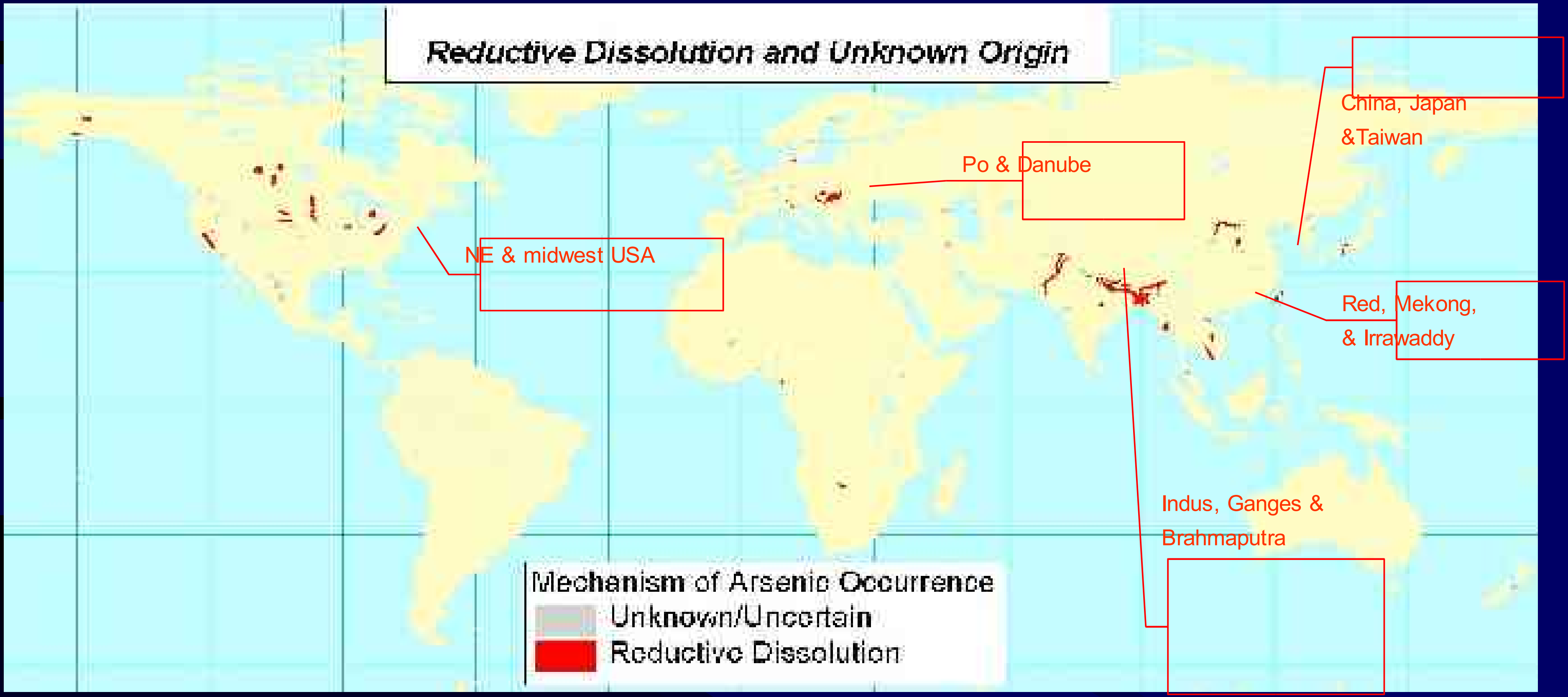

Mobilsation mechanism
Unknown/Uncertain
Alkali-Desorption
Geothermal
Reductive Dissolution
Sulphide Oxidation
Tertiary Mountain Belts

Arsenic occurrence: Geology and Climate

- Consider a matrix of arsenic occurrences, classified by aquifer geology, climate and process

Geology:	Cool-temperate	Humid - tropical	Semi-arid, warm
Alluvium: deltaic, aeolian & lacustrine	15	20	13
Alluvial-volcaniclastic	3		4
Glacial, and fluvio-glacial	6		
Alluvium over limestone	1	1	
Laterite			1
Tertiary, intracontinental sediments	2		4
Tertiary-Recent, volcanic terrain	2	3	8
Palaeozoic - Mesozoic sedimentary rocks	7		2
Palaeo- & Mesozoic, igneous &metamorphic rock	2		1
PreCambrian-Palaeozoic crystalline bedrock	7	2	3

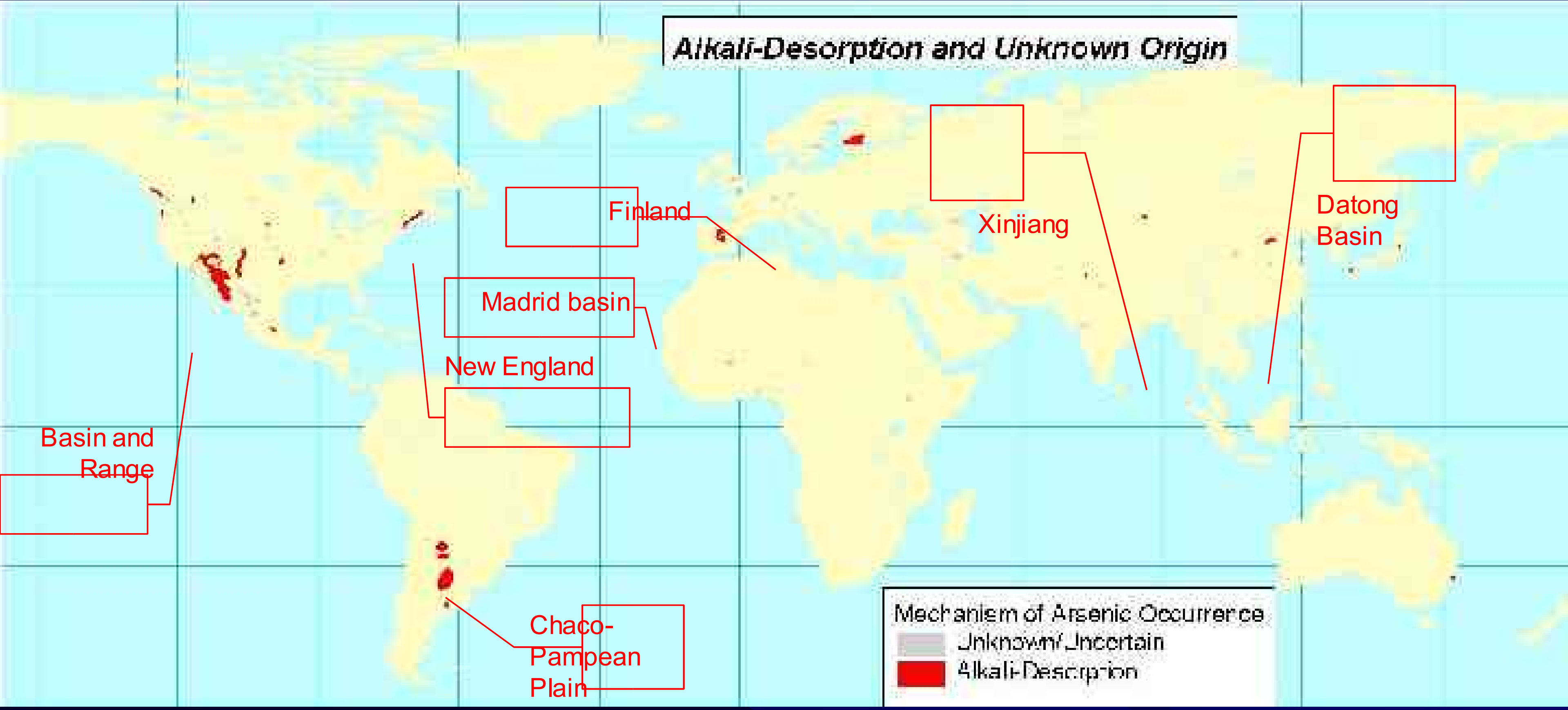
Reductive-Dissolution



Reductive-Dissolution

Geology:	*Cool-temperate*	*Humid - tropical*	*Semi-arid, warm*	*Arid, hot*
Alluvium; alluvial-deltaic / lacustrine / aeolian	Wairu Plain, New Zealand Bridgwater, UK Danube Basin, Hungary Gouda, Netherlands Paderborn, Germany	Tripura, India Assam, India Bengal Basin, BGD & India Ganga Plains, India Chittagong coast, Bangladesh Hat Yai, Thailand Irrawaddy Delta, Myanmar Mekong Delta, Vietnam Mekong plains, Cambodia Nakorn Chaisi, Thailand Red River Delta, Vietnam SW Taiwan	Indus valley, Pakistan Inner Mongolia, China Osaka, Japan Shanxi province, China Transyvania, Romania Okavango Delta, Botswana	Sindh Province, Pakistan Carson Desert, Nevada
Alluvial-volcaniclastic				
Glacial, and fluvio-glacial sediments	Cook Inlet, Alaska, USA Midwest, USA Fairbanks, Alaska, USA Illinois & Michigan, USA Saskatchewan, Canada			
Alluvium over limestone				
Laterite				
Tertiary, sedimentary rocks				
Tertiary-Recent, volcanic rocks				
Palaeozoic - Mesozoic-				
Palaeozoic - Mesozoic, granitic				
Palaeozoic - Mesozoic, metamorphic				
PreCambrian- Palaeozoic crystalline bedrock			~~Chattisgarh, India~~	

Alkali-Desorption



Alkali-Desorption

Geology:	Cool-temperate	Humid-tropical	Semi-arid, warm	Arid, hot
Alluvium; alluvial-deltaic / lacustrine / aeolian			Basin and Range, USA Datong Basin, China Fukoka Prefecture, Japan Stuarts Point, NSW, Australia	Xinjiang province, China
Alluvial-volcaniclastic	Williamette Bsn, Org, USA		Chaco-Pampean plains, Argentina	
Glacial, and fluvio-glacial sediments				
Alluvium over limestone			Zimapan, Mexico	
Laterite				
Tertiarv. sedimentary rocks			Madrid Basin, Spain Duero Basin, Spain	
Tertiary-Recent, volcanic				
Palaeozoic - Mesozoic- sedimentary rocks	Oklahoma, USA			
Palaeozoic - Mesozoic, granitic	Bowen Island, Canada Sunshine Coast, Canada			
Palaeozoic - Mesozoic, metamorphic				
PreCambrian - Palaeozoic crystalline bedrock	New England, USA SW Finland			

Sulphide Oxidation

Sulphide Oxidation

Geology:	*Cool-temperate*	*Humid - tropical*	*Semi-arid, warm*	*Arid, hot*
Alluvium; alluvial-deltaic; alluvial-lacustrine; alluvial-aeolian			Perth, Australia Rio Verde basin, Mexico	
Alluvial-volcaniclastic				
Glacial, and fluvio-glacial sediments				
Alluvium over limestone				
Laterite				
Tertiary-Recent, volcanic				
Palaeozoic - Mesozoic-sedimentary	Wisconsin, USA			
Palaeozoic - Mesozoic, granitic			E. Thessalonika, Greece	
Palaeozoic - Mesozoic, metamorphic				
PreCambrian -Palaeozoic crystalline bedrock	Washington State, USA Nova Scotia, Canada Finnish Lapland, Finland	Iron Quadrangle, Brazil	Ashanti, Ghana	

Where arsenic is present and absent

- Principal occurrence in **Alluvial Aquifers (59%)**, especially:
  - Holocene age
  - Foreland Basins
- Principally mobilised by:
  1. **Reductive Dissolution** in humid / anoxic depositional environments
  2. Alkali-Desorption in arid climates
- NO reports from
  - vast areas of Africa, Australia, South America and Peninsular India (Gondwanaland!)
- **BUT** is this evidence of absence, or absence of evidence?

The Character of Gondwanan Terrain

- Ancient peneplains
- Weathering processes
- Ferallitic and fersialitic soils
- Kaolinite and iron oxide residues

To see the breakup of Gondwanaland, and relate it to the occurrences of arsenic shown earlier
Visit: http://www.kartografie.nl/gondwana/ftp.html

Arsenic In River Basins

Arsenic Affected basins:

e.g. Ganges, Brahmaputra, Indus, Mekong, Red, Yellow, Irrawaddy, Salween

- •Physical weathering in upper catchment
- •Gradient & sediment load
- •Humid lower catchment, abundant OM
- •Rapid subsidence
- •Deep incision in Delta

Unaffected basins:

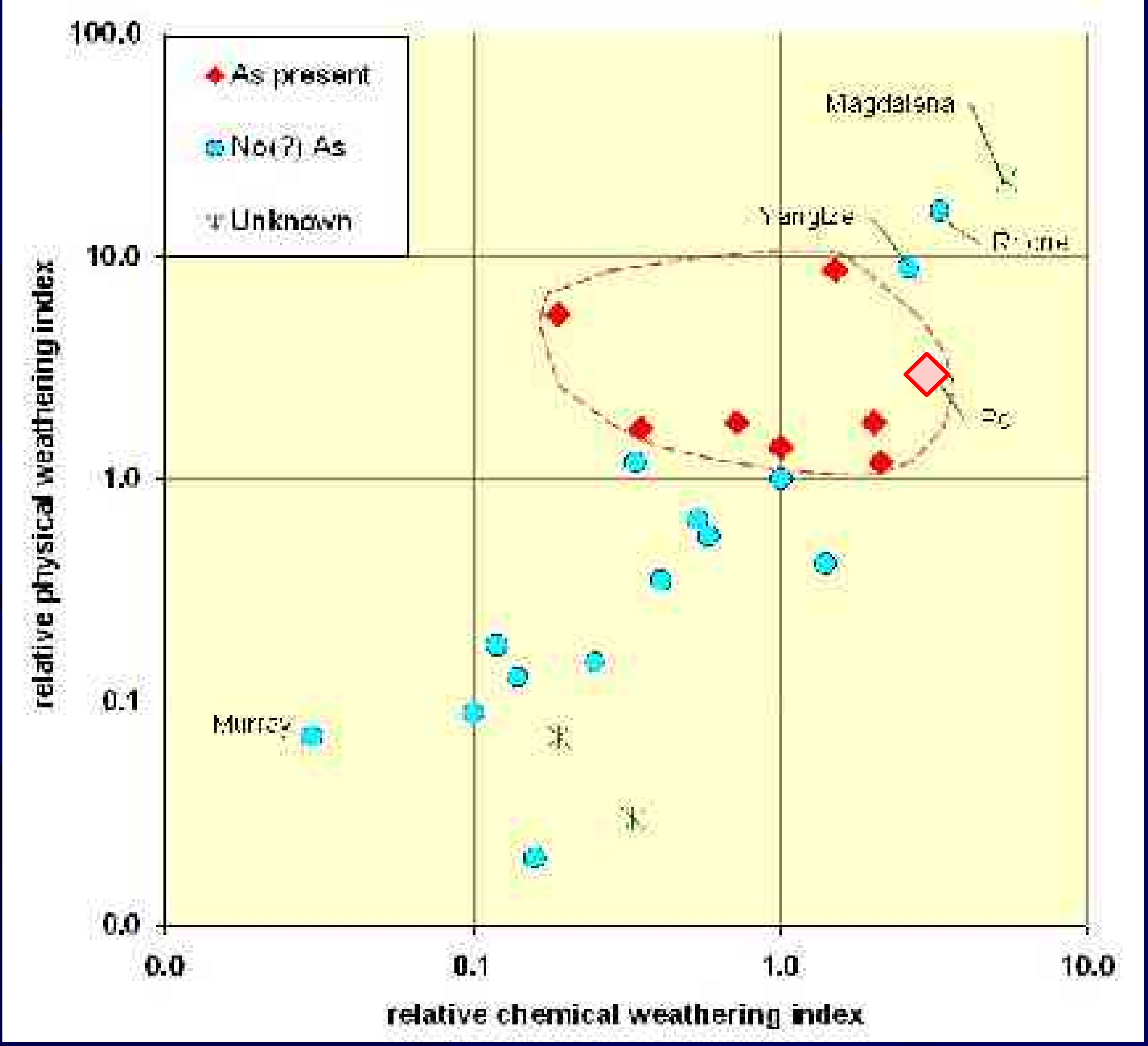
e.g. Congo, Nile, Amazon, Orinoco

- •Chemical weathering dominant
- •Gentle gradients & low sediment load
- •Humid lower catchment, abundant OM
- •Gentle uplift of coastal regions
- •Little incision & shallow bedrock

Can we find a simple approach to predicting the occurrence of arsenic contamination in river basins?

Chemical and Weathering Indices

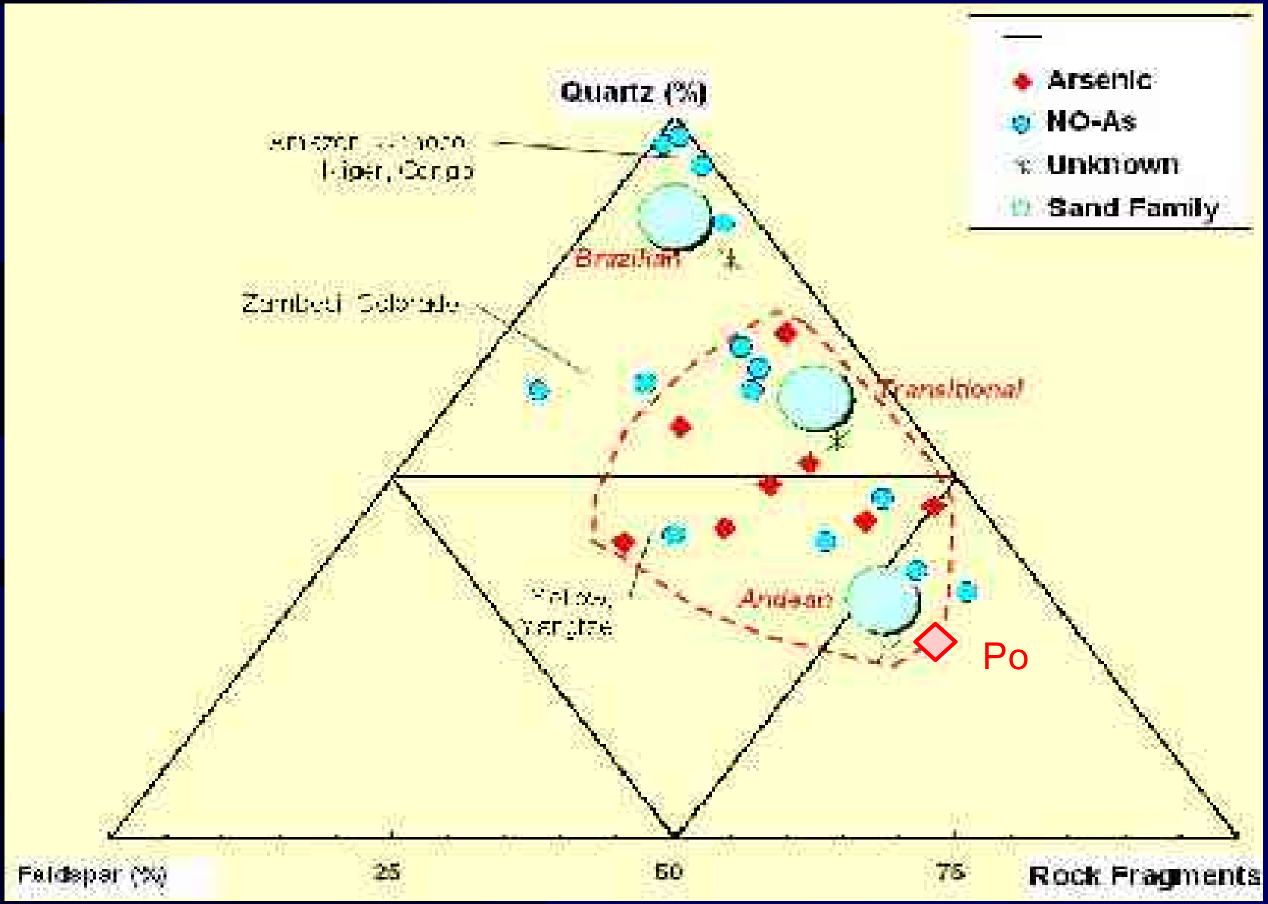
- As-affected basins have characteristic weathering regimes in the upper and lower catchments
- consider chemical and physical weathering indices[1] (relative to the Amazon).



- Note the Po was identified subsequent to creating the original diagram

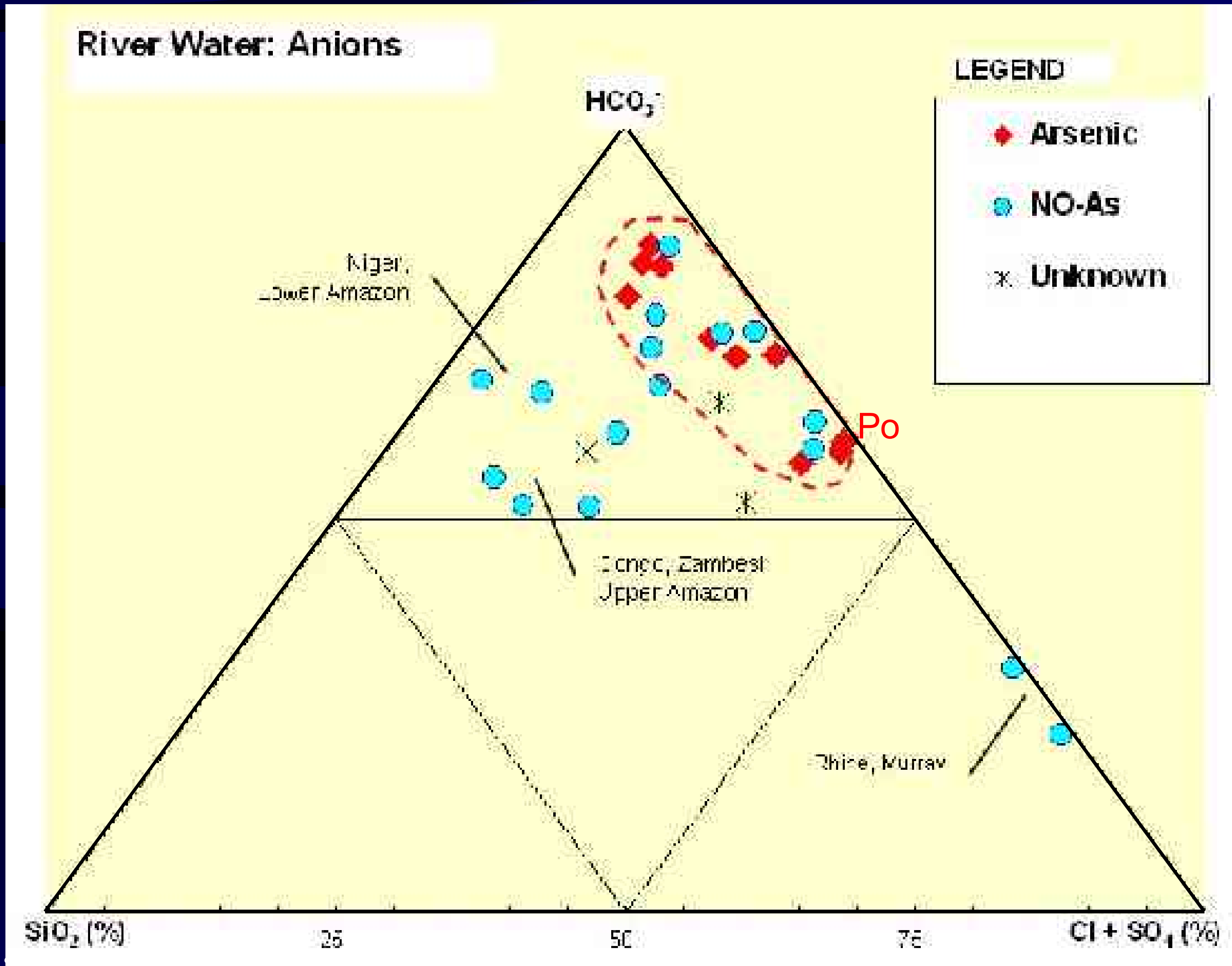
1. Gaillardet et al. (1999, *Chemical Geology; 159, 30-30*)

River Sand Composition



- **QFR** (quartz, feldspar and rock) diagrams reflect:
  - The source rocks
  - Chemical weathering

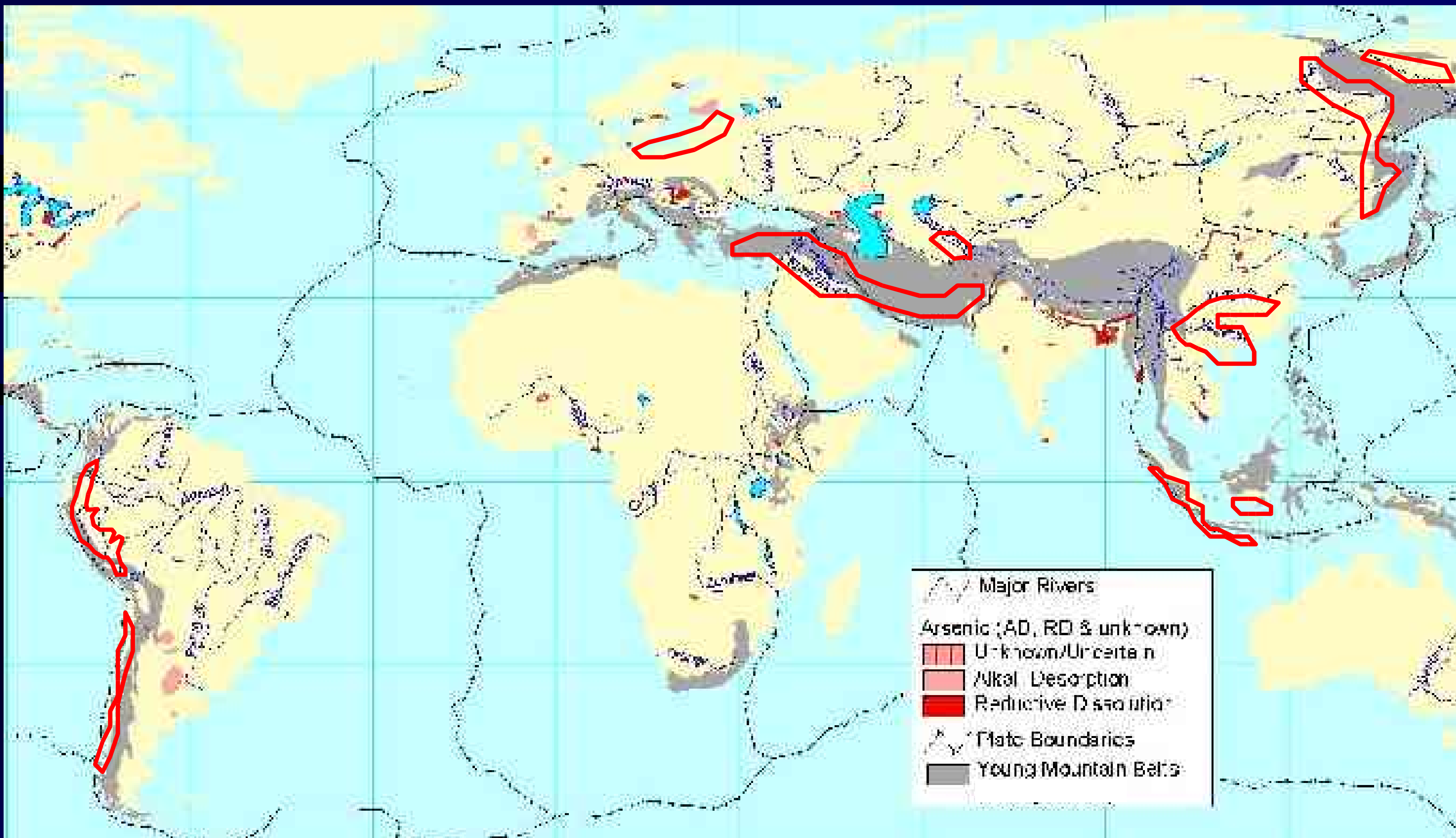
River Water Composition



Predictions: 1. Where can arsenic be expected?

- South and East Asia:
  - SE China, Yangtze-Kiang basin (RD)
  - Indonesia and Malaysia (RD + GT)
  - Siberia
- West Asia and Middle East
  - Arabian Peninsula (AD + GT)
  - Turkey and Iran (AD + GT)
- South America
  - Western Amazonia (RD)
  - Pacific Plains (AD)
- Europe
  - Danube delta
  - Baltic fringes

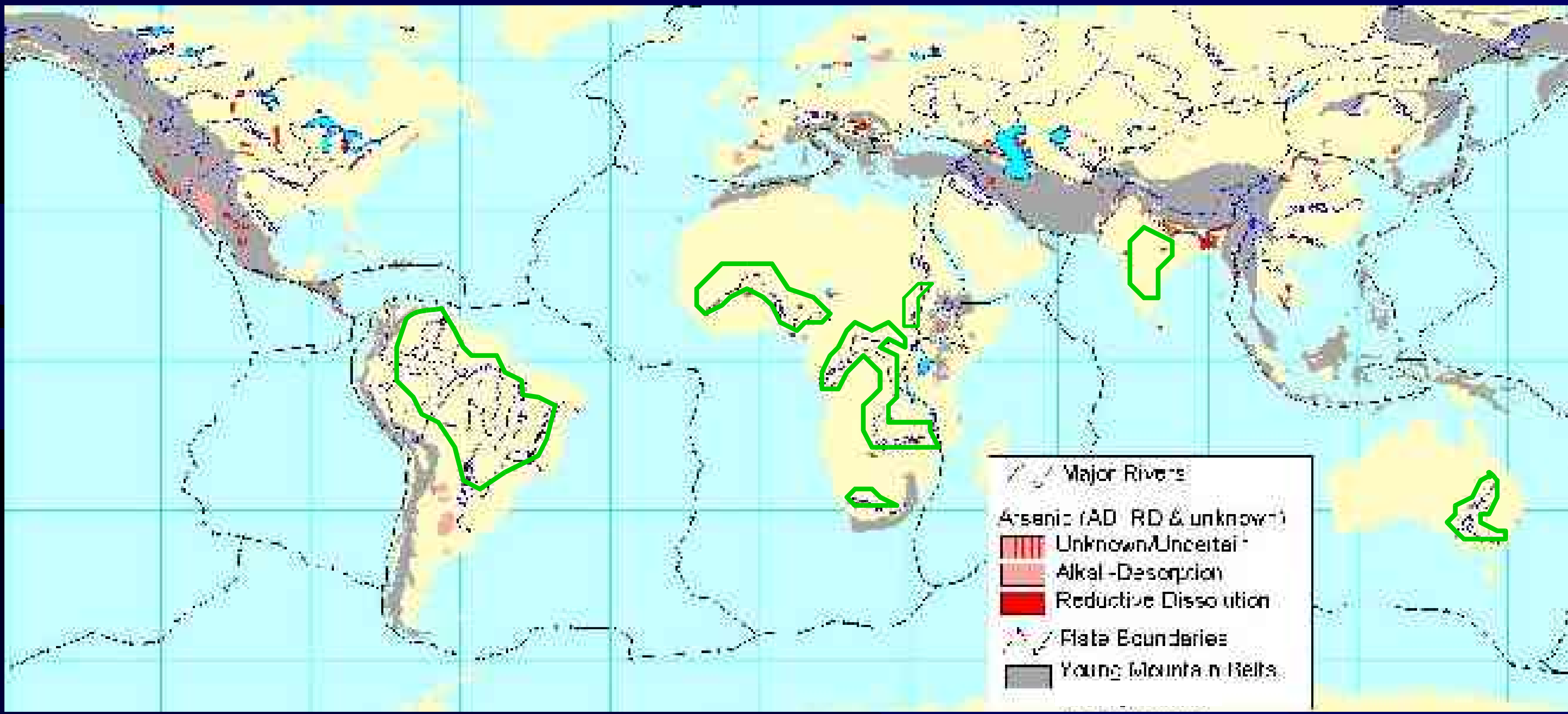
Predictions: 1. Where can arsenic be expected?



2: Where extensive arsenic pollution of river basins is NOT expected

- Alluvial basins draining Gondwanan terrain, including large parts of:
  - Africa
  - Australia
  - Eastern South America
  - Peninsular India

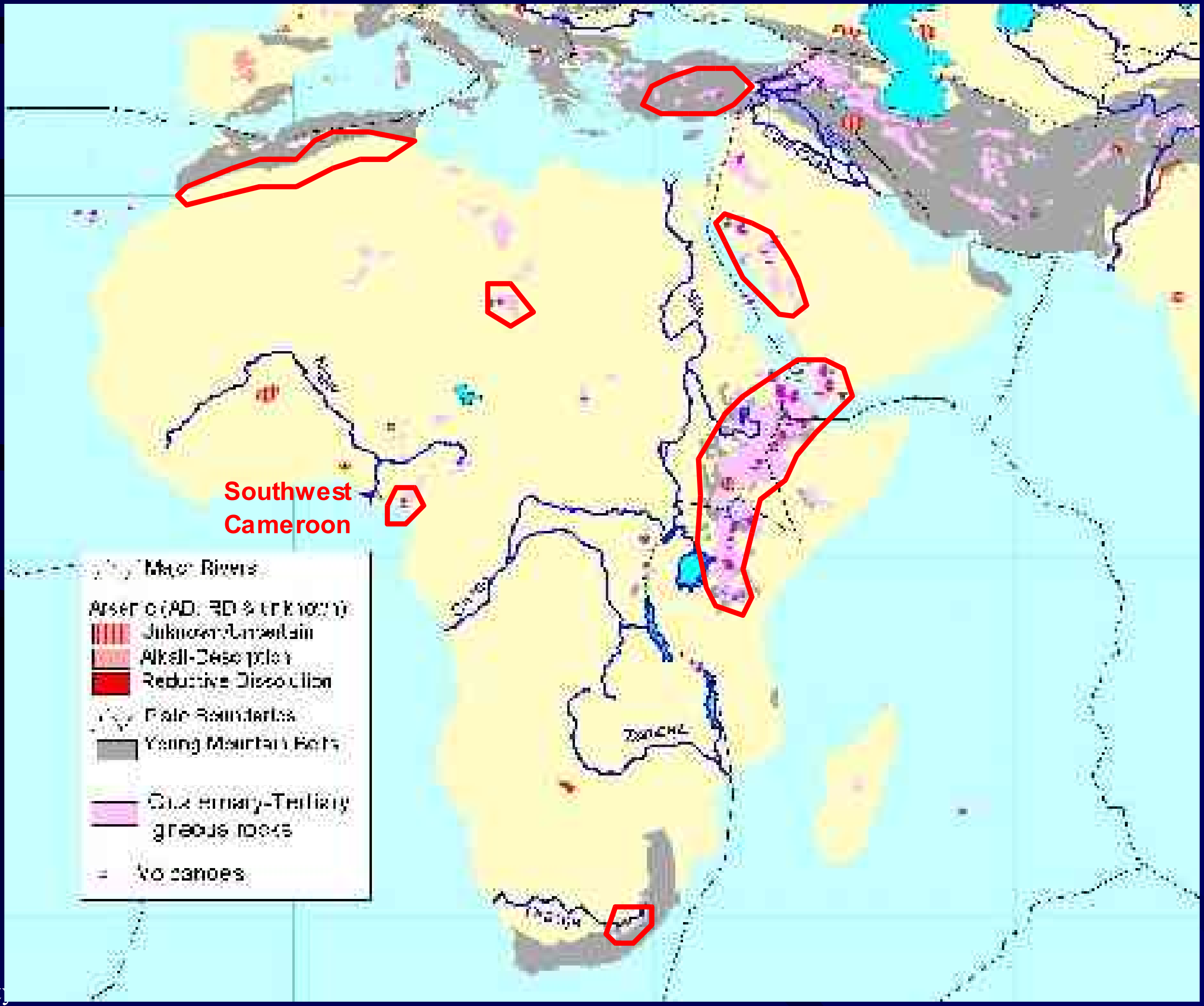
2: Where <u>extensive</u> arsenic pollution of river basins is NOT expected



3. Some predictable exceptions

- Areas of intense sulphide mineralisation
  - SW Ghana, Chhattisgarh(?)
- Areas of recent mountain building in Africa
  - Atlas Mts, Tibesti and Ahaggar Massifs, SW Cameroon (now identified)
- Areas of geothermal activity

3. Some predictable exceptions



Conclusions

- The distribution of arsenic is rational but incomplete.
- Pollution occurs dominantly in alluvial aquifers, by reductive-dissolution, and in all climates.
- Significant gaps are identified adjacent to young mountain chains in NE, SE & SW Asia; and S. America
- Despite serious data gaps, it is predicted that tropical basement is substantially free of extensive As pollution, but ...
- Exceptions WILL occur, especially in areas of shallow sulphide mineralisation.
- Past predictions of arsenic occurrence have often been wrong, hence:
- URGENTLY survey areas lacking data to establish the safety of water supplies.