The Rumen Model, A new mineral deposit type for cobalt mineralisation near Broken Hill

and comments on the formation of other cobalt deposits

Broken Hill PROSPECTING

Ian Pringle

Managing Director

(22 March, 2012)

Macquarie Drilling is now drill testing Big Hill NE anomalies

Photo from Macquarie Drilling

Important notices

Disclaimer This presentation contains forward-looking statements that involve subjective judgement and analysis and accordingly, are subject to significant uncertainties and risks, many of which are outside the control of, and are unknown to, Broken Hill Prospecting Pty Ltd (“BPL”). In such circumstances, the forward-looking statements can be identified by the use of forward-looking words such as “may”, “will”, “expect”, “intend”, “seek”, “estimate”, “believe”, “continue” or other similar words.

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In particular, BPL wishes to caution readers that these forward-looking statements are based on economic predictions and assumptions on reserves, mining method, production rates, metal prices and costs (both capital and operating) developed by BPL management in conjunction with consultants.

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The exploration target and potential being reported under Section 18 of the JORC Code is based on assessments of prospects within BPL’s tenure which are supported by drilling, geophysics, geological studies, imagery analysis, metallurgical test-work and preliminary modelling. However, the potential quantity and grade is conceptual in nature, there has been insufficient exploration to define a Mineral Resource and it is uncertain if further exploration will result in discovery of a Mineral Resource.

Competent Person Statement The review of exploration activities and results contained in this report is based on information compiled by Dr Ian Pringle, a Member of the Australasian Institute of Mining and Metallurgy. Dr Pringle is the Managing Director of Broken Hill Prospecting Pty Ltd and also a Director of Ian J Pringle & Associates Pty Ltd, a consultancy company in minerals exploration. He has sufficient experience which is relevant to the style of mineralization and types of deposits under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the December 2004 edition of the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (the JORC Code). Dr Pringle has consented to the inclusion in this report of the matters based on his information in the form and context in which it appears.

Outline of this talk

In this talk I plan to ....

- Outline recent exploration of Paleoproterozoic cobaltiferous pyritic deposits near Broken Hill
- Suggest modern analogues for the formation of sedimentary cobalt-pyrite deposits
- Comment on the formation of Proterozoic sedimentary basin deposits with emphasis on Co-pyrite formation
- Discuss an end-member syngenetic model for these deposits
- Finish with some interesting trends in recent Co use

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Cobalt – deposit types

- Cobalt is a widespread and abundant metal (average 25ppm)
- Only limited in concentrates and almost all is produced as bi-product:
  - Stratabound Cu-(Co) deposits (Copper Belt of central Africa), DRCongo (**40%**), Zambia (**20%**)
  - Ni-(Co) laterite deposits (Australia, New Caledonia, PNG, Cuba) **25%**
  - Ni-Cu-(Co) sulphide deposits (Russia, Canada WA, Scandinavia) **10%**
  - Ag-As-(Co) deposits in Morocco + others (**5%**)
  - Mn-(Co) seafloor nodules and crusts (**not mined**)

- *Annual* world (reported) production about 98,000t Co in 2011 (USGS)
- Current LME price is about US$31,500/t
- Main uses: metal alloys, batteries(Li-ion, rechargeable), magnets, colouring, food supplements (vitamin B12), chemical/catalysts
- Growing demand for energy, environmental and military uses
- Conclusion **;-)** Uncertain supply and growing demand

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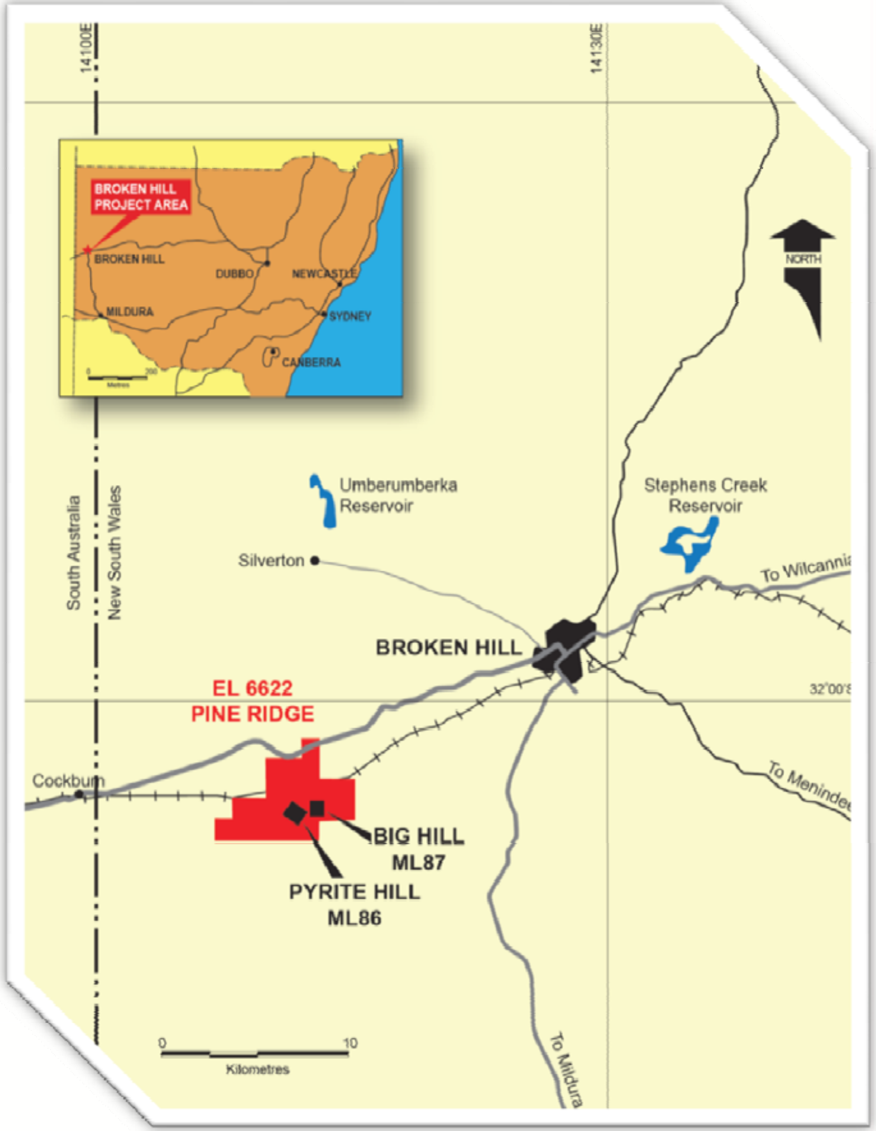
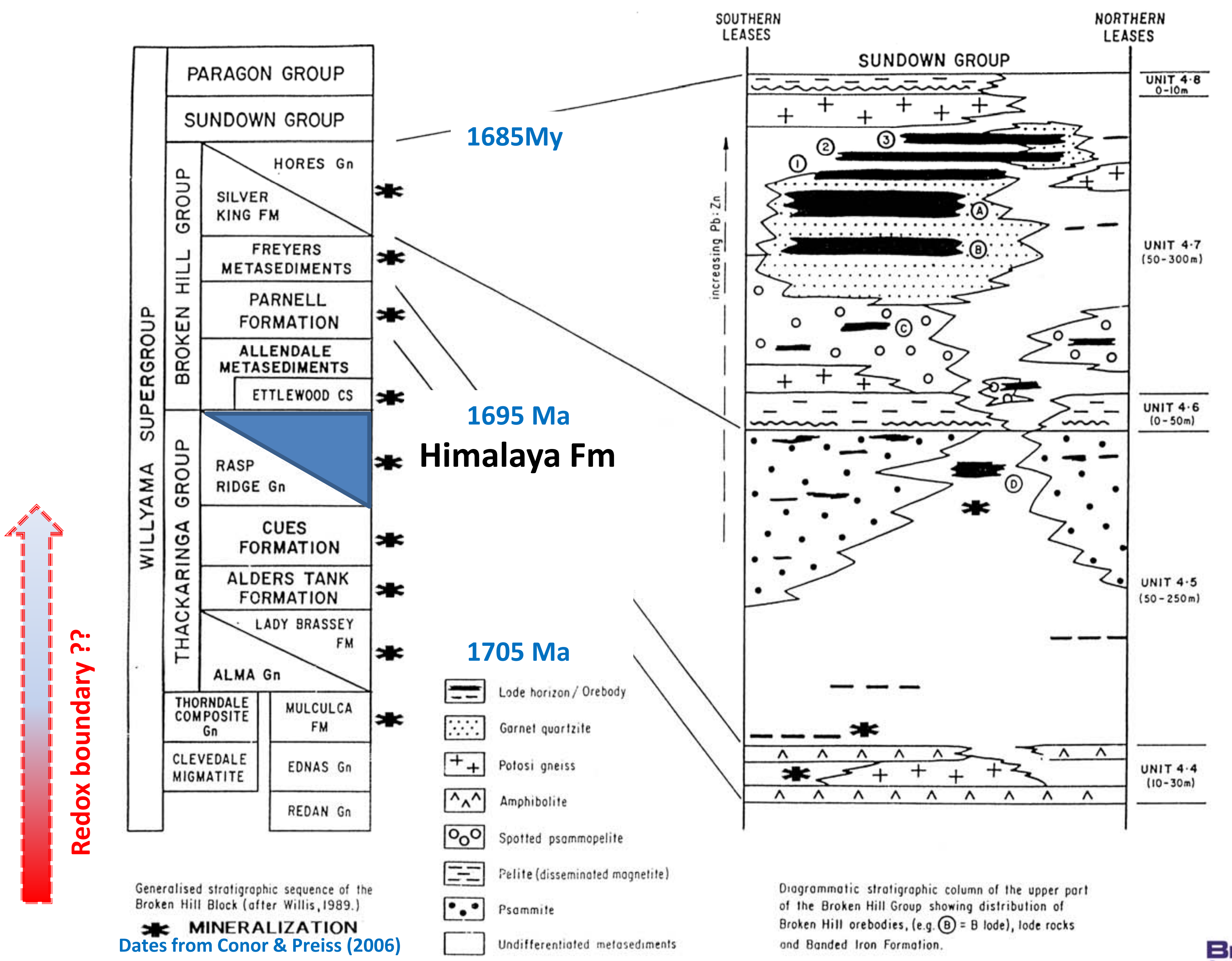
Location is important for development future

- BPL's project is located 25km SW of Broken Hill in western NSW
- Main highway to Adelaide joins the northern part of the project
- Main trunk railway line 500 metres from the deposits
- Exploration license (EL6622) and two mining leases (ML86, ML87)
- Geophysics (IP survey) and Pyrite Hill resource confirmation drilling completed in late 2011
- New target drilling assessment in progress



Big Hill Silver Mining Coy. 1885-1889



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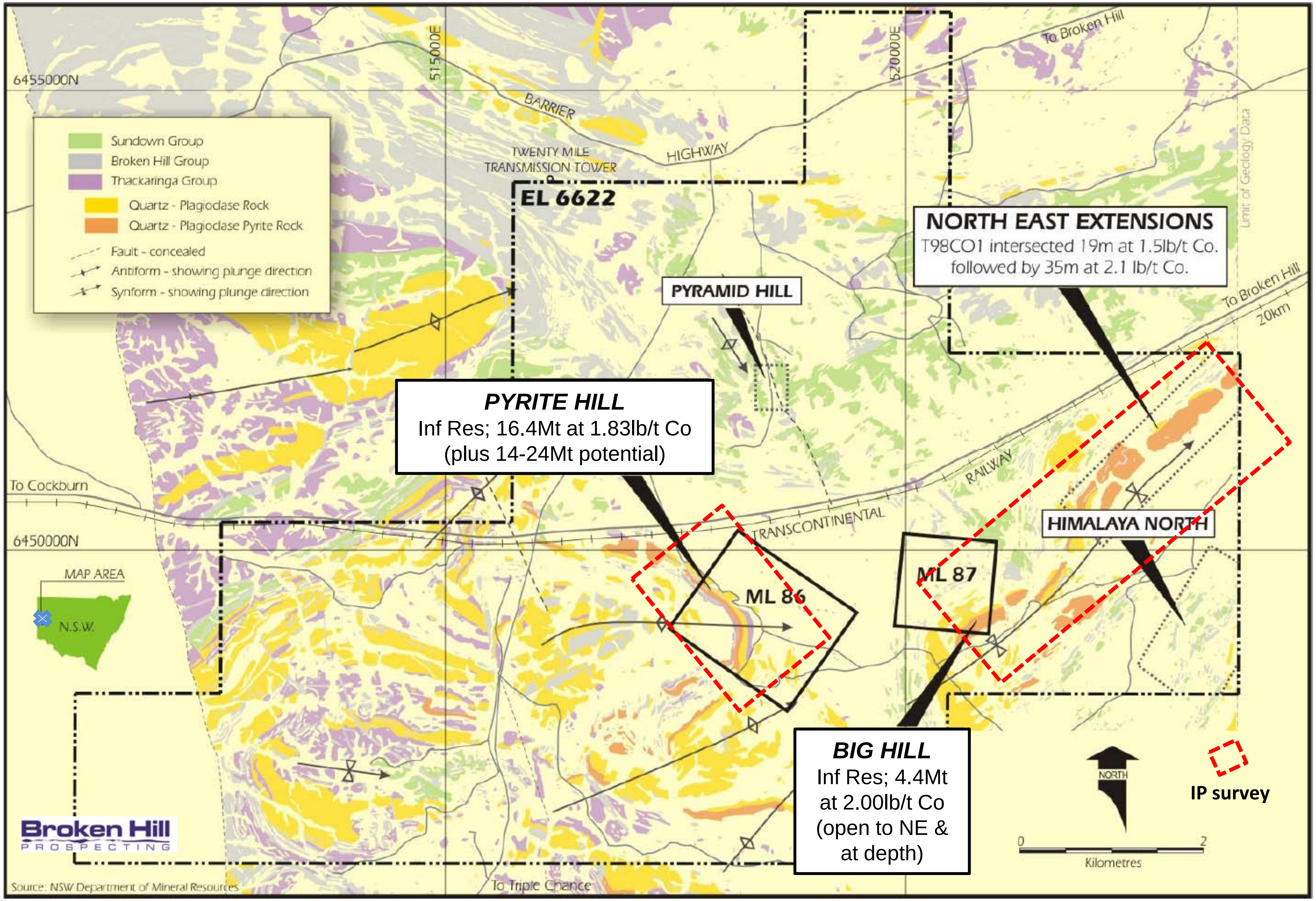
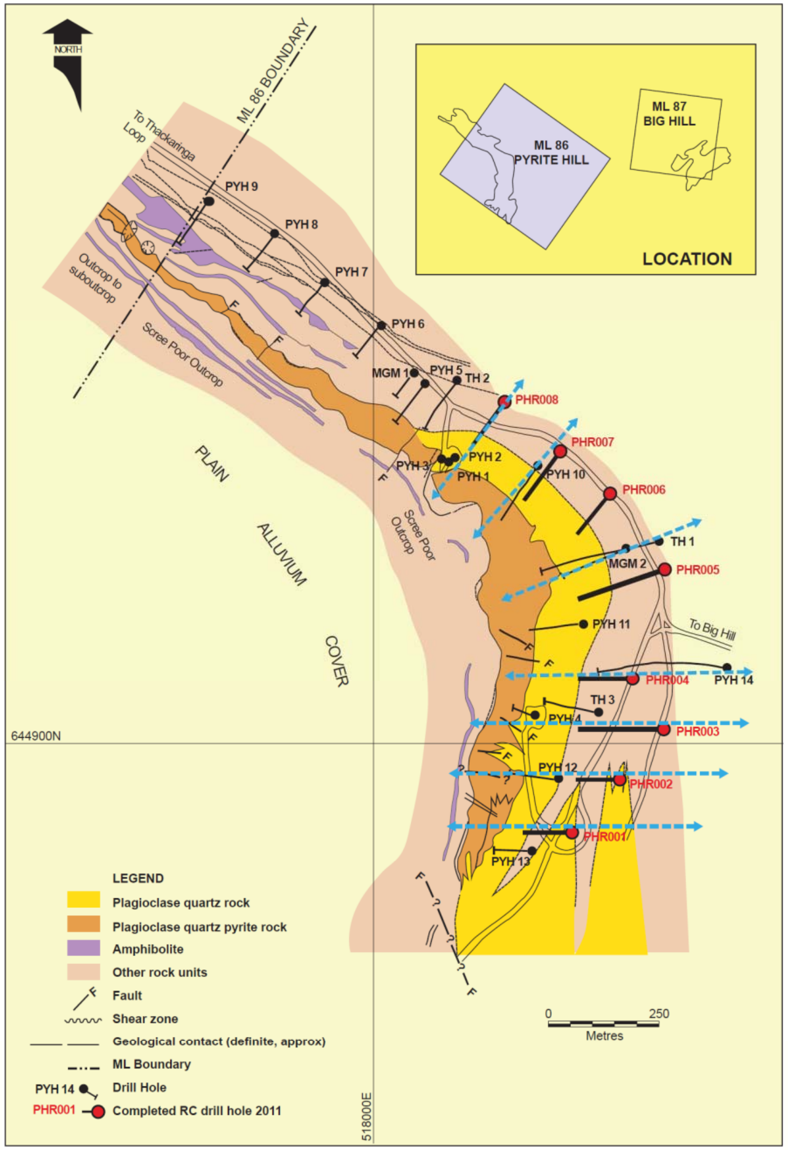
Project Geology



Pyrite Hill Cobalt Deposit - map

- Albite-quartz-pyrite gneiss in folded antiform of stratabound cobalt-rich pyrite.
- Drilled extent is over 1.2km (out crop is over +6km)
- Shallow oxidation. Limited surface gossan and oxidation/weathering above 10-30m and fresh pyrite at the surface.
- Mineralisation dips to east at about 50 degrees and is thickest in plunging fold hinge.
- Cobalt occurs in solid solution in early formed pyrite (usually 10-25% of rock).
- Can be concentrated by flotation or gravity (+90% recov) to form pyrite con (+95%pyr).
- Pyrite can be oxidised by pressure leach, roasting or hydrometallurgical methods, or bioleaching then SX-EW.
- By-products; sulphuric acid, iron, ceramic grade feldspar and glass grade feldspar could be produced as by-products.



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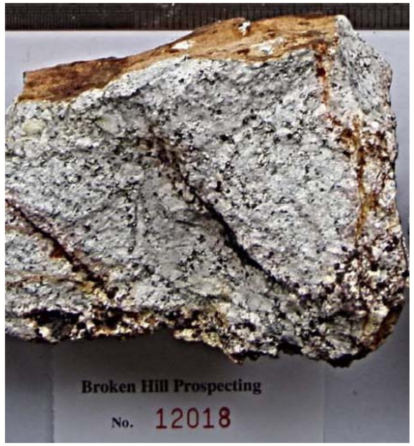
Pyrite composition

- Majority is early euhedral, coarse pyrite (0.35-0.9% Co, no Ni). Grainsize is typically 0.5-1mm. Disseminated and massive.
- Lesser, younger, finer colloform, crusty and interstitial supergene pyrite occurs with and partially replaces minor pyrrhotite. Both contain lower cobalt but higher nickel contents (0.1% Co, 0.1-0.2% Ni).
- Very rare galena, sphalerite, chalcopyrite as minute grains and inclusions in pyrite. No gold, platinoids or REEs
- Plagioclase is albite and rock is typically high Na_2O (6-10%)

Limonite gossan vs pyritic gneiss

	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Co	Cr	Cu	Fe	Ga	K	La
	ppm	%	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	%	ppm	%	ppm
gossan 12008	<0.5	0.16	97	50	<0.5	6	0.05	<0.5	1	23	24	**41.3**	10	0.02	30
sulphide 12018	<0.5	4.45	27	40	0.8	4	0.21	<0.5	867	8	32	12	20	0.12	20

Mg	Mn	Mo	Na	Ni	P	Pb	S	Sb	Sc	Sr	Th	Ti	Tl	U	V	W	Zn
%	ppm	ppm	%	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm
0.01	16	20	0.01	<1	340	8	0.29	<5	1	6	<20	0.05	<10	<10	94	<10	<2
<0.01	17	9	3.05	253	300	35	12.8	<5	3	65	<20	0.07	<10	<10	10	<10	<2



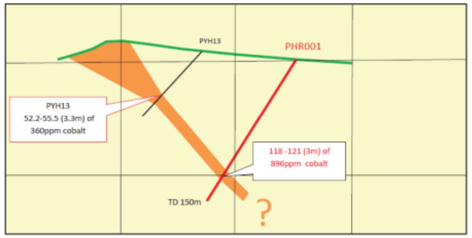
Typical samples of surface gossan (12008) and slightly oxidised albite-quartz-pyrite gneiss (12018) from approx. 10m at bottom of pit, Pyrite Hill.

High mobility of Co in an Fe-rich, oxidising secondary environment

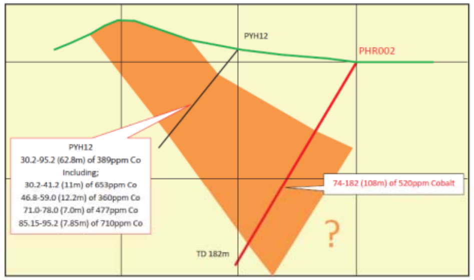
Pyrite Hill – Oct 2011 drilling extends Cobalt zone

- •108m of 520g/t Co (fr 74m) in **PHR002**, including 1m of 4,230g/t Co
- •79m of 720g/t Co (fr 150m) in **PHR003**, including 3m of 2,133g/t Co
- •49m of 1,037g/t Co (fr 123m) in **PHR004**, including 4m of 2,388g/t Co
- •28m of 1,096g/t Co (fr 192m) in **PHR005**
- •17m of 1,150g/t Co (fr 104m) and 40m of 856g/t Co (fr 131m) in **PHR006**, including 2m of 2,435g/t Co.
- •51m of 941g/t Co (fr 96m) in **PHR007**
- •41m of 783g/t Co (fr 103m) in **PHR008**

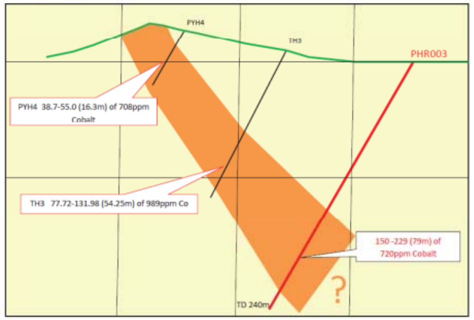
PHR001



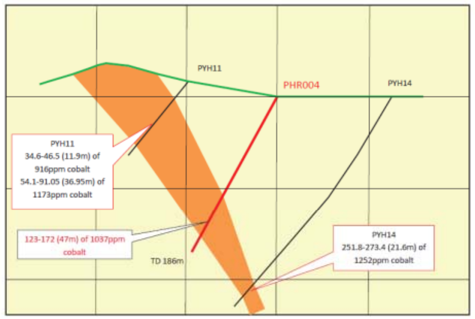
PHR002



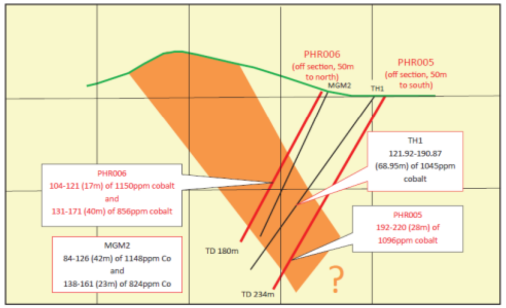
PHR003



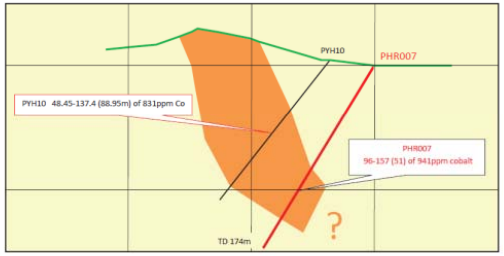
PHR004



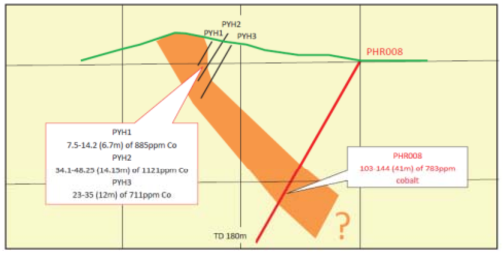
PHR005 and PHR006

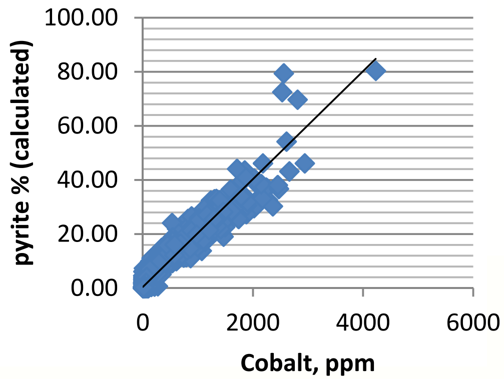


PHR007



PHR008





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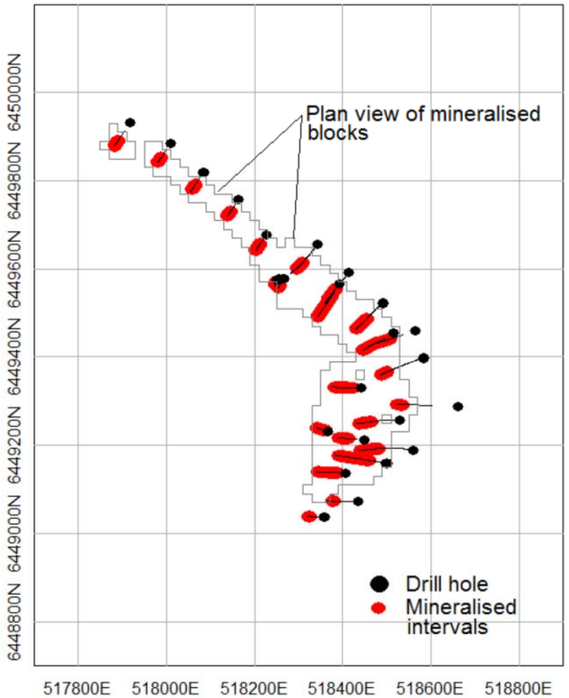
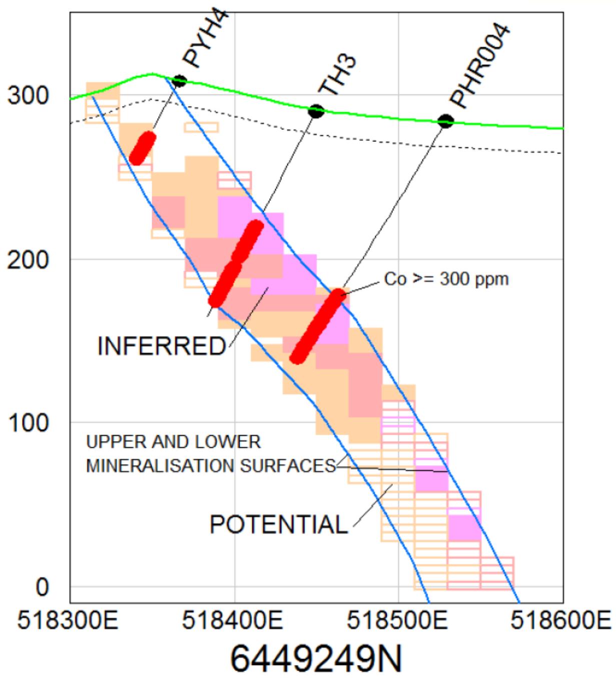
Pyrite Hill Cobalt Deposit – Resource update

Hellman & Schofield, November 2011





Cut-Off (Co ppm)	Million Tonnes	Co (ppm)	Mlb Co
300	19.3	769	32.7
400	18.1	797	31.7
500	16.4	832	30.1
600	13.9	881	27.1
700	11.1	938	23.0

- **Inferred Resource based on; 500ppm Co cut, an SG 2.8g/cc and a 75x75x15m search**
- **Used Ordinary kriging and two different resource estimation software packages**

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Pyrite Hill Cobalt Deposit – Resource update

Hellman & Schofield, November 2011

STUDY and CLASSIFICATION	Mt	Co (ppm)	Co (lb/t)	Contained Co (Mlbs)
Pyrite Hill, H&S 14 Nov 2011 Inferred Resource	16.4	830	1.83	30
Pyrite Hill, previous Inferred Resource	10.6	1000	2.20	23
Big Hill, previous Inferred Resource	4.4	910	2.00	8.9
PH + BH (combined) previous Inferred Res	15.0	850	1.87	32
Updated Combined Pyrite Hill and Big Hill Inferred Resources				
14 November, 2011	20.8	850	1.87	39

- Also defined potential for 14 – 24Mt of cobalt mineralisation of similar grade peripheral to the resource at Pyrite Hill

- The Pyrite Hill and Big Hill deposits are open at depth and along trend
- The mineralisation can be concentrated (gravity or flotation) to form a pyrite concentrate with plus 0.5% cobalt
- Concentrate process options include bacterial leach, pressure leaching or oxidation of pyrite to produce cobalt and sulphuric acid.

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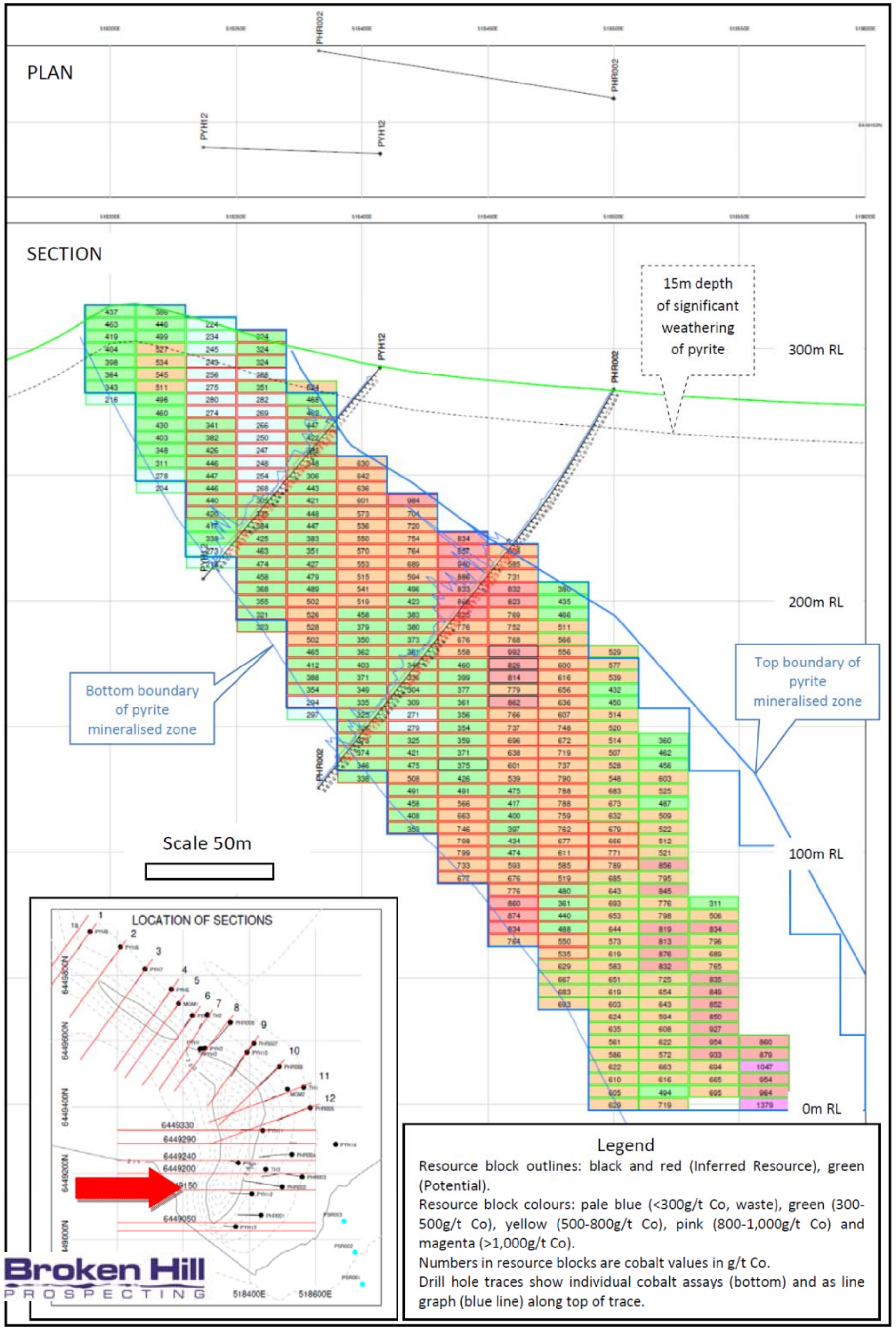
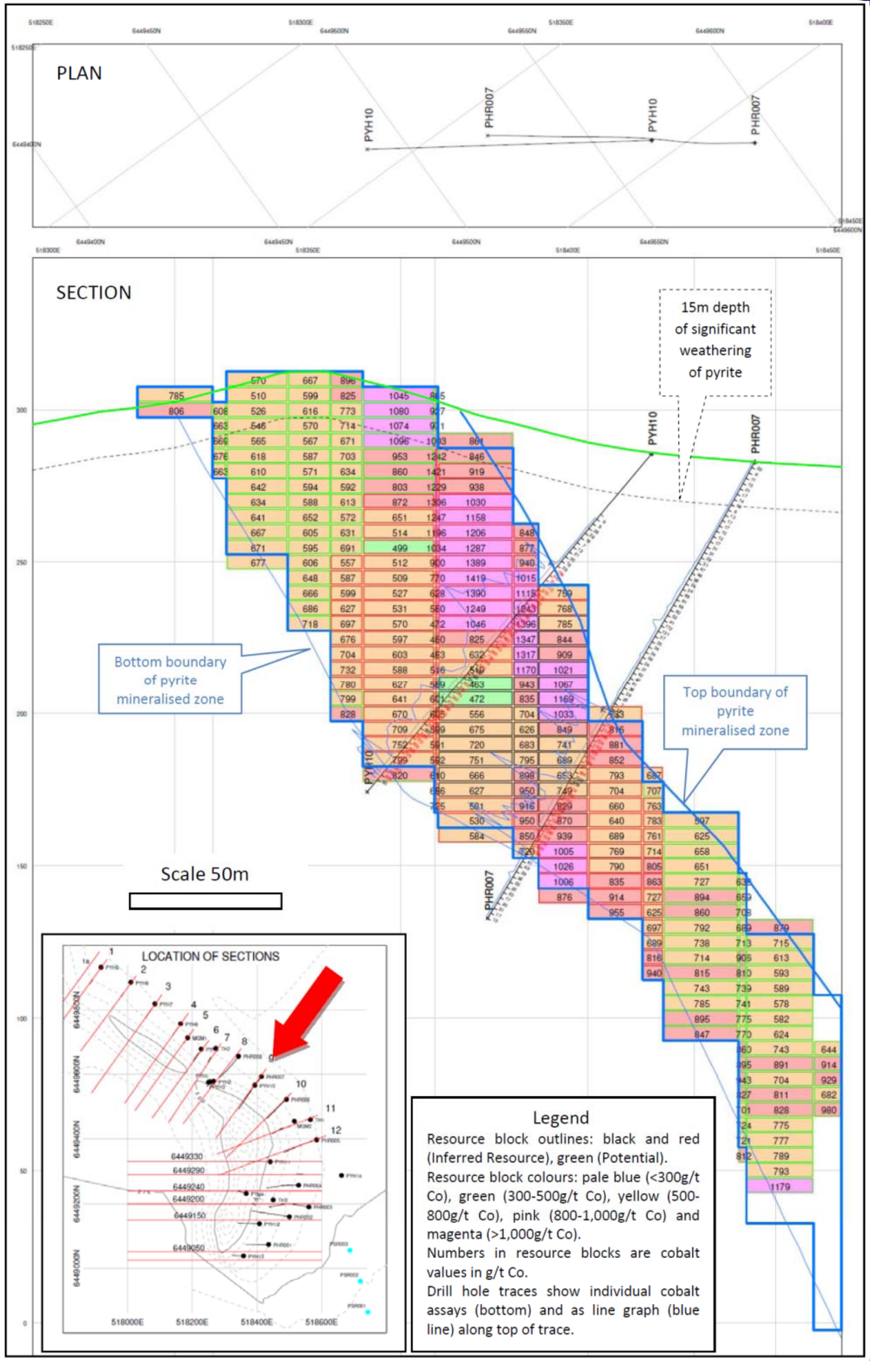

PLAN
SECTION
15m depth of significant weathering of pyrite
300m RL
200m RL
100m RL
0m RL
Top boundary of pyrite mineralised zone
Bottom boundary of pyrite mineralised zone
Scale 50m
LOCATION OF SECTIONS
Legend
Resource block outlines: black and red (Inferred Resource), green (Potential).
Resource block colours: pale blue (<300g/t Co, waste), green (300-500g/t Co), yellow (500-800g/t Co), pink (800-1,000g/t Co) and magenta (>1,000g/t Co).
Numbers in resource blocks are cobalt values in g/t Co.
Drill hole traces show individual cobalt assays (bottom) and as line graph (blue line) along top of trace.
Broken Hill PROSPECTING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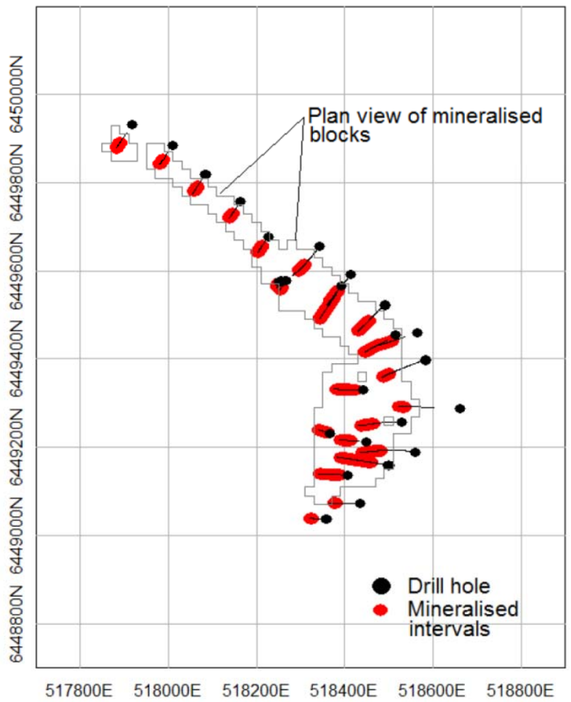
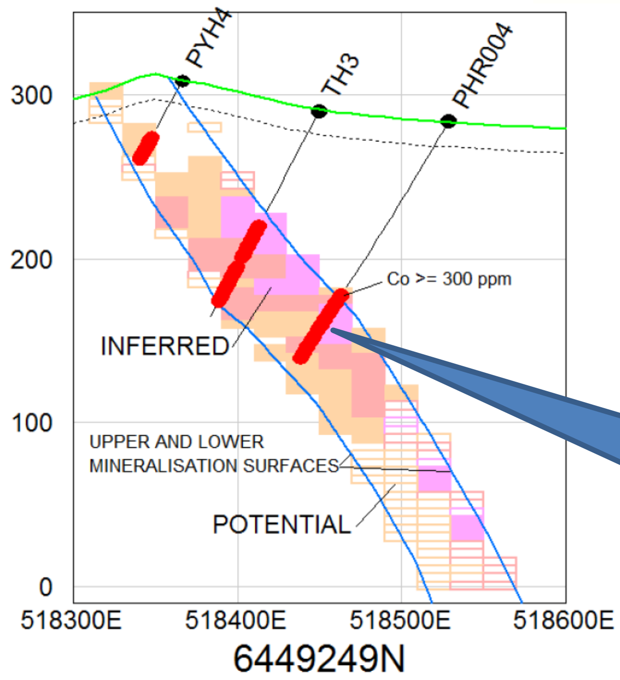
Pyrite Hill Cobalt Deposit – Resource update

Hellman & Schofield, November 2011





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600	13.9	881	27.1
700	11.1	938	23.0

Next slides show metal ratios for PHR004

- Inferred Resource based on; 500ppm Co cut, an SG 2.8g/cc and a 75x75x15m search
- Used Ordinary kriging and two different resource estimation software packages

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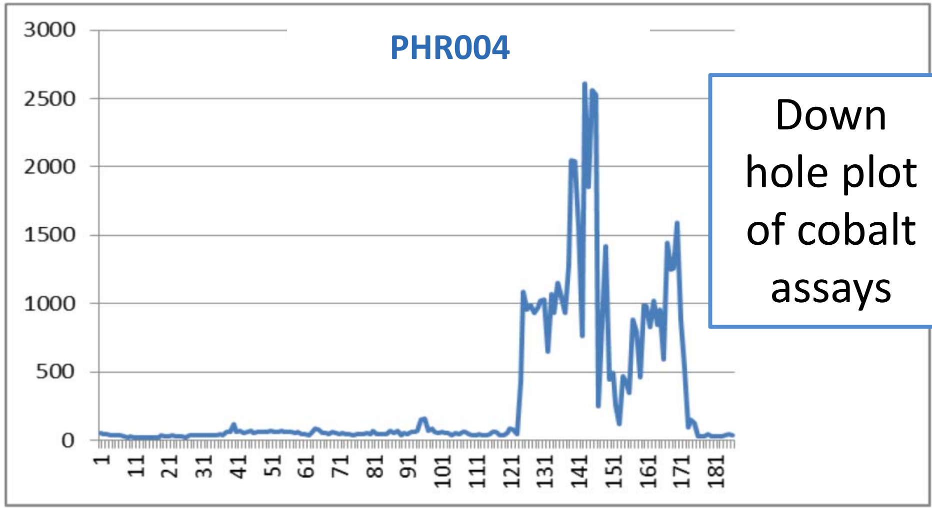
Pyrite Hill Co Deposit

Co vs S

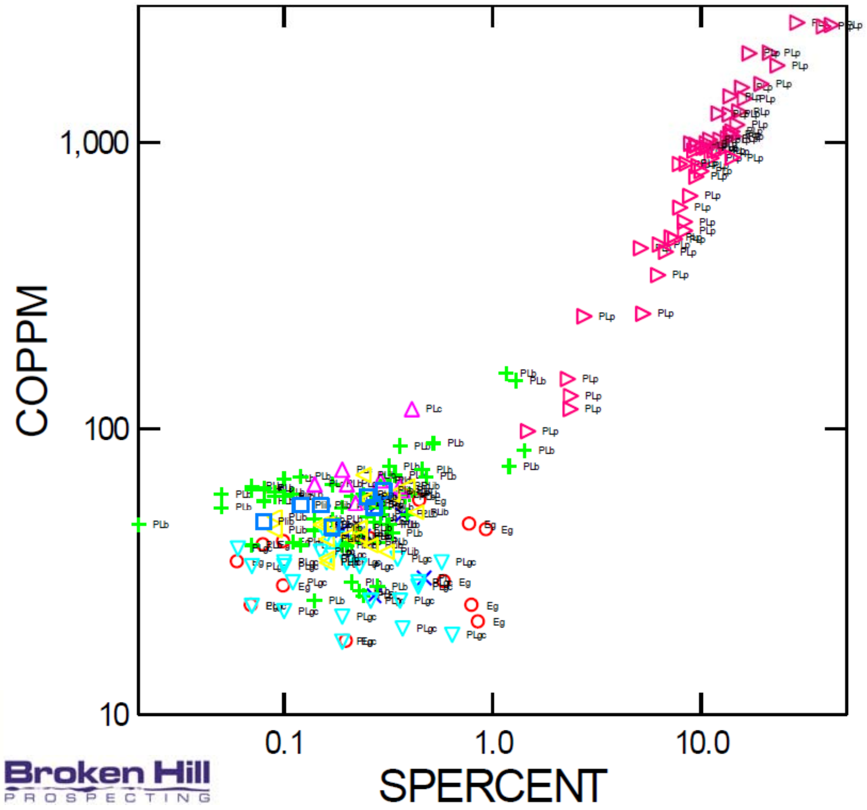
and

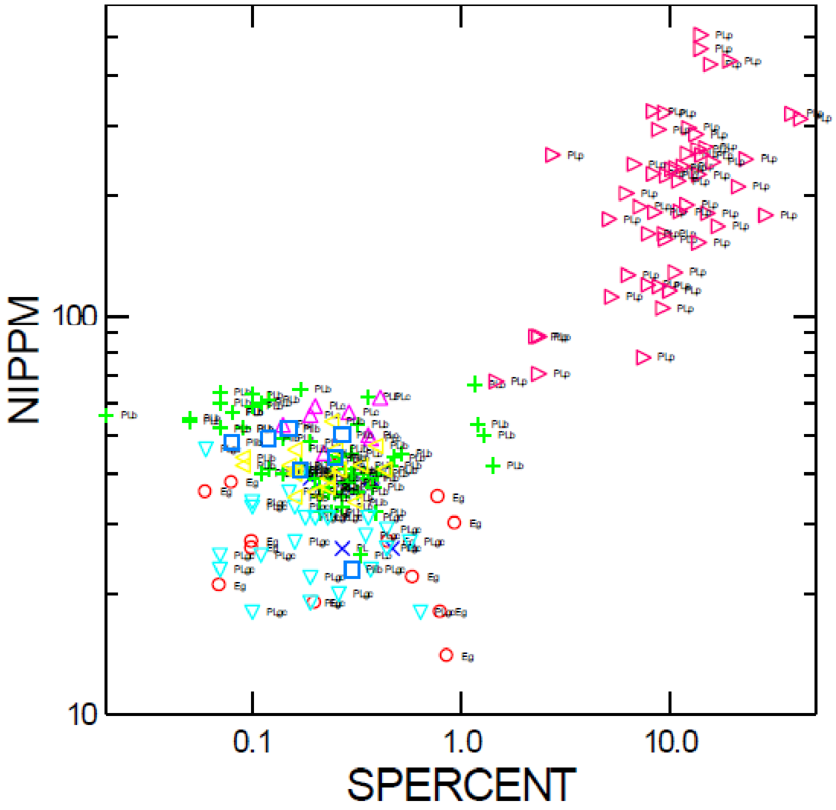
Ni vs S

for PHR004



Down hole plot of cobalt assays





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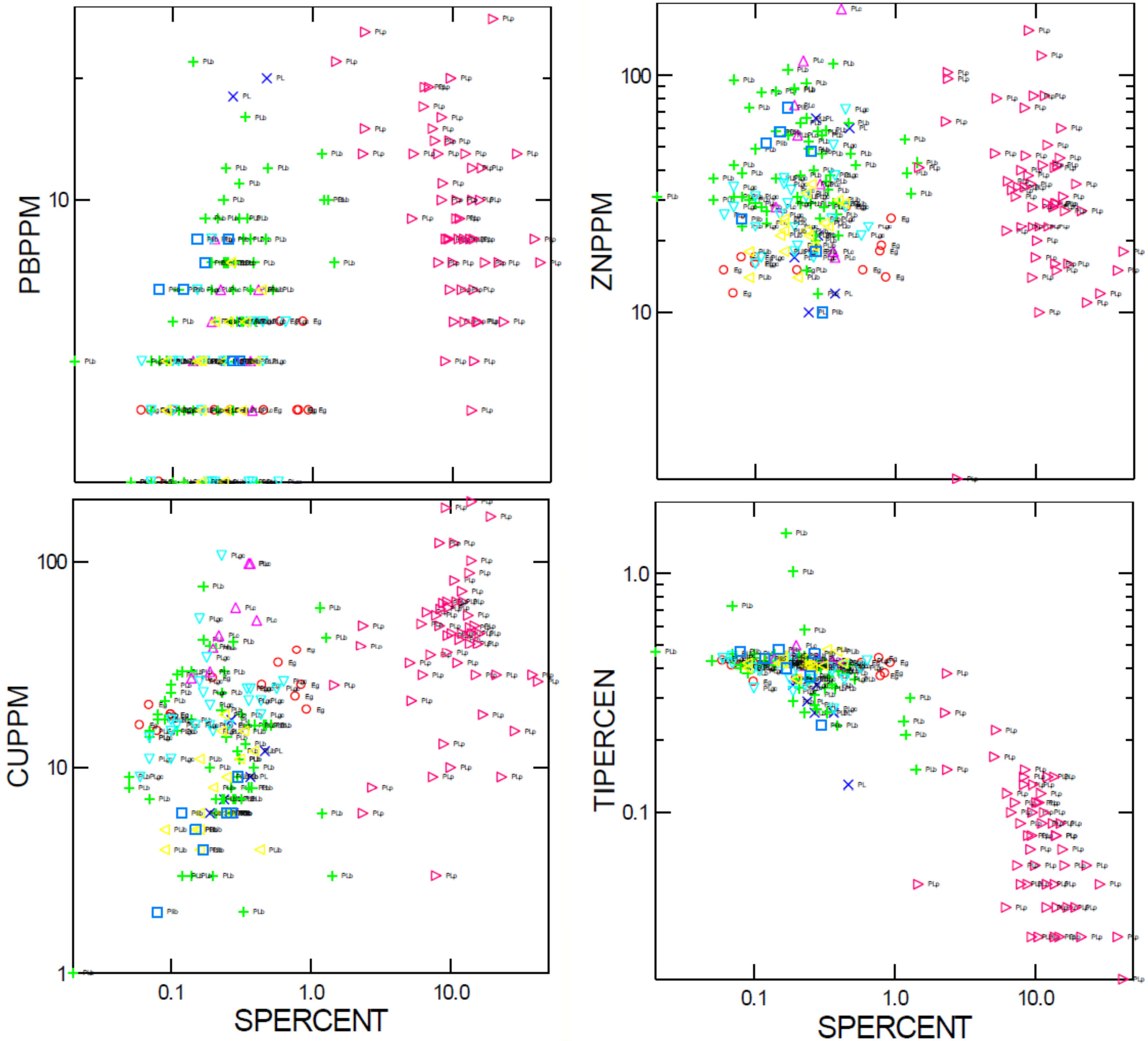
Assay data for RC drill hole PHR004



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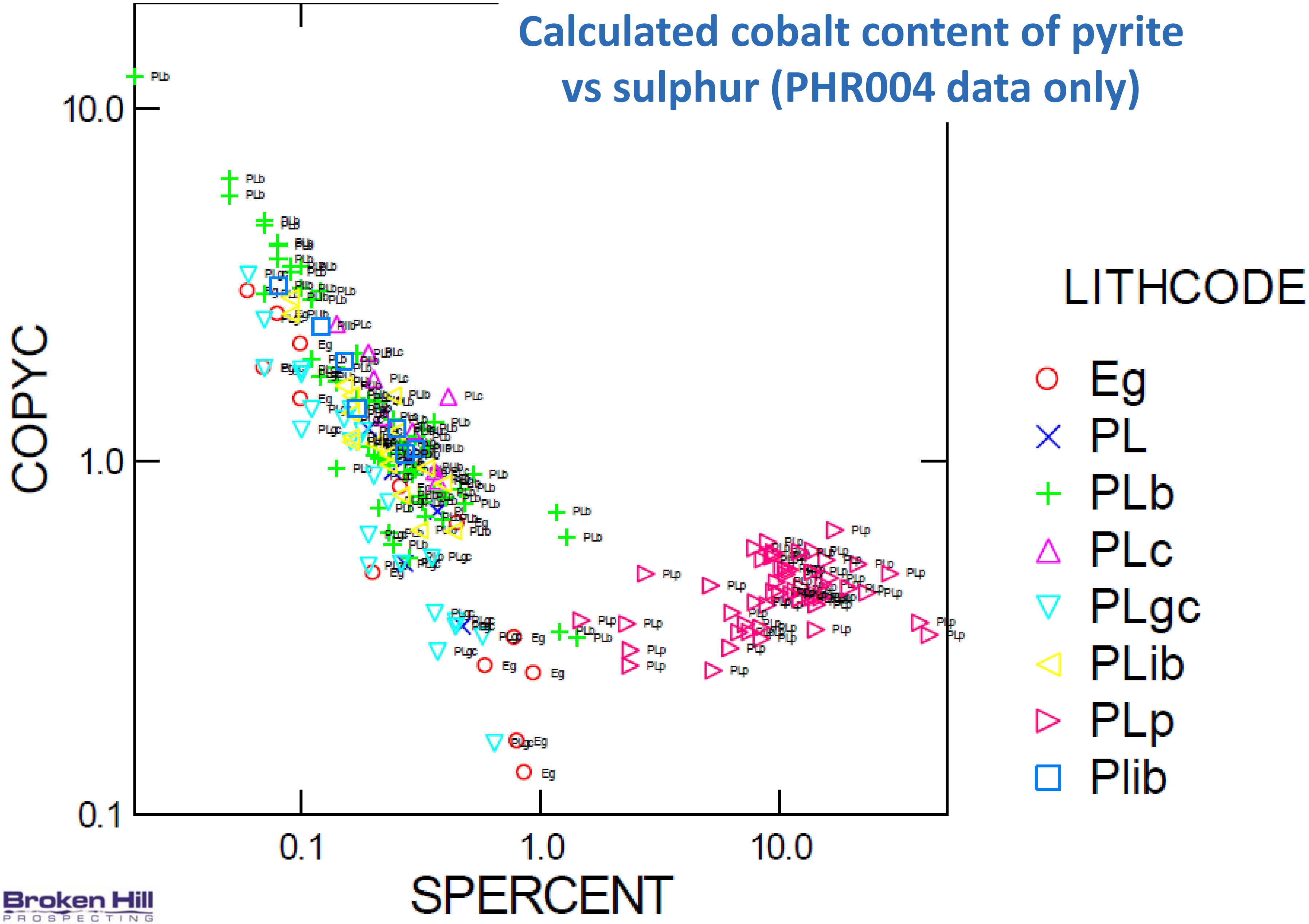
Calculated cobalt content of pyrite vs sulphur (PHR004 data only)



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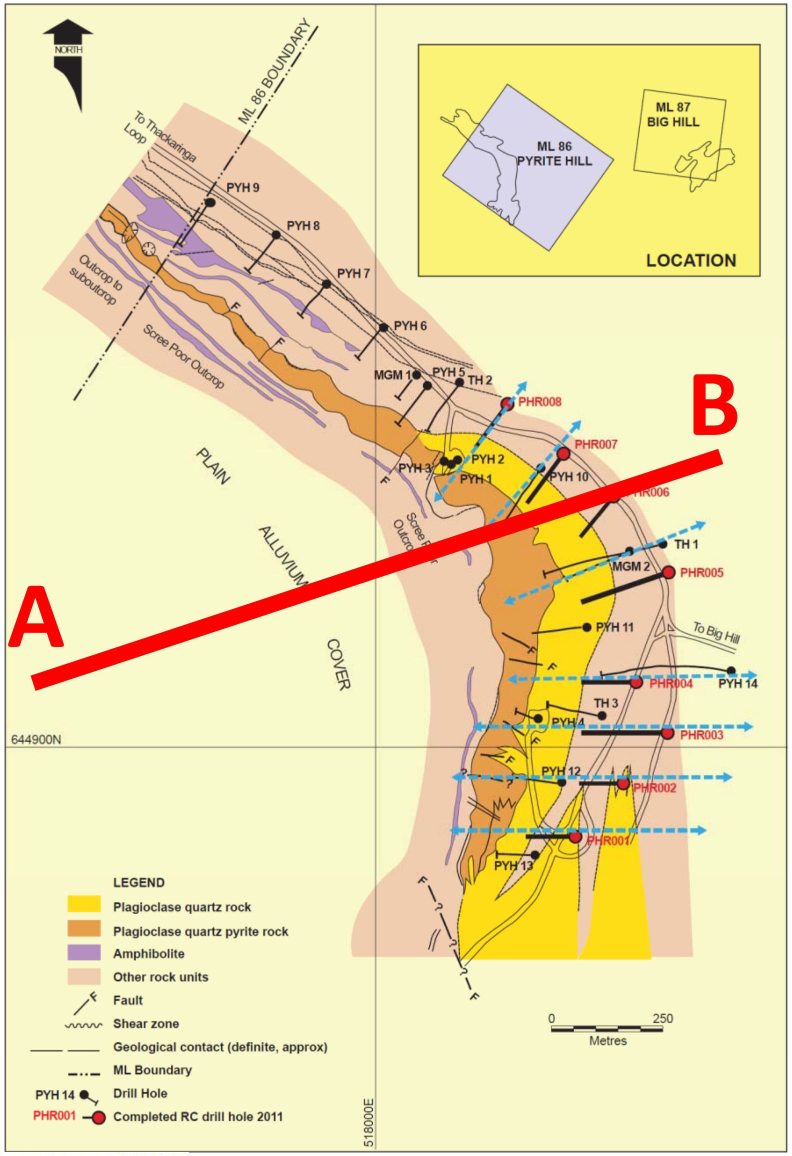
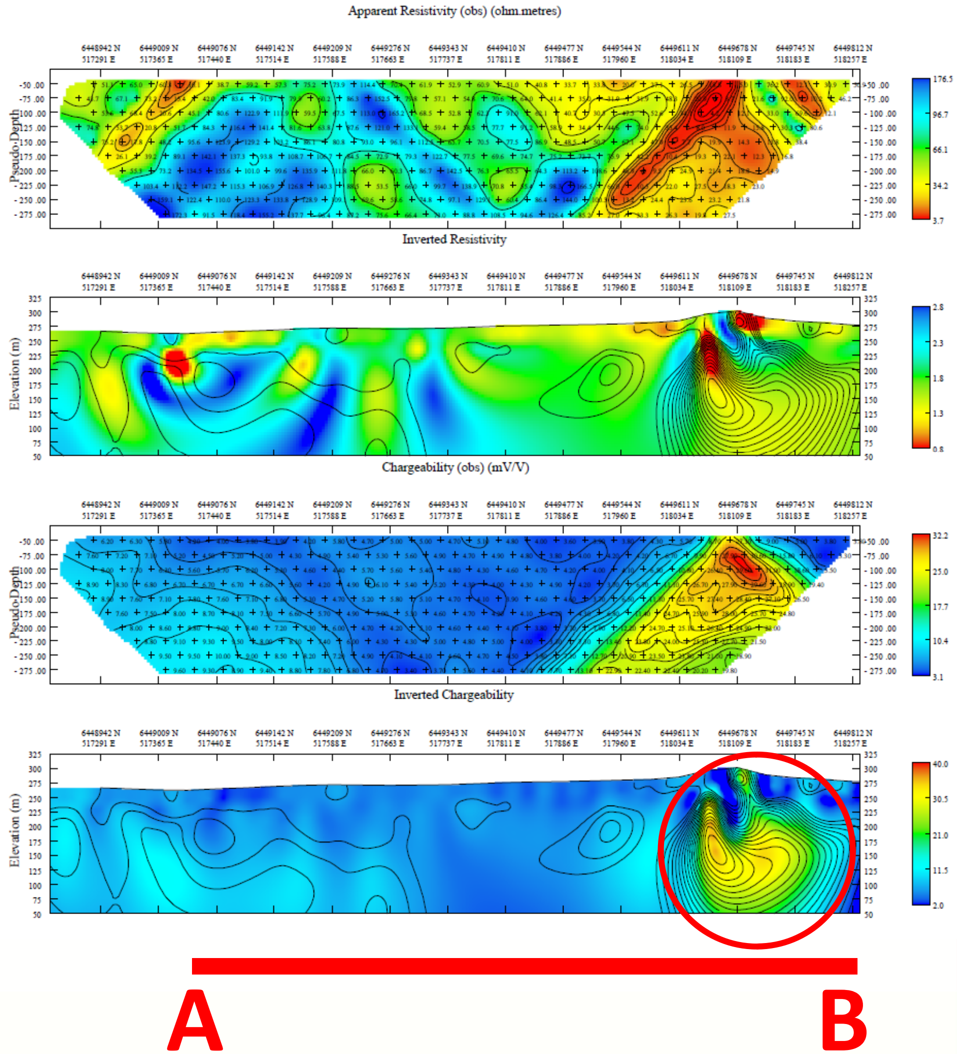
IP Line 22750N, Pyrite Hill showing 'expression' of 51m of 941g/t Co in PHR007





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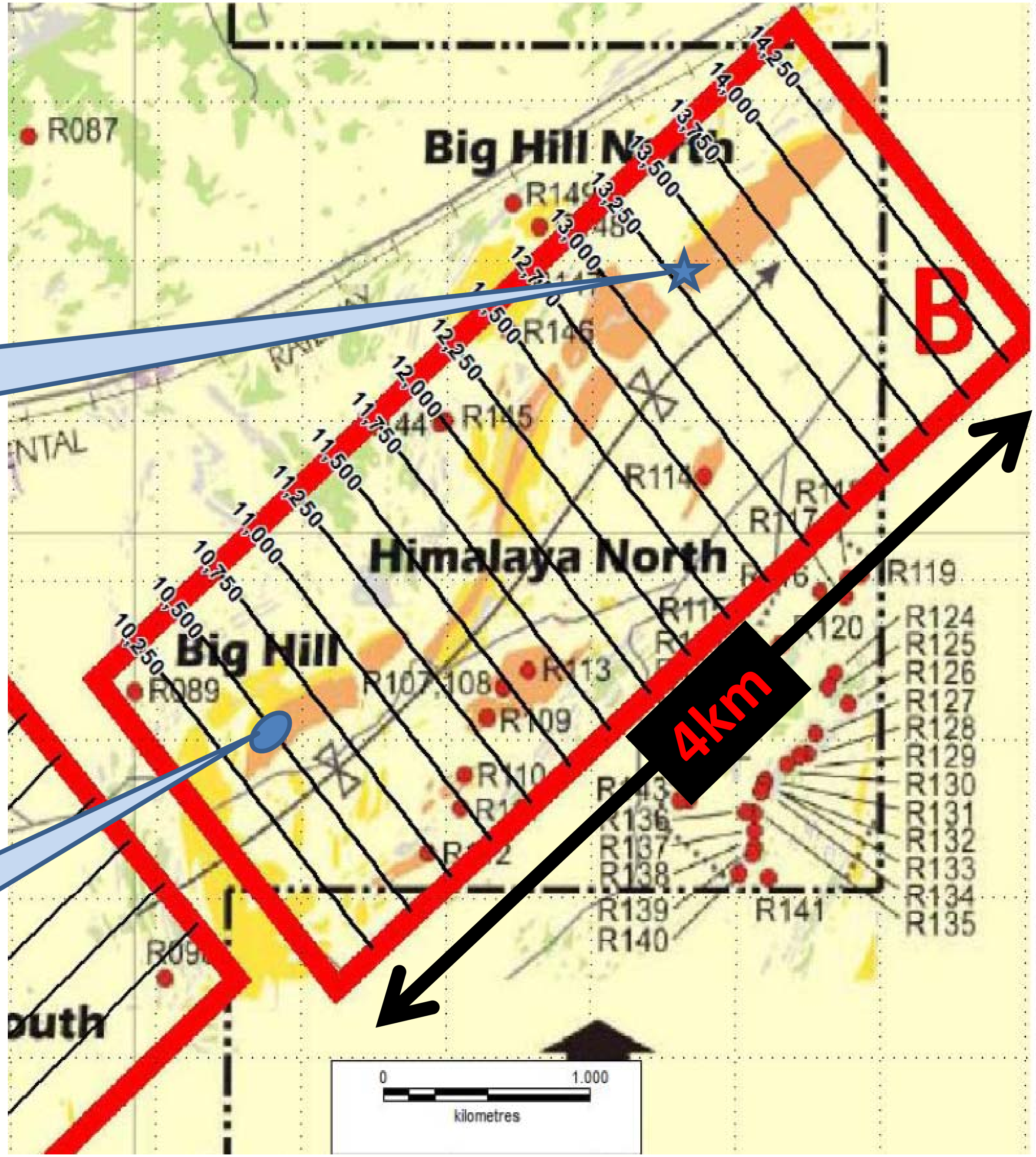
Big Hill – IP survey area

Hunter Resources drillhole T98C01
13-32(19m) of 1.5lb/t Co
35-71 (36m) of 2.1lb/t Co

Gradient array IP dipole – dipole survey with 50-100m station spacing on lines 250m apart

Big Hill deposit Inf Res 4.4Mt of 2.0lb/t cobalt



Big Hill NE – exploration for cobalt extensions....size?

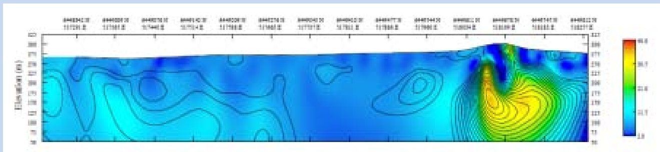
Priority exploration planned in this poorly tested area 2km.

Hunter Resources drill hole T98C01

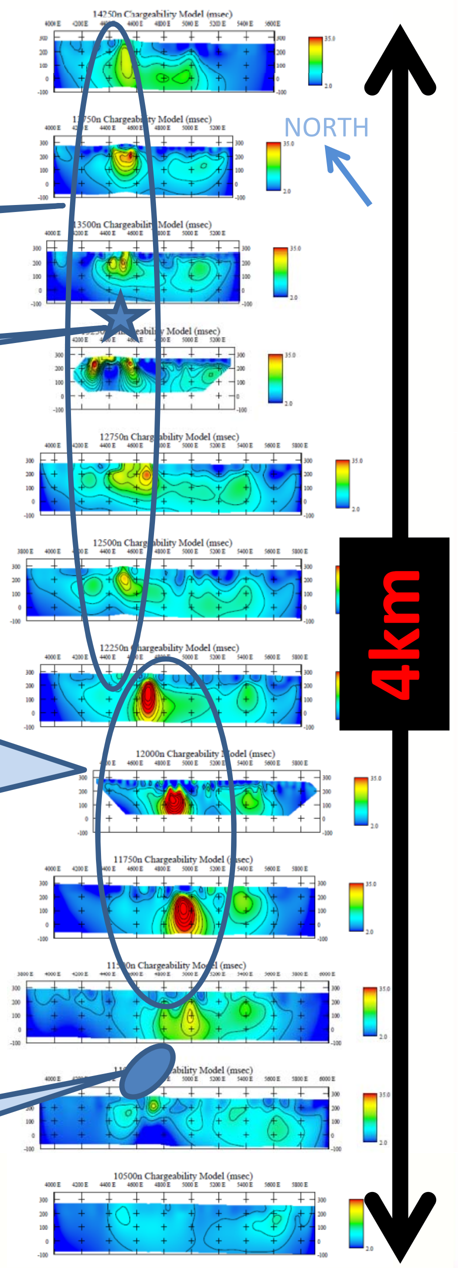
13-32(19m) of 1.5lb/t Co

35-71 (36m) of 2.1lb/t Co

Untested area for a new deposit has strong IP response. For comparison chargeability section through Pyrite Hill which has an Inf Res of 16.4Mt of 1.83lb/t Co as well as potential for 14-24Mt of similar grade mineralisation:



Big Hill deposit Inferred Resource of 4.4Mt of 2.0lb/t cobalt



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Conductivity plan 120m

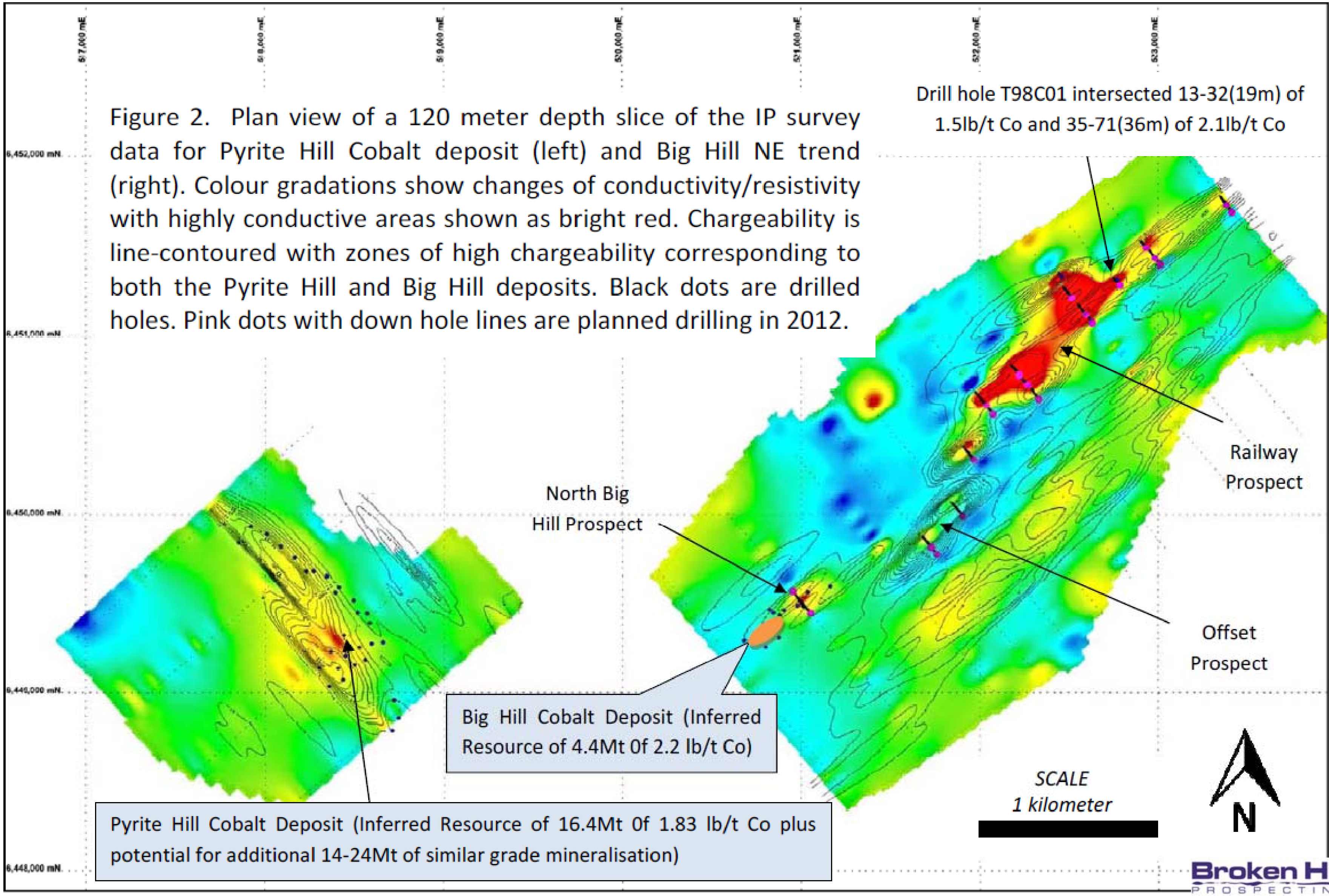

Figure 2. Plan view of a 120 meter depth slice of the IP survey data for Pyrite Hill Cobalt deposit (left) and Big Hill NE trend (right). Colour gradations show changes of conductivity/resistivity with highly conductive areas shown as bright red. Chargeability is line-contoured with zones of high chargeability corresponding to both the Pyrite Hill and Big Hill deposits. Black dots are drilled holes. Pink dots with down hole lines are planned drilling in 2012.

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Chargeability slices along Big Hill trend

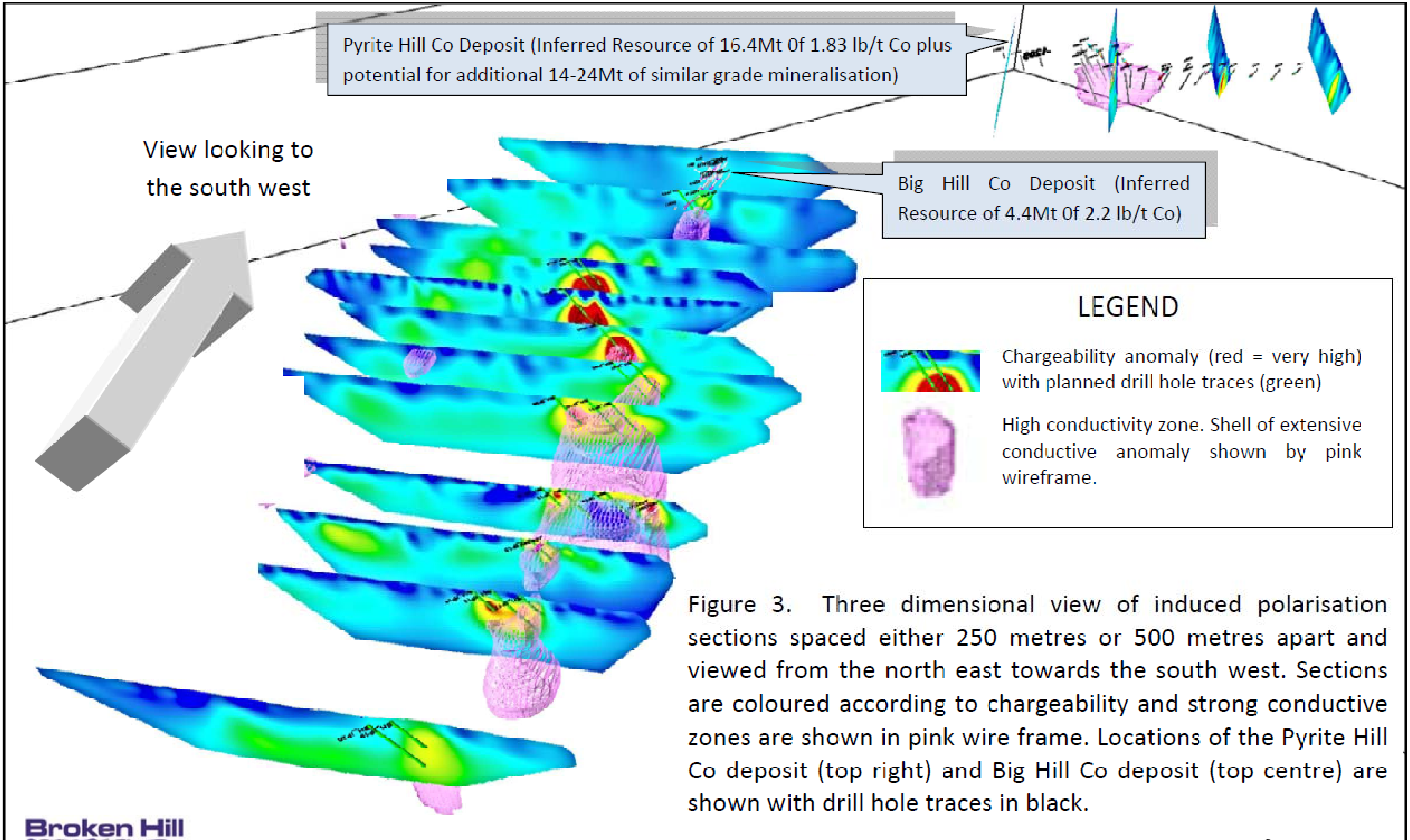
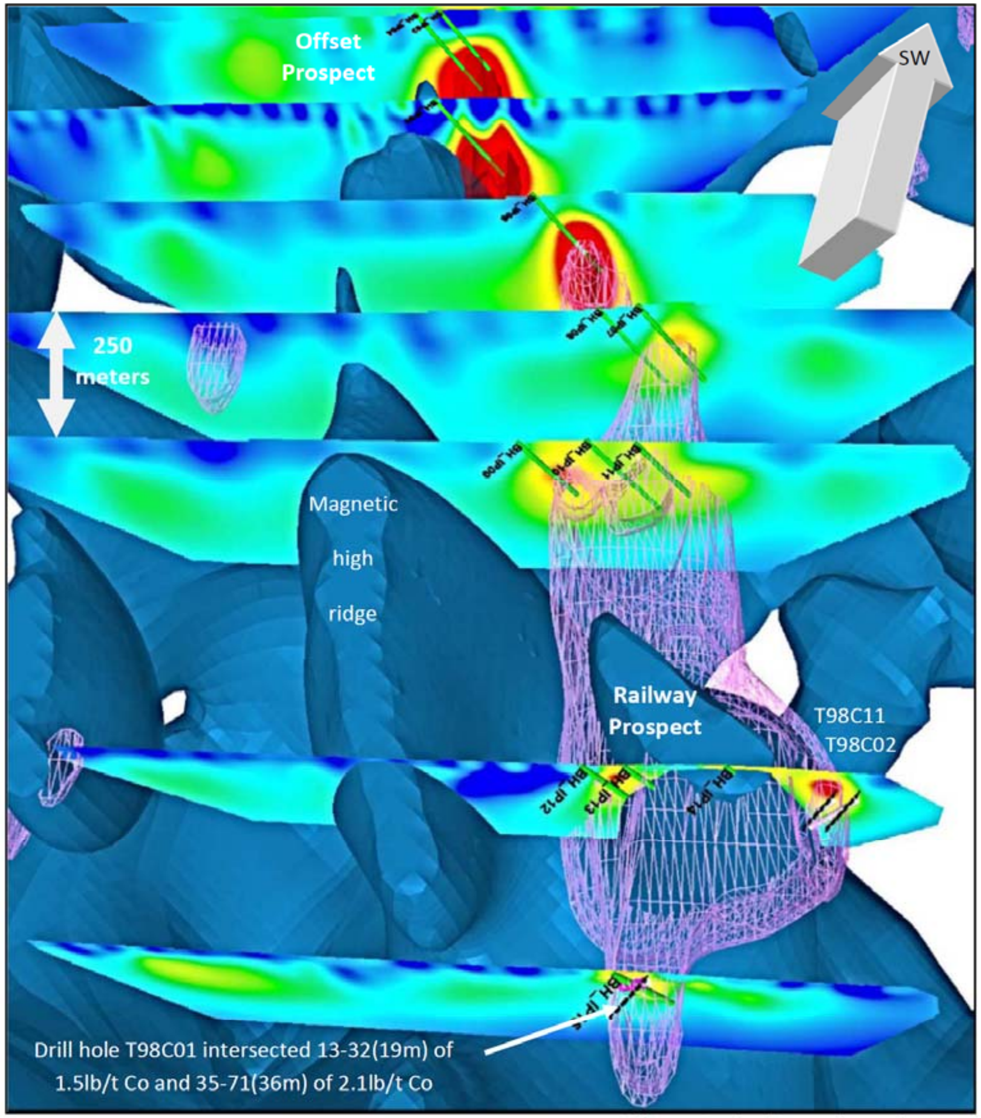


Figure 3. Three dimensional view of induced polarisation sections spaced either 250 metres or 500 metres apart and viewed from the north east towards the south west. Sections are coloured according to chargeability and strong conductive zones are shown in pink wire frame. Locations of the Pyrite Hill Co deposit (top right) and Big Hill Co deposit (top centre) are shown with drill hole traces in black.

Broken Hill Prospecting

IP summary Big Hill trend

Close up of 3D view of IP sections spaced either 250m or 500m apart and viewed from the NE towards the SW. Sections are coloured according to chargeability and strong conductive zones are shown in pink wire frame. Magnetic data is shown in three dimensional format (blue background) to illustrate the magnetic ridge 'high' along the southern margin of the Railway Prospect which also has a centrally located magnetic anomaly. Locations of the Offset Prospect and Railway Prospect are shown with proposed test drill hole traces in green. Locations of drill holes T98C01, 02 and 11 are shown at the northern portion of the Railway Prospect.



Oblique view looking to the south west

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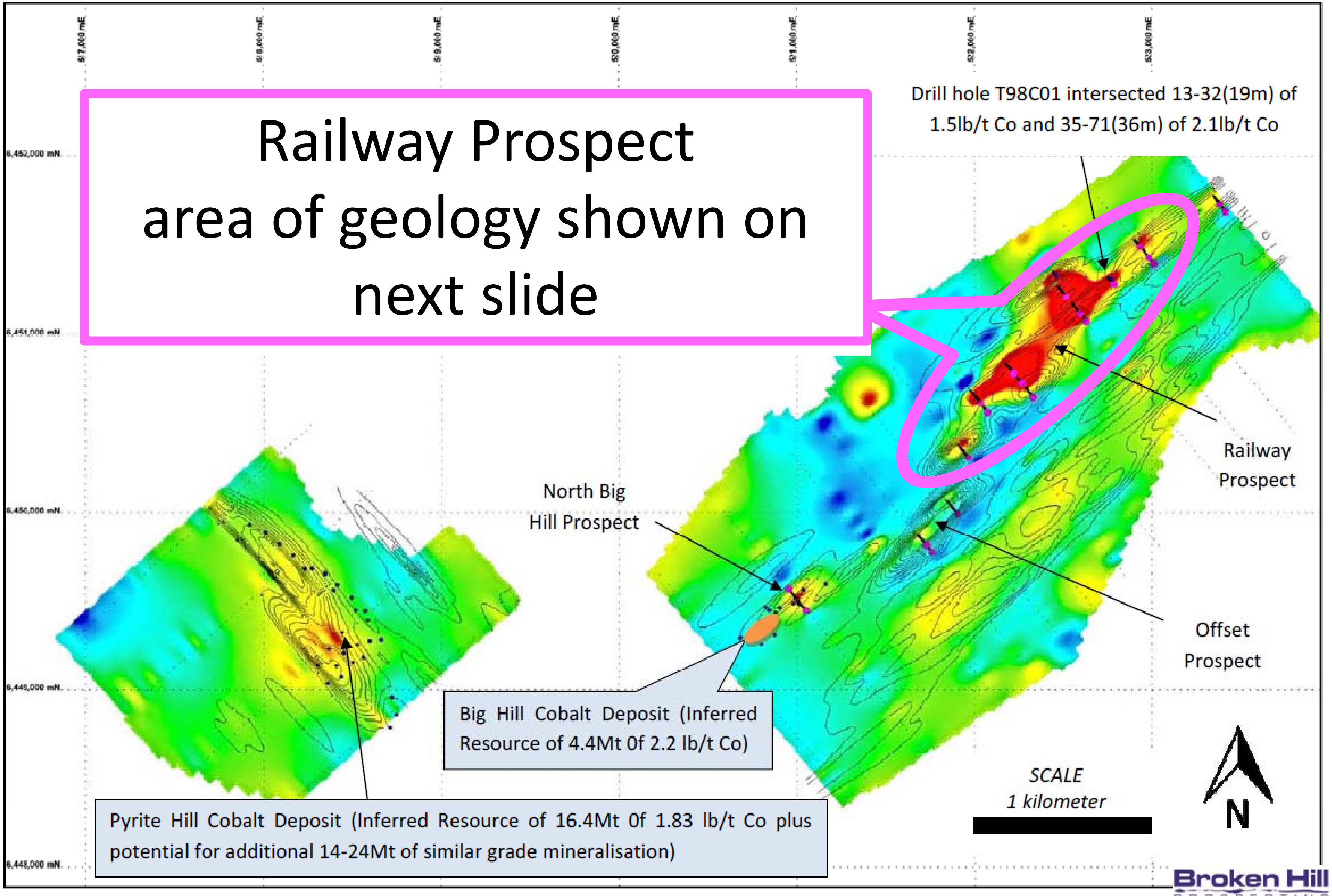
Conductivity plan 120m



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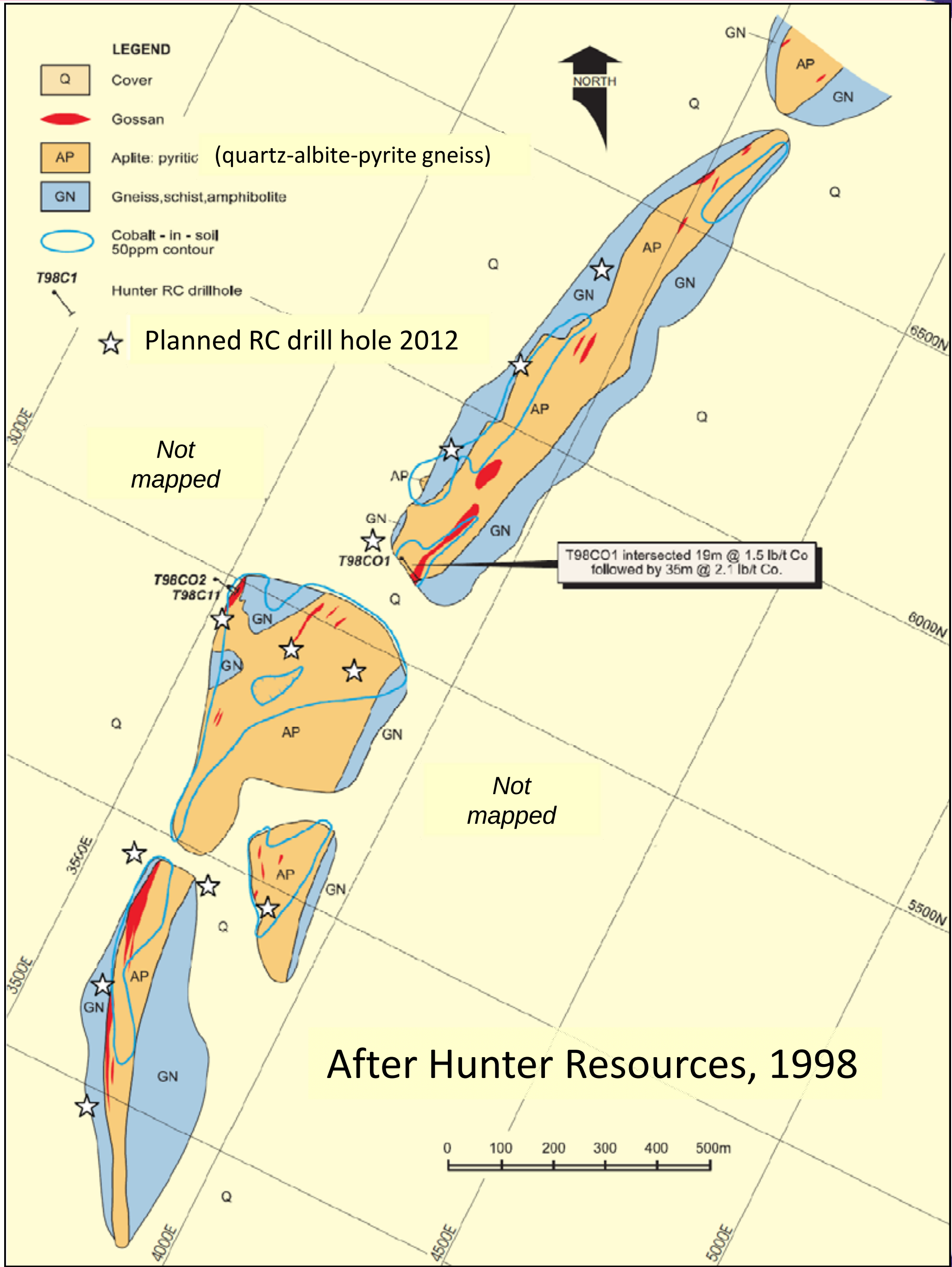
Railway Prospect

- Continuity of outcropping pyrite-quartz-albite gneiss
- Numerous gossans (after pyrite, some shown in red)
- Correlation with anomalous cobalt in soil (range to 500g/t Co)
- Planned 2012 drilling at about 250m spacing
- Pyrite gneiss outcrop 50-400m wide, >2.5km long
- Steep west to vertical dip
- ?Room for a new, large strata-bound deposit
- Drill results expected in mid 2012



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Albite-quartz gneiss

- Well defined, thin, regular and continuous layering, sometimes massive and recrystallised
- Average grainsize approx 1mm
- >200m thick at Pyrite Hill & Big Hill
- Graded bedding, cross bedding
- Scour and fill structures
- Nodules and pebbly horizons
- Stratabound, continuity and conformable
- Zones of cobaltiferous pyrite, massive (to 10m thick) and disseminated (to 50m thick)
- Origin?
  - Evaporative salt lake, sabkha
  - Volcano-sedimentary (Plimer,1976)?
    - Na rhyolite
    - Analcime-rich glassy tuffs (Coombs, 1965)
  - Intrusive, metasomatic (Vernon, 1961), metamorphic?
    - “aplite”, Na schist
  - Others? ..... Sediment basin?

average of 10 albite quartz gneiss drill samples (Plimer, 1976)

SiO_2	**68.35**
TiO_2	0.67
Al_2O_3	**18.11**
Fe_2O_3*	1.22
MnO	0.01
MgO **	**1.08**
CaO	0.35
Na_2O	**7.96**
K_2O	0.81
P_2O_5	0.08
H_2O	0.83

* total iron as Fe_2O_3 (trace pyrite?)

** Mg occurs in albite and trace biotite

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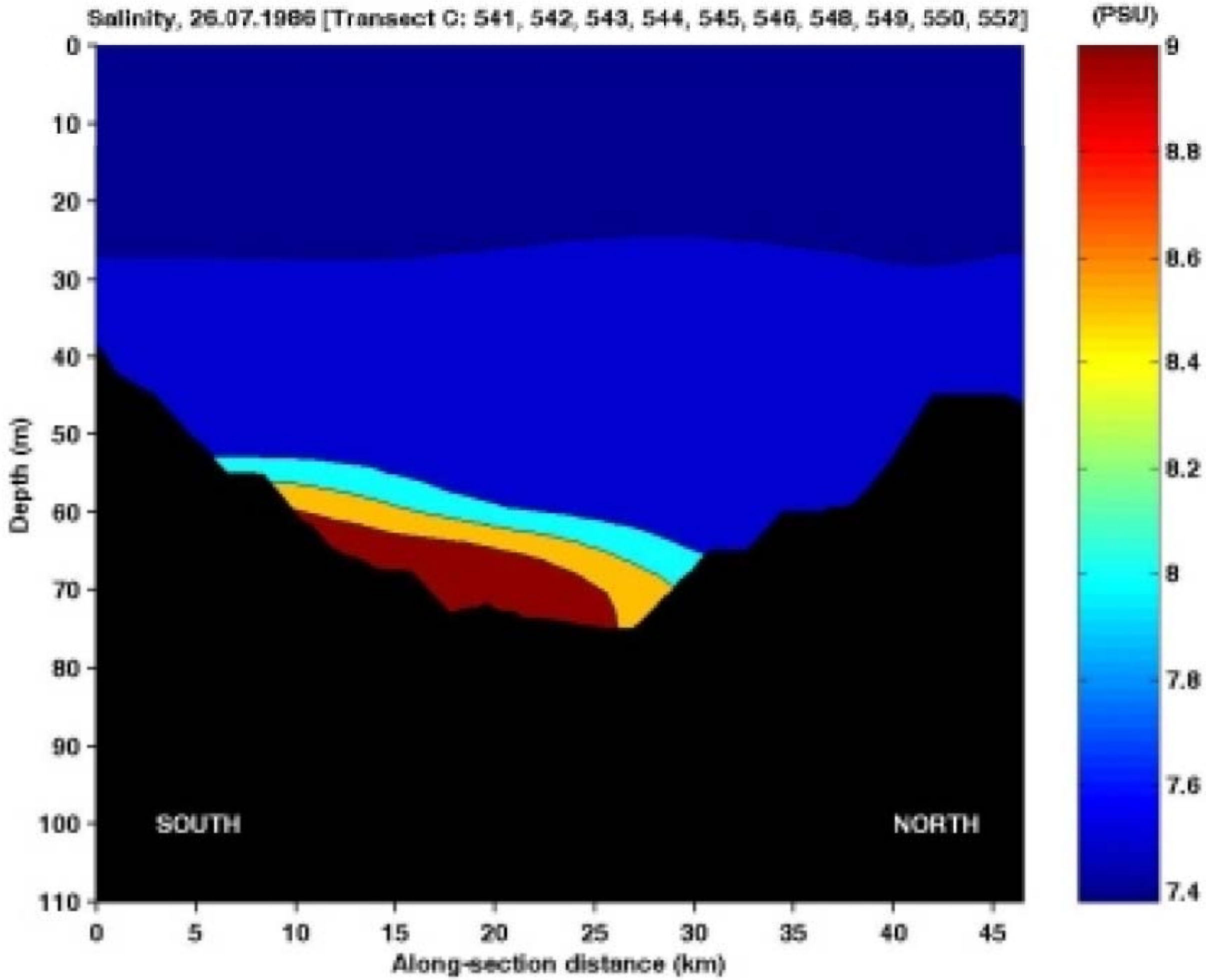
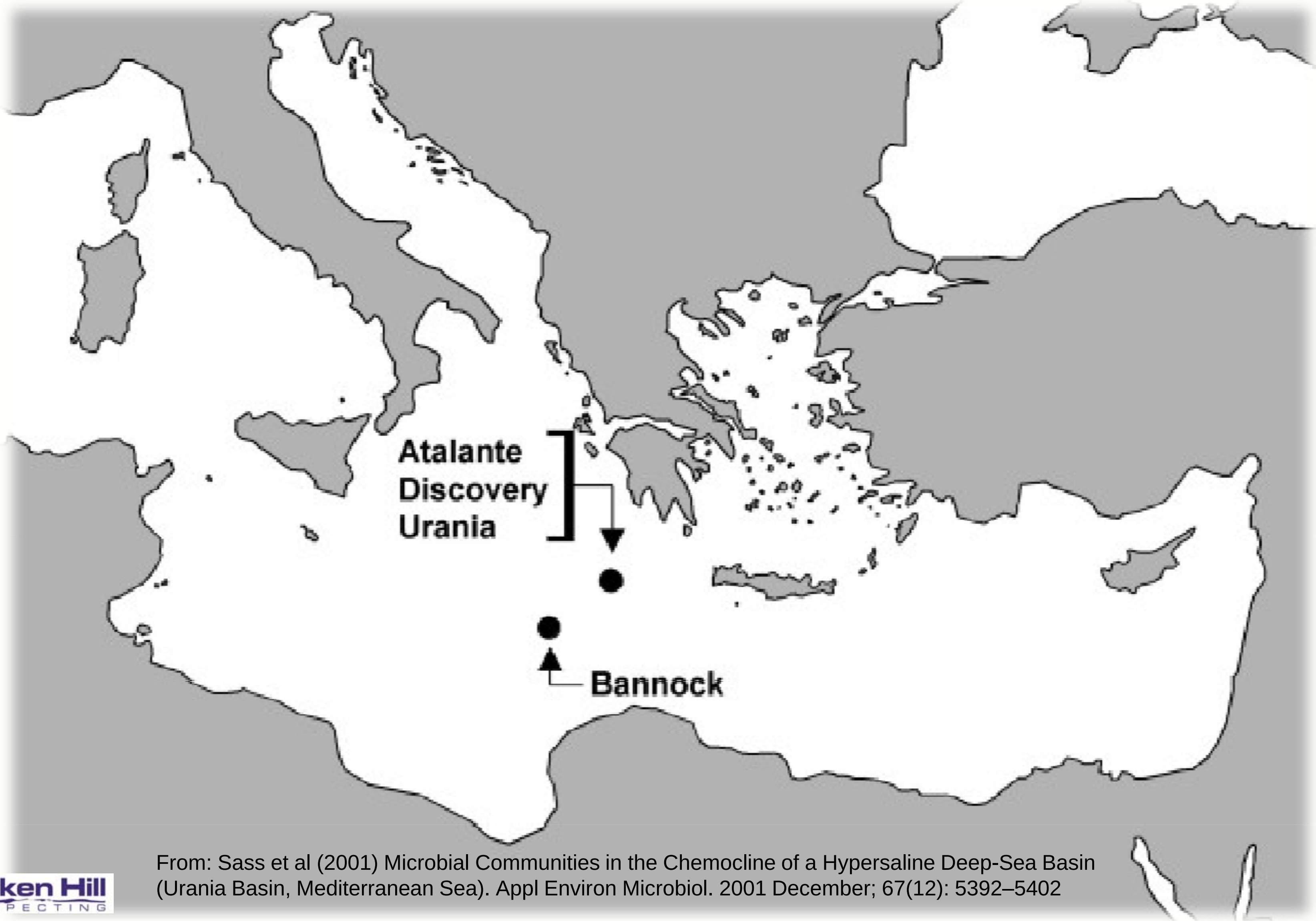
Modern analogues?



Cross-section of salinity in the Stolpe Channel (Baltic Sea) showing a well defined bottom layer of dense saline water that is transported eastward.(From Borenäs et al., Tellus, 2007)

Modern analogues? Anoxic basins



From: Sass et al (2001) Microbial Communities in the Chemocline of a Hypersaline Deep-Sea Basin (Urania Basin, Mediterranean Sea). Appl Environ Microbiol. 2001 December; 67(12): 5392–5402

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Deep hypersaline anoxic basins (DHABS)

- very salty, sulphidic water fills depressions (10s – 100s metres) at ocean deeps (usually >3km water depth)
- includes the most sulphidic water on Earth with thriving microbe communities
- recently discovered and only recent research
- no light, high pressure (350x), salty (can be >10x seawater), no oxygen (anoxic)
- high bottom water temperatures up to 45°C
- anaerobic bacteria use nitrate and sulphate for respiration, carbon comes from CO2 and CH4 (methane)

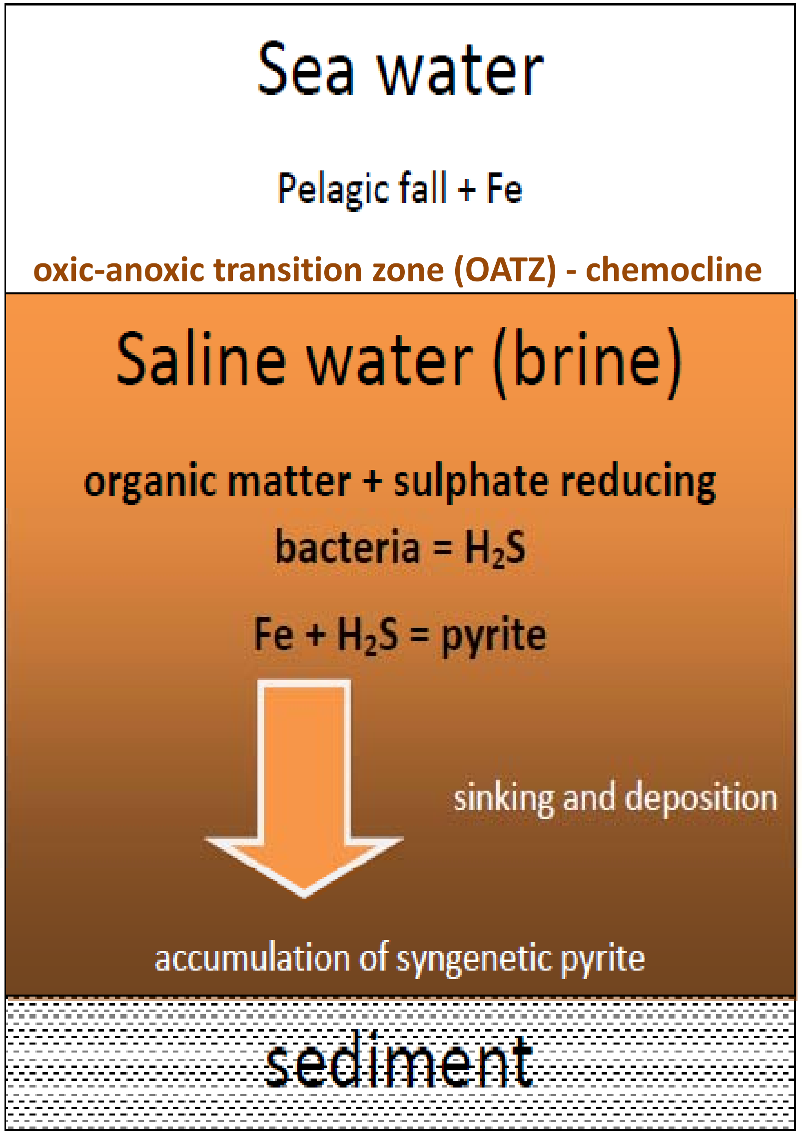
Concentration (Millimolar)	**Discovery Basin**	**Urania Basin**	**Normal seawater**
Salt ions			
Sodium (Na^+)	68	3503	528
Magnesium (Mg^{2+})	4995	316	60
Chloride (Cl^-)	9491	3729	616
Sulfate (SO_4^{2-})	96	107	32
Toxic compounds			
Hydrogen sulfide (HS^-)	0.7	16	2.6×10^{-6} (0.0000026)
Methane (CH_4)	0.03	5.6	1.5×10^{-6} (0.0000015)


Sulphide mud from Urania Basin floor

Brine/sea water data and photograph are from WHOI, Dive and Discover Expedition 14, Mediterranean Deep Basins 28 Nov – 9 Dec 2011

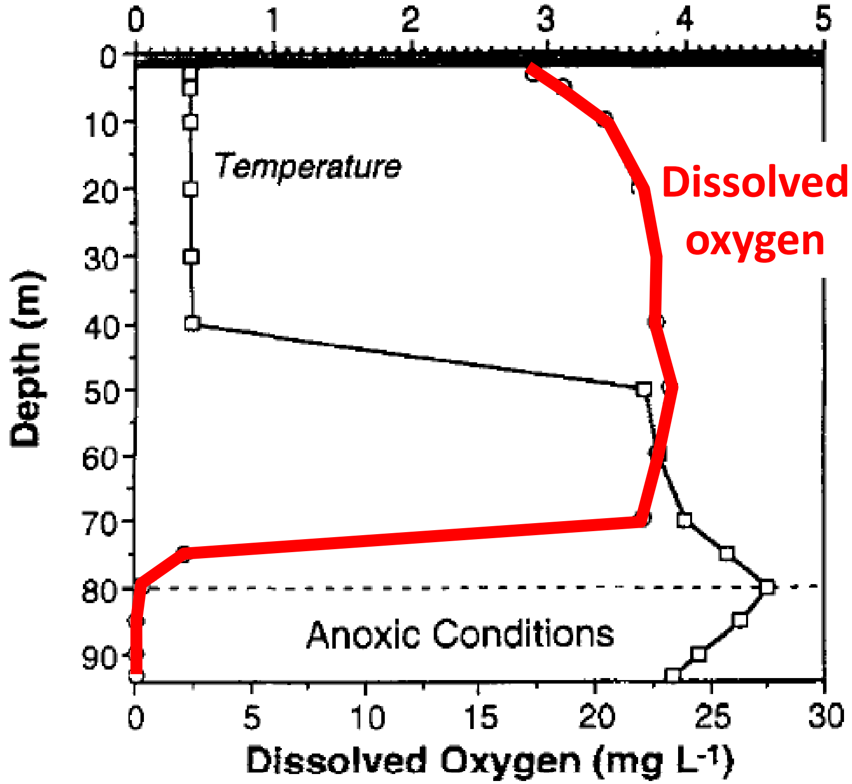
DHABS..... continued

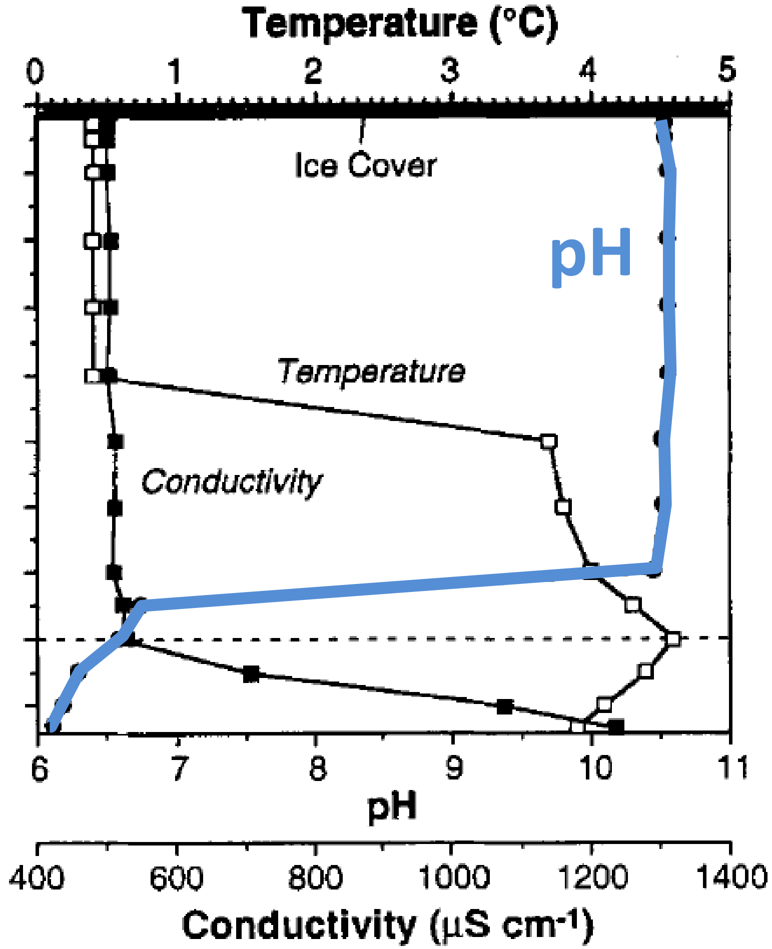
- Hypersaline anoxic basins (Dead Sea, Orca, Urania, Discovery, Tyro, Bannock Basins, fjiords, Black Sea........)
- Tyro/Bannock (Med); 3,300m deep; 10x salinity of normal seawater
- Organic matter + sulphate reducing bacteria = H_2S, H_2S + Fe = pyrite
- Sulphide forms at the sea water-OATZ interface (chemocline) as well as in the anoxic saline water above the sea floor
- Large density difference between sea water and dense saline brine. Pelagic fall/ detrital iron minerals captured at the OATZ as they sink from surface
- Sulphide forming in water column (10s - 100s metres thick) below the OATZ (syngenetic), warm water
- Settling of fg pyrite to the sea floor, turbidity deposition, sediment layering, X- bedding, graded seds, slumping from 'bathtub ring' along steep sides of basin, crystalline pyrite.
- Further diagenesis/recrystallisation of sulphide in sediment at the sea floor?



Lake Untersee, ice covered lake in N Antarctic

Fresh water lake, 6.5 x 2.5km, max depth 169m,
Permanent ice cover (2-6m thick) for 100,000yrs,
Chemocline at 80m.





After; U. Wand et. al. (Antarctic Science (1997), 9 : pp 43-45)

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Lake Untersee DHAB - stromatolites

100,000yr ‘fresh water’ ice covered lake, only microbial life forms, no light

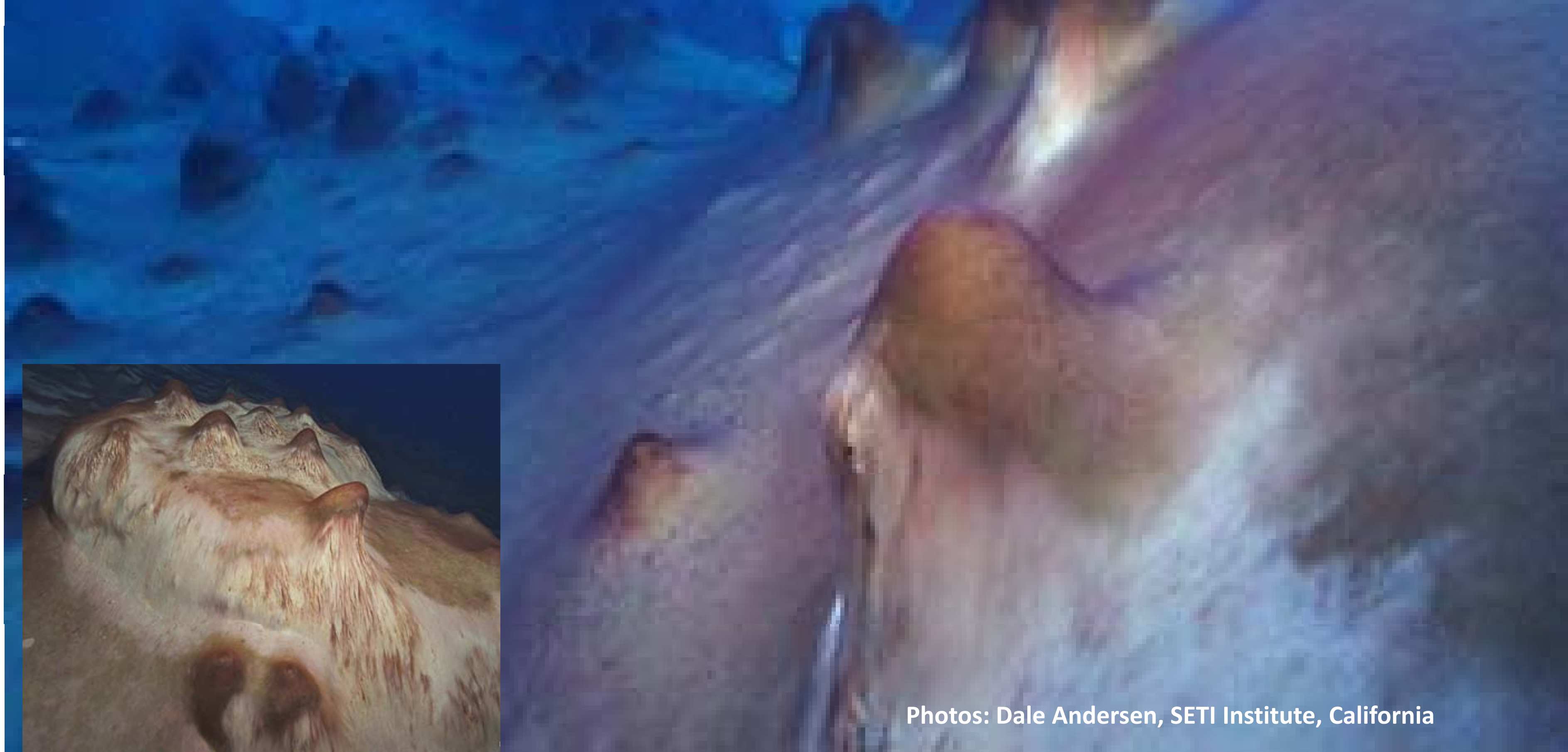
Stromatolites up to half a metre high (cyanobacteria *phormidium* & *leptolynbya* spp)

Sulphate reduction, anaerobic oxidation of methane (AOM)

$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$ (+ plus energy)

high Na, pH6 in bottom anoxic water, pH10.5 at top

warm bottom water (lake Vanda +25°C)



Photos: Dale Andersen, SETI Institute, California

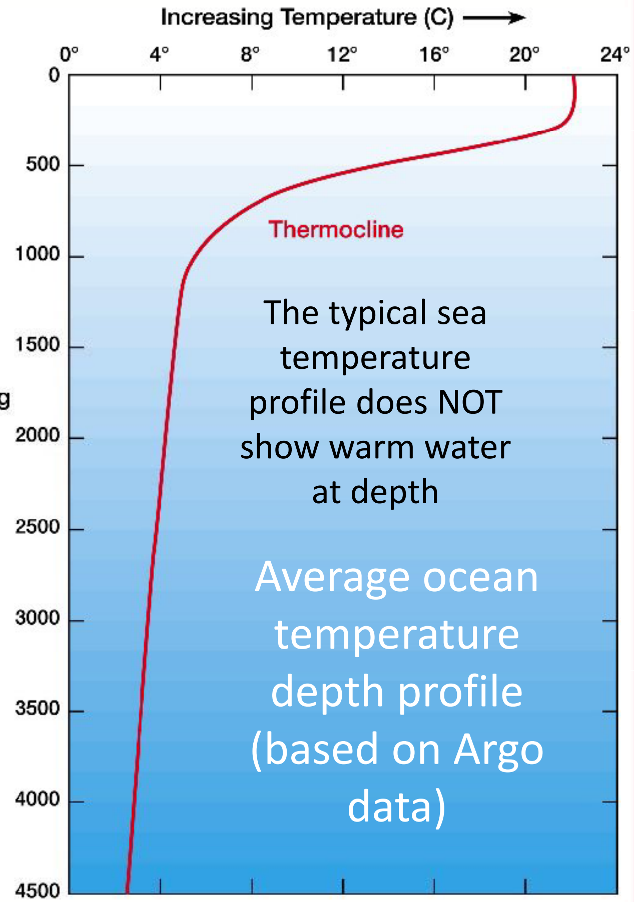
Report on Victoria University of Wellington Antarctic Expedition 1961-62: VUWAE 5
LAKE VANDA AN ANTARCTIC LAKE, A SOLAR ENERGY TRAP

Temperature versus Depth Profiles for lower part of Lake Vanda

(Temperatures in degrees centigrade)

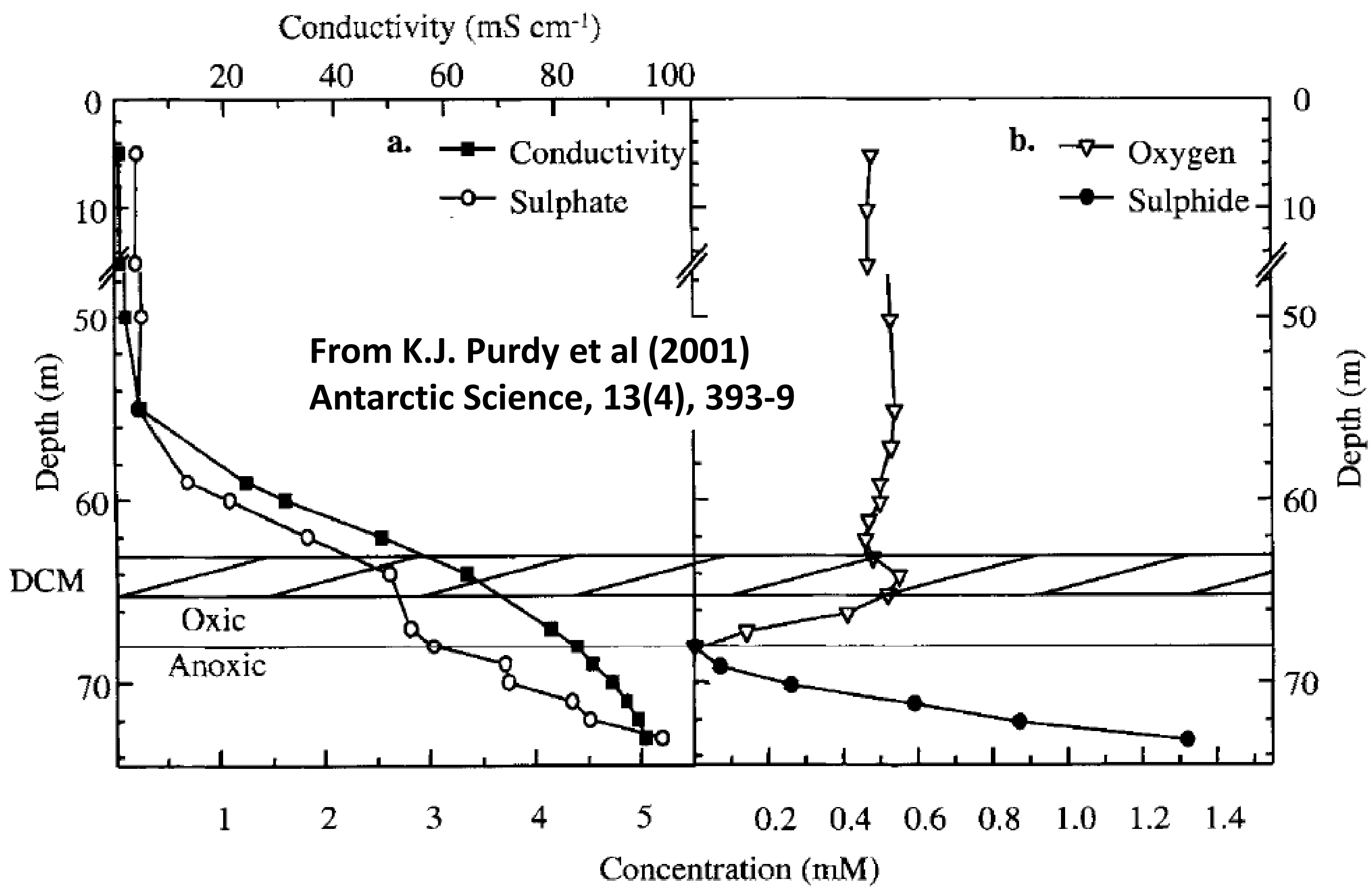
Depth below water level (in feet)	*1	2	2N	2S	3	4	In situ Density (g/cm³) hole 2.
160	12.4	12.4	12.6	12.5	12.5	12.5	1.008
165	14.3	14.2	14.5	14.3	14.2	14.3	1.014
170	16.1	16.1	16.3	16.1	16.3	16.1	1.024
175	17.7	17.8	18.0	17.9	17.3	17.8	1.034
180	19.3	19.4	19.5	19.4	19.4	19.3	1.044
185	20.8	20.8	20.9	20.8	20.8	20.6	1.054
190	22.1	22.1	22.3		22.1	22.2	1.064
195	23.3	23.3	23.4		23.4	23.4	1.073
200	24.2	24.1	24.3		24.2	24.3	1.080
205	24.8	24.7	24.8		24.8	24.8	1.087
210		25.2	25.2		25.2	25.1	1.091
215		25.4	25.6				1.096
	Bottom 208 ft 25.2°C	Bottom 216 ft 25.6°C	Bottom 218 ft 25.7°C	Bottom 187 ft 21.4°C	Bottom 212 ft 25.4°C	Bottom 213 ft 25.1°C	

*Positions of holes 1, 2, 3, 4 are on an east-west line at 100 ft



Lake Vanda; surface temp av -18°C, bottom water +25°C, area 5.2km³, average depth 31m, max depth 75m, 160m m³ water. **Microbial heat energy could power a small city!**

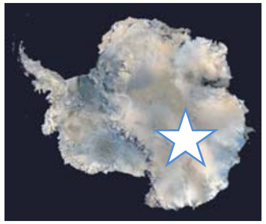
Lake Vanda sulphide concentration



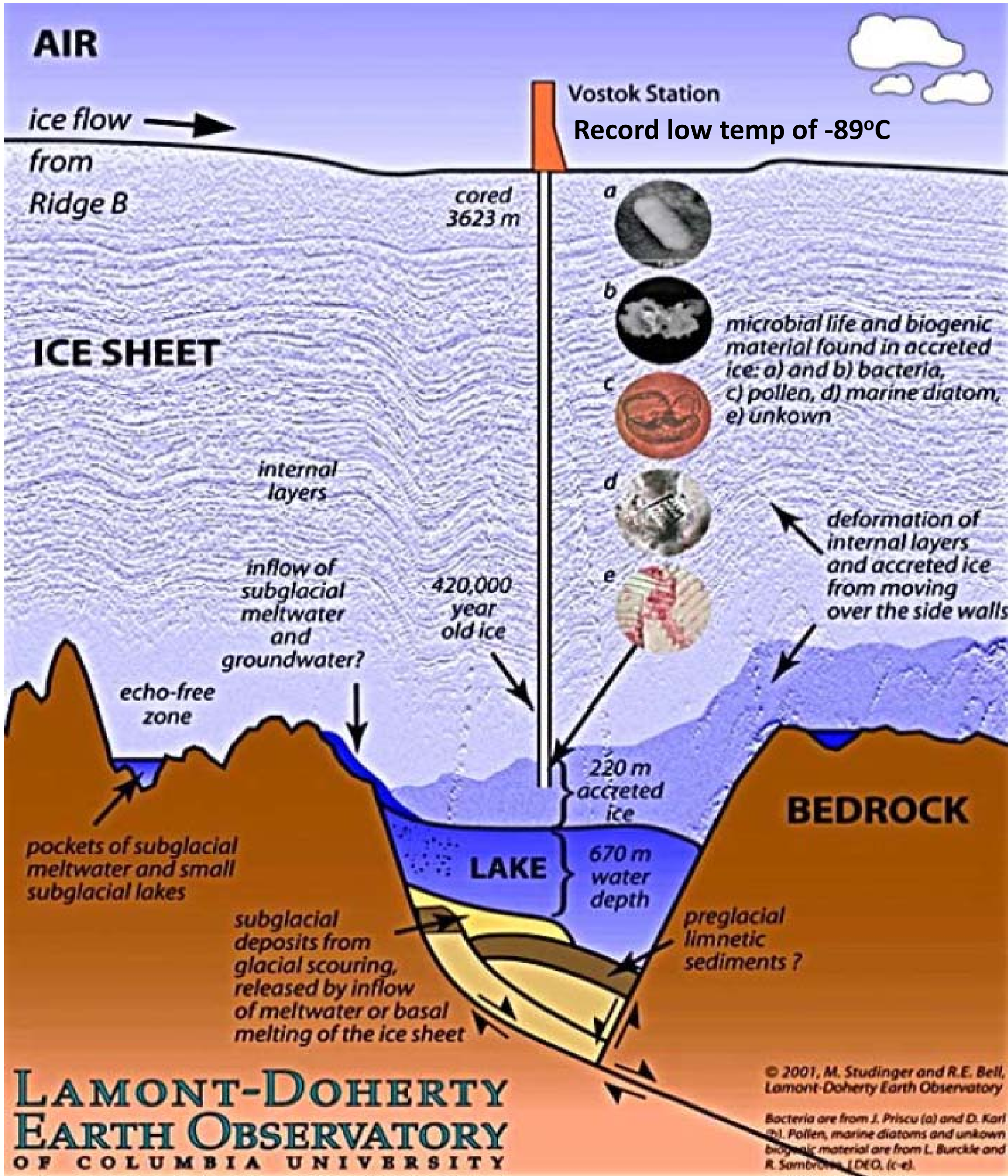
Sulphate in Vanda are depleted in ^{32}S due to removal of biologically enriched ^{32}S to form metal sulphides

Lake Vostok DHAB drilling – news!

Russian drillers have broken through the ice after 20 years of drilling and will collect samples late in 2012.



- Lake Vostok is a subglacial lake under the East Antarctic Ice Shelf. It is about 500m below sea-level, and is buried under 3.7km of ice.
- The lake is approx 250km x 50km and has an average depth of 344m.
- Lake Vostok has been covered by ice for 15 - 25Ma
- Strong magnetic anomaly
- Why warm water and not ice?
- Thermograph imaging shows +10º C average water temperature with "hot spots" +18º C.
- Micobial activity?



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DHAB drilling results - next summer

	LAKE VOSTOK	LAKE ELLSWORTH	LAKE WHILLANS
Country	Russia	U.K.	U.S.
Depth beneath ice to dig (meters)	3,769	3,000	800
Time under glacier (million years)	15–25	0.1–1.0	0.1–1.0
Volume of lake (km^3)	5,400	0.5–1.4	0.5
Depth of lake (meters)	200–800	150	10–15
Area of lake (km^2)	14,000	29	60
Funding (millions of U.S. dollars)	na	10.5	10.0

Extreme environment & toxic bugs

- DHABS are arguably the most extreme environment on earth (saline, deep water, low/no oxygen, no light, warm, sulphidic.....)....BUT.........studies report brine-lake sediments have the highest concentration of extracellular DNA reported in a natural environment!!
- The chemocline (2 to +5m thick) separates seawater from brine, the OATZ (usually tens of metres thick) separates oxic and anoxic water:

• steep salinity gradient and warm bottom water
• supports some of the most biomass-rich and active microbial communities known but no light!
• dominated by bacteria and archea
• higher metabolic activities occur at the chemocline/OATZ rather than in the overlying oxic sea water and underlying anoxic brine . Usually located tens/hundreds of metres above basin floor sediments.
•bacteria species/communities vary between brine basins. Two types of **Magnetostatic bacteria** based on magnet; **magnetite (Fe_3O_4) and greigite (Fe_3S_4).** The latter dominate in anoxic sulphidic basins. Use magnetic field to move to OATZ. Cobalt incorporation into Fe_3S_4 makes for stronger magnet!!
• a 'diverse, sharply stratified, deep-sea ecosystem with sufficient biomass to potentially contribute to organic geological deposits'

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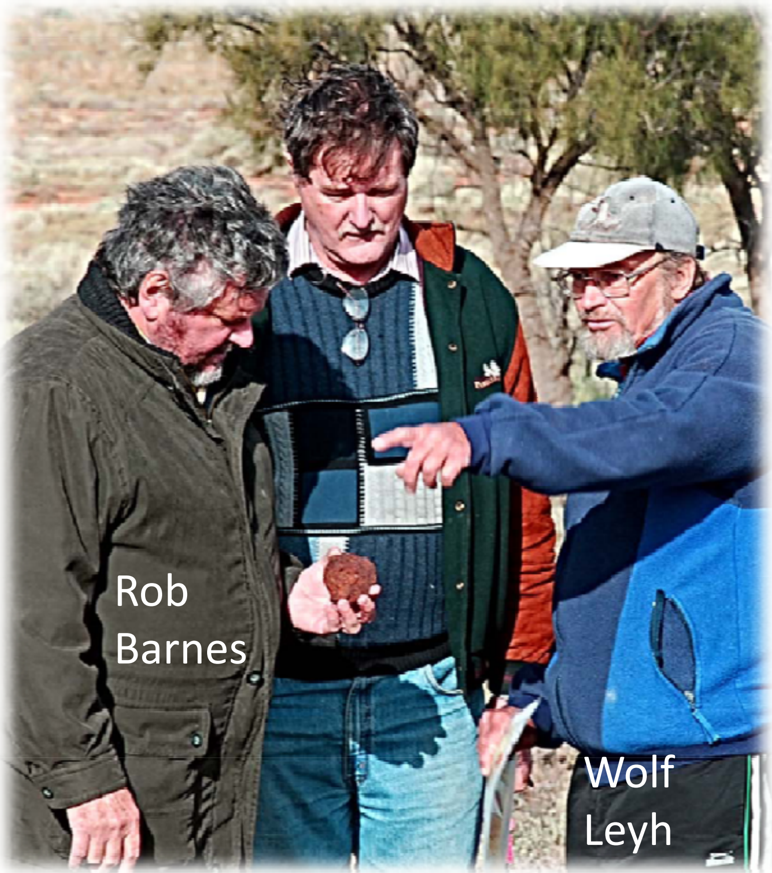
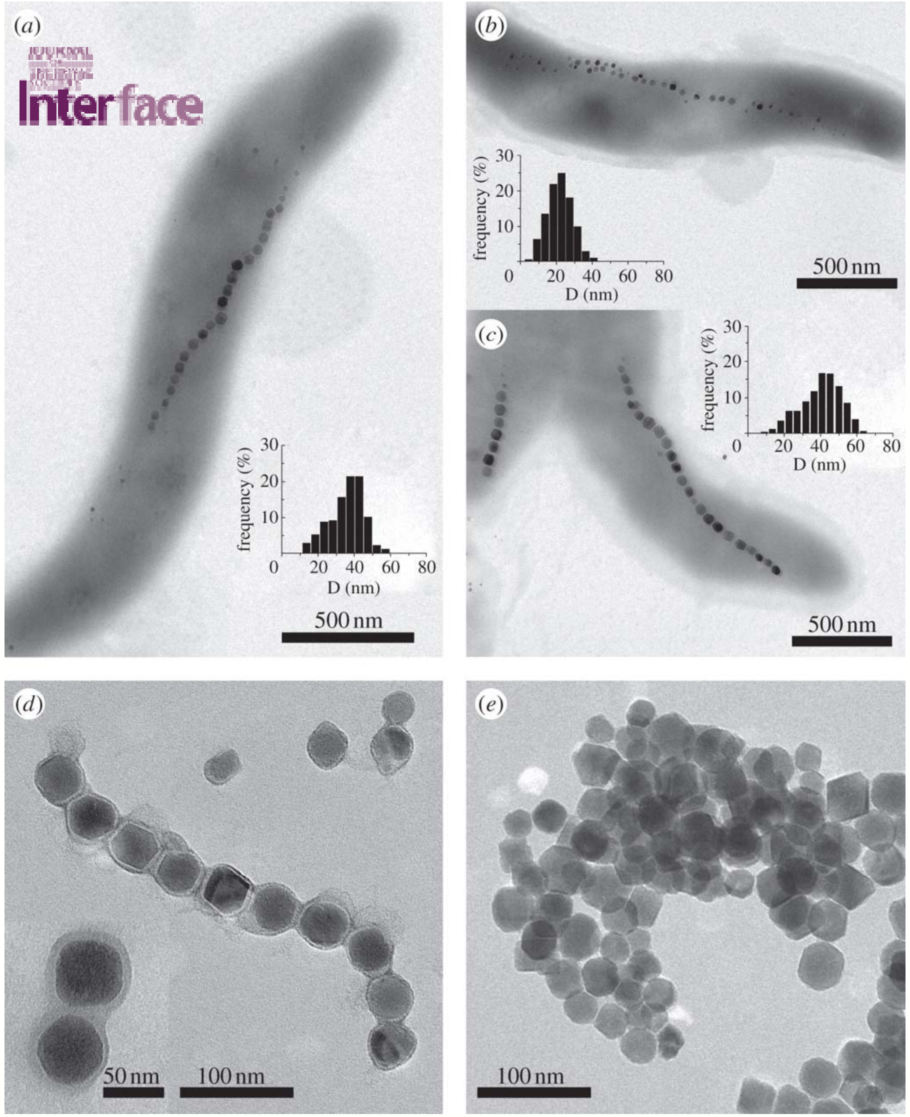
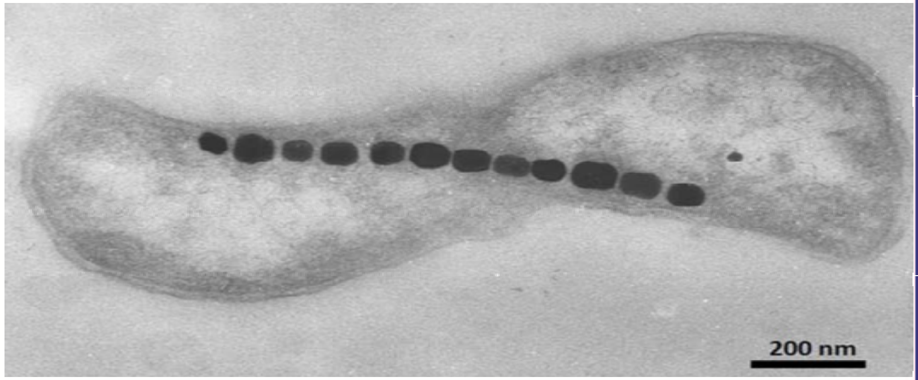


TEM micrographs and particle size distribution of magnetite particles in magnetotactic bacteria: (a) MSR-1, (b) ΔmamGFDC and (c) AMB-1 cell (scale bar, 500 nm).



Fischer A et al. J. R. Soc. Interface 2011;8:1011-1018



Chen, L., Bazylinski, D. A. and B.H. Lower (2010)
Bacteria that synthesize nano-sized compasses to navigate using earth's geomagnetic field.
Nature Education Knowledge 1(10):14

Broken Hill PROSPECTING

Bacteria divide and multiply

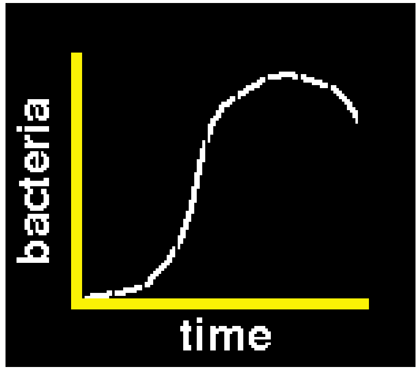
by binary Fission................

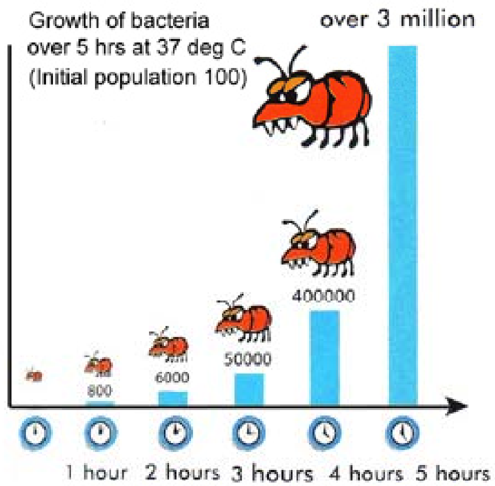
LAG PHASE: Growth is slow at first, while the "bugs" acclimatise to the food and nutrients in their new habitat.

LOG PHASE: Once the metabolic machinery is running, bacteria **start multiplying exponentially, doubling in number every few minutes**.

STATIONARY PHASE: As more and more bacteria are competing for dwindling food and nutrients, booming growth stops and the number of bacteria stabilizes.

DEATH PHASE: Toxic waste products build up, food is depleted and the bugs begin to die.





Bacteria can divide every 20-30 minutes.
With a single bacterium after 24 hours there would be 2^{48} bacteria.
This is approx the number of eukaryotic cells in the human body.

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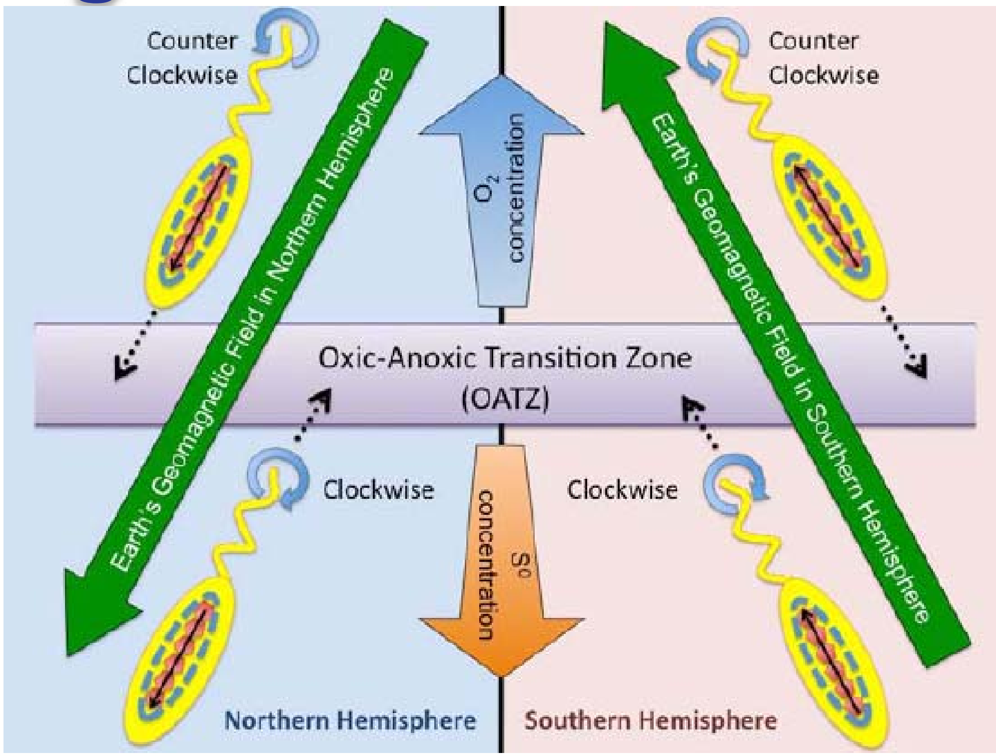
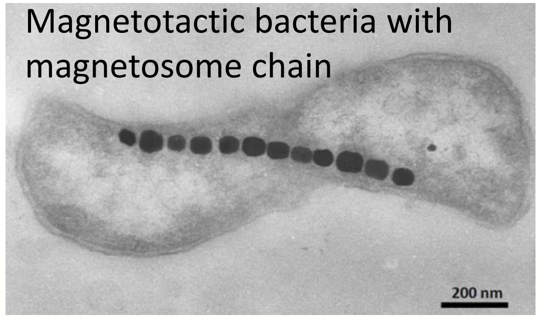
Magnetotactic bacteria move using the earths magnetic field

In both N and S hemispheres, cells at higher than optimal oxygen concentration in the oxidized state swim forward by rotating their flagella counter clockwise.

Cells at lower than optimal oxygen concentration in the reduced state rotate their flagella clockwise and swim backward without turning around.



Movement can be fast! (100x cell length per second)



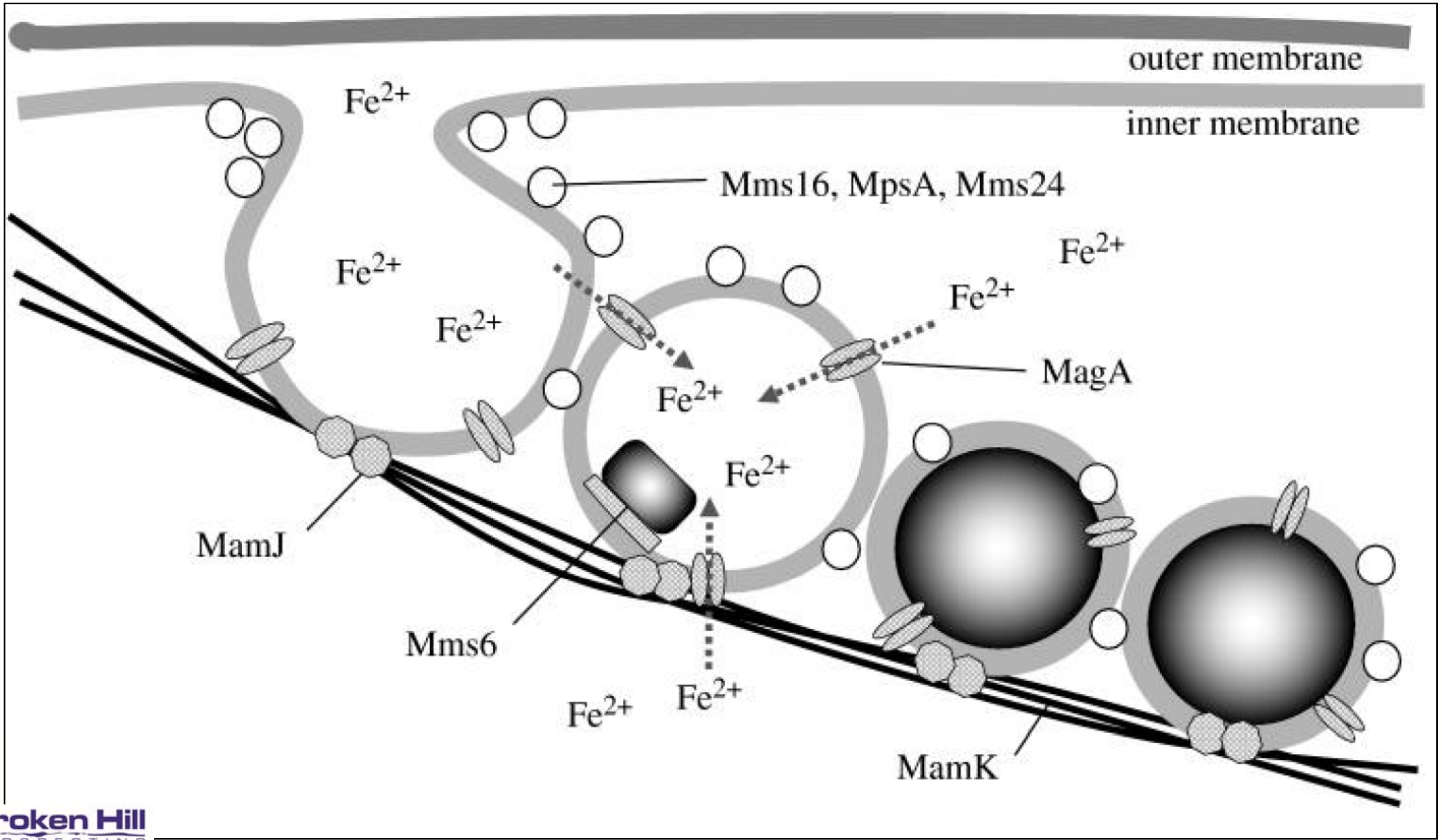
Diagrams from; Chen, L., Bazylinski, D. A. and B.H. Lower (2010) Bacteria That Synthesize Nano-sized Compasses to Navigate Using Earth's Geomagnetic Field. Nature Education Knowledge 1(10):14

Broken Hill PROSPECTING

Biomineralisation

Hypothesized mechanism for formation of bacterial magnetic particles

From "**Formation of magnetite by bacteria and its application**"
Atsushi Arakaki, Hidekazu Nakazawa, Michiko Nemoto, Tetsushi Mori, and Tadashi Matsunaga.
J R Soc Interface. 2008 September 6; 5(26): 977–999.



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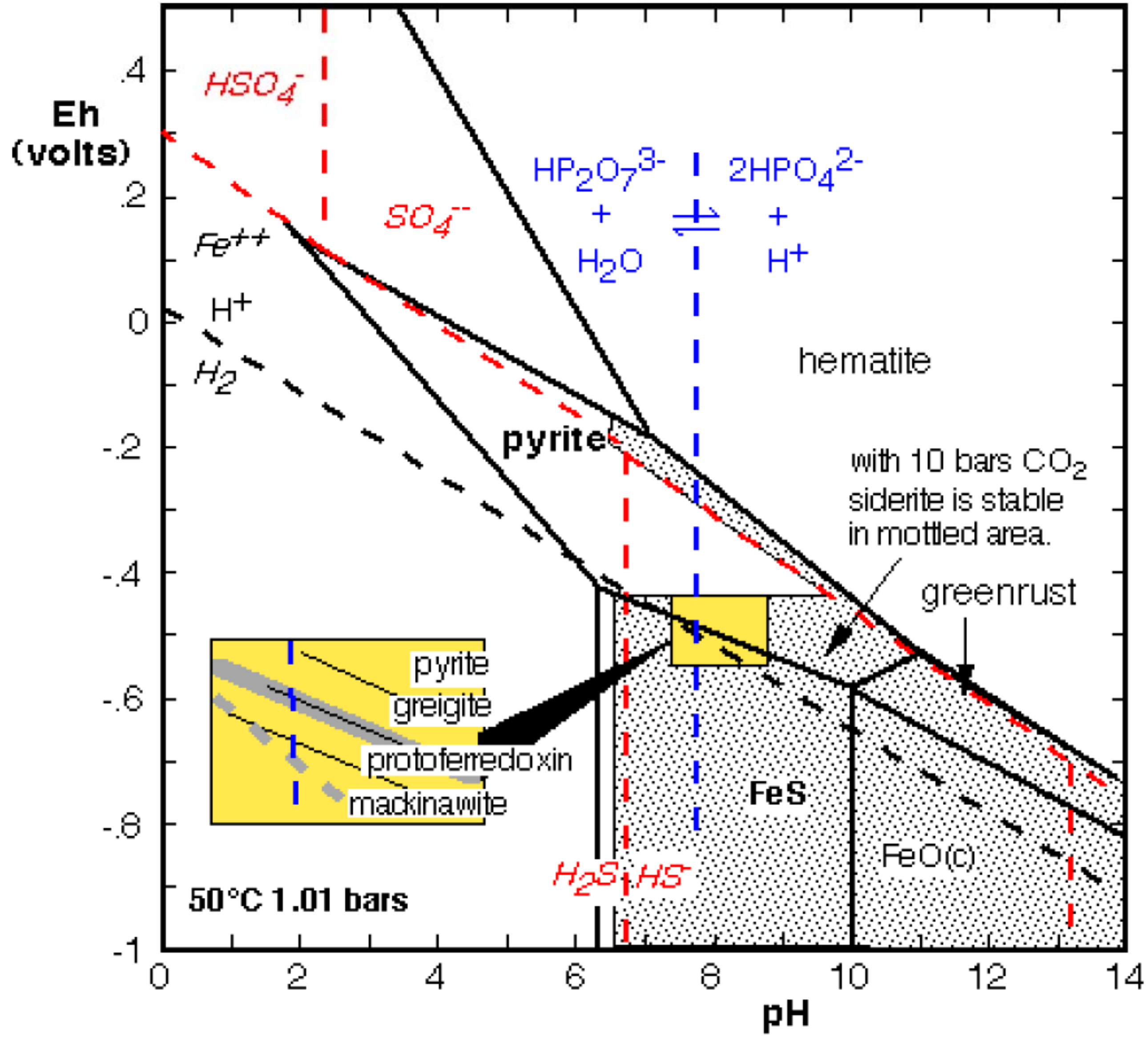
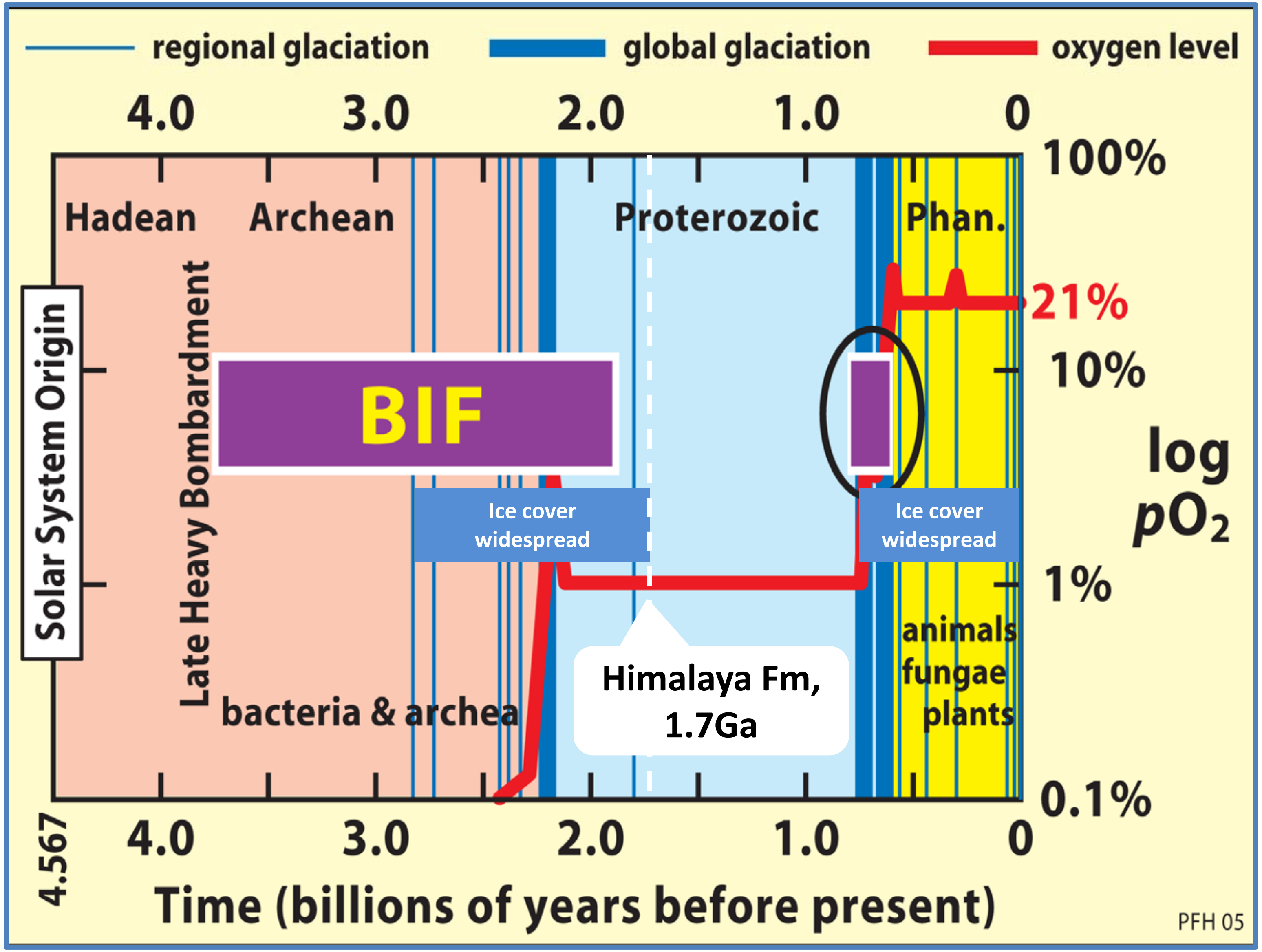
Greigite – strongly magnetic, limited stability



From; University of Glasgow 'Origin of Life' web site... http://www.gla.ac.uk/projects/originoflife/html/2001/figures/fig13.htm

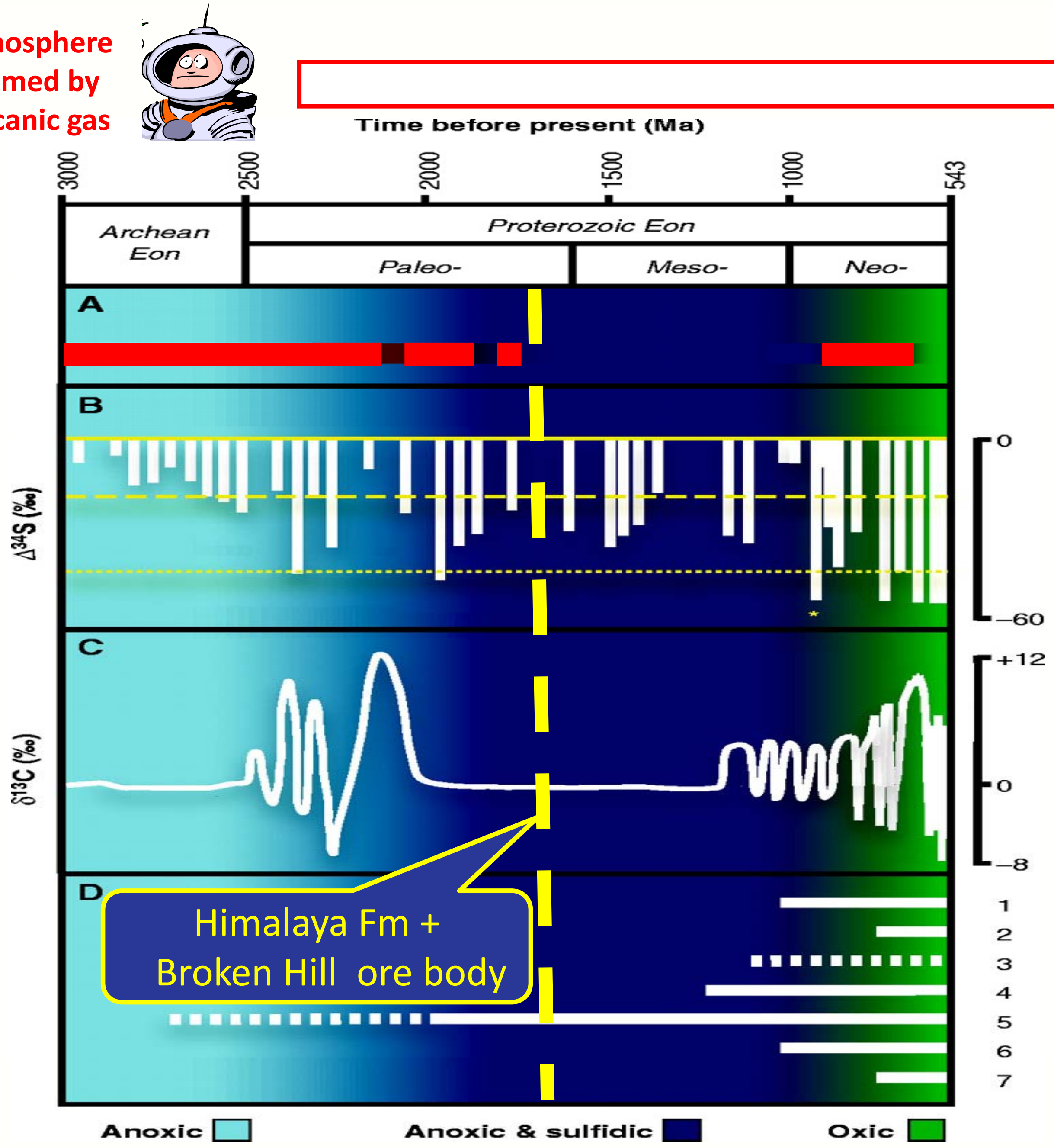
BIF and glaciation

After; "Snowball Earth" teaching slides (P. Hoffman et al, 2005)



Atmosphere formed by volcanic gas

21% oxygen and increasing aeobic bacteria/algae



Banded iron formation

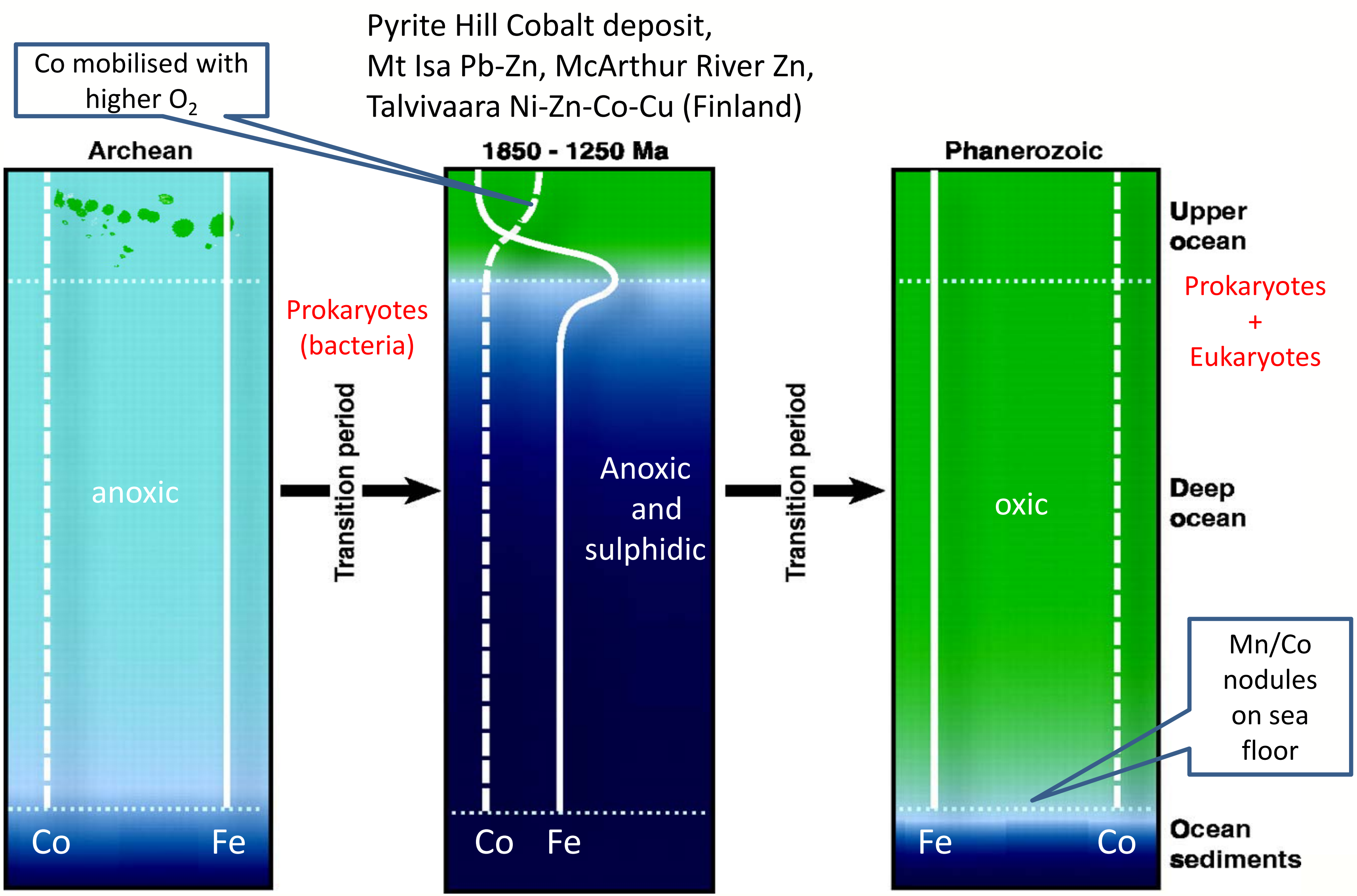
difference in $\delta^{34}S$ Between coeval marine sulfides and sulfates

Range of values of $\delta^{13}C_{carb}$

Eukaryotic evolution (Note: significant algae, cellulose etc only in last 1000 Ma)

Modified after A D Anbar, A H Knoll, Science 2002;297:1137-1142

Changing water chemistry over time



Modified after A D Anbar, A H Knoll, Science 2002;297:1137-1142

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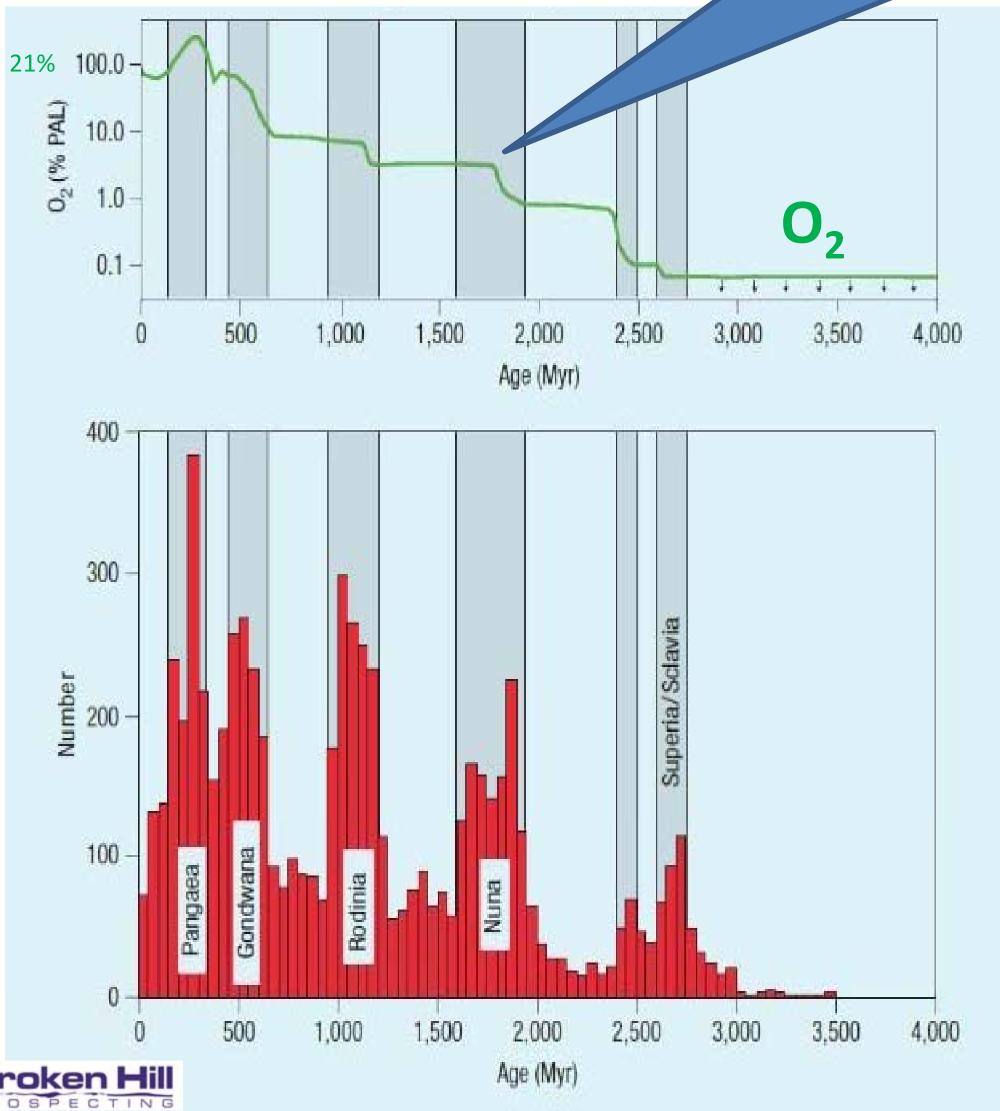
Oxygen, life, plate tectonics & ore formation

Himalaya Fm, 1730-1700Myrs



Close correlation between continental break-up and oxygen spikes in the entire geological record.

This could just be confusing correlation and causation, but .... with the break-up of continents, there is a corresponding increase in erosion, leading to more nutrients leaching into the oceans, and resulting in 'blooms' of biological activity, including oxygen-producing organisms.

Modified from Campbell, I. H. & Allen, C. M. (2008). Formation of supercontinents linked to increases in atmospheric oxygen. *Nature Geoscience* 1, 554-558.

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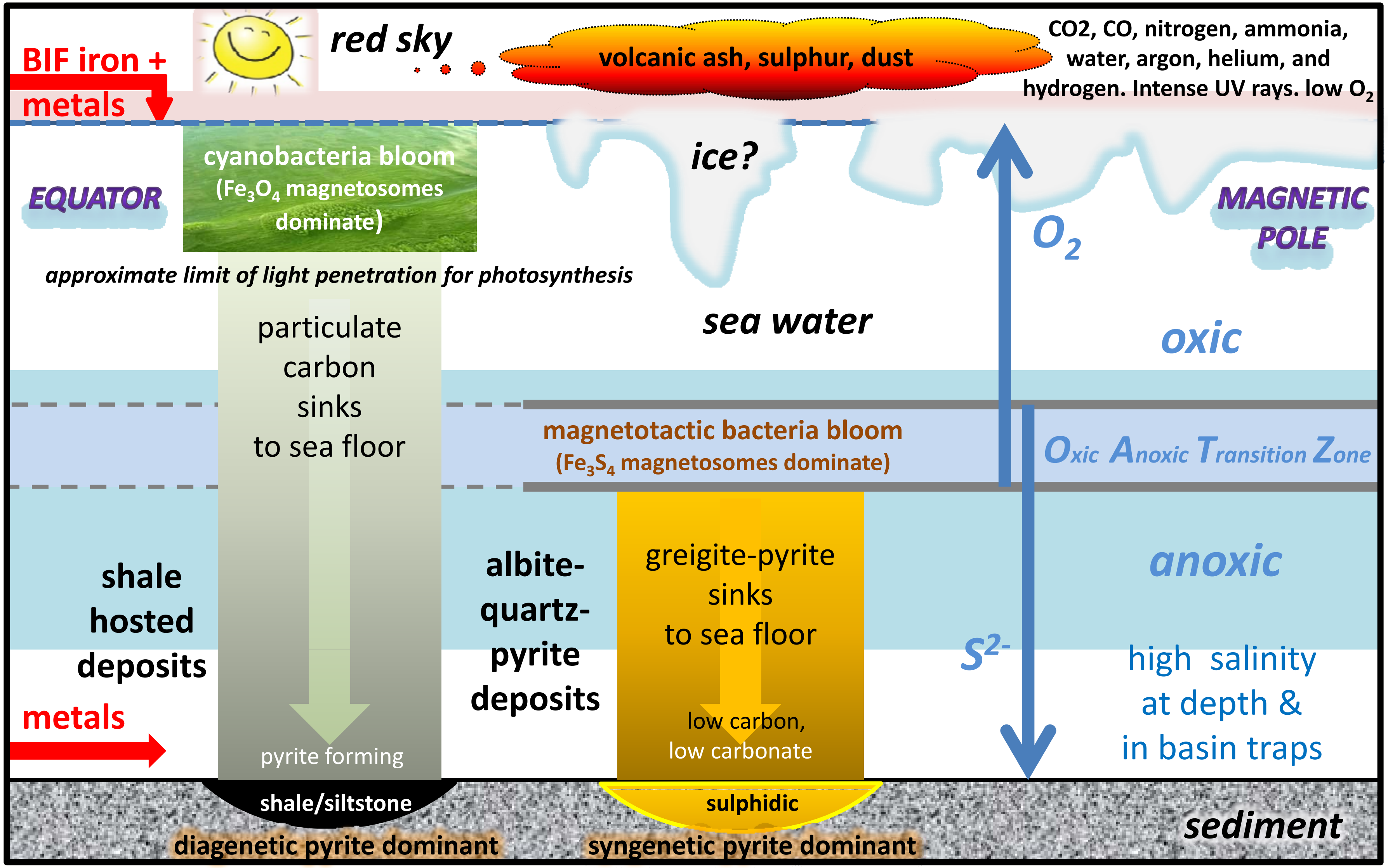

Models for end-member Proterozoic sedimentary basin-hosted base metal deposits.

Magnetotactic bacteria are found in greatest numbers in the OATZ. They use the earth's magnetic field for optimal positioning with respect to S^{2-} and O_2.

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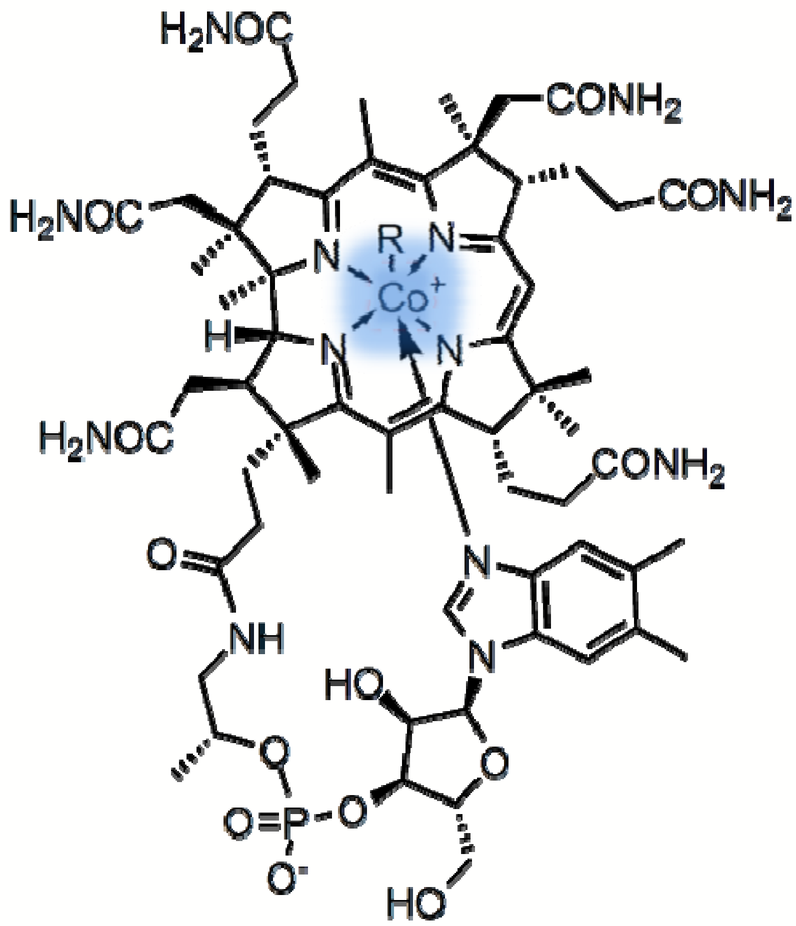
Rumen Deposits – cobalt based

- Co deficiency causes 'coastal disease', 'bush sickness', 'pining', 'denmark disease', 'salt sickness' in sheep and cattle....Australian, CSIRO discovery in 1935
- 1948 discovery found Co in vitamin B12, a cornerstone to metabolism
- 1954 Lewis described sulphate to sulphide production by bacteria in sheep stomach
- Co vital to blood and brain function in mammals
- Co formed in the stomachs of ruminators (sheep, goats, cattle etc) - by bacteria.
- Rumen bacteria synthesize approximately 2-3 mg vitamin B12 per day when provided with adequate dietary cobalt.
- Only bacteria have the enzymes required for B12 synthesis.
- Industrial production of B12 is through fermentation of selected microorganisms

Co is 4.4% of the molecular weight of

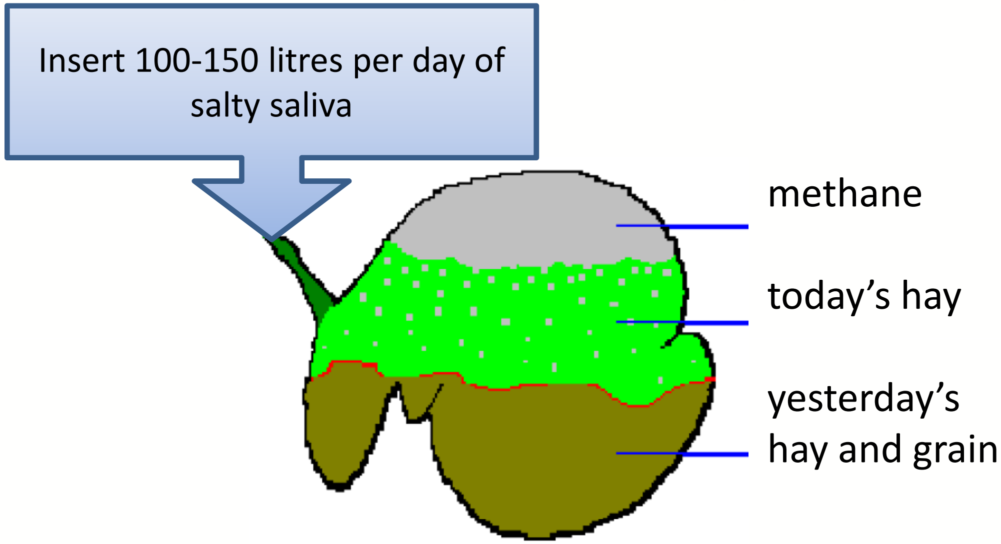
vitamin B12



R = 5'-deoxyadenosyl, Me, OH, CN

Rumen Deposits – a modern working model

Cellulose (grass, hay, grain), water and saliva are delivered to the reticulorumen through the oesophagus.
Heavy objects (stones, grain, nails) fall into the reticulum, while lighter material (grass, hay) enters the rumen proper. Added to this mixture are voluminous quantities of gas produced during fermentation.
Also add 100-150 litres of saliva per day to provide fluid and alkali buffering. The rate of flow of solid material through the rumen is quite slow and dependent on its size and density. Water flows through the rumen rapidly and appears to be critical in flushing particulate matter 'downstream'.



Movement brings gas bubbles forward to the oesophagus for eructation (high in methane 'carbon pollution' *sic*). Fermentation in the rumen generates enormous quantities of gas (30-50 litres per hour in adult cattle and about 5 lph in a sheep/goat).
Ruminants are responsible for over 20% of global methane emissions.

Notes from R. Bowen, 2009
'**Rumen Physiology and Rumination** '

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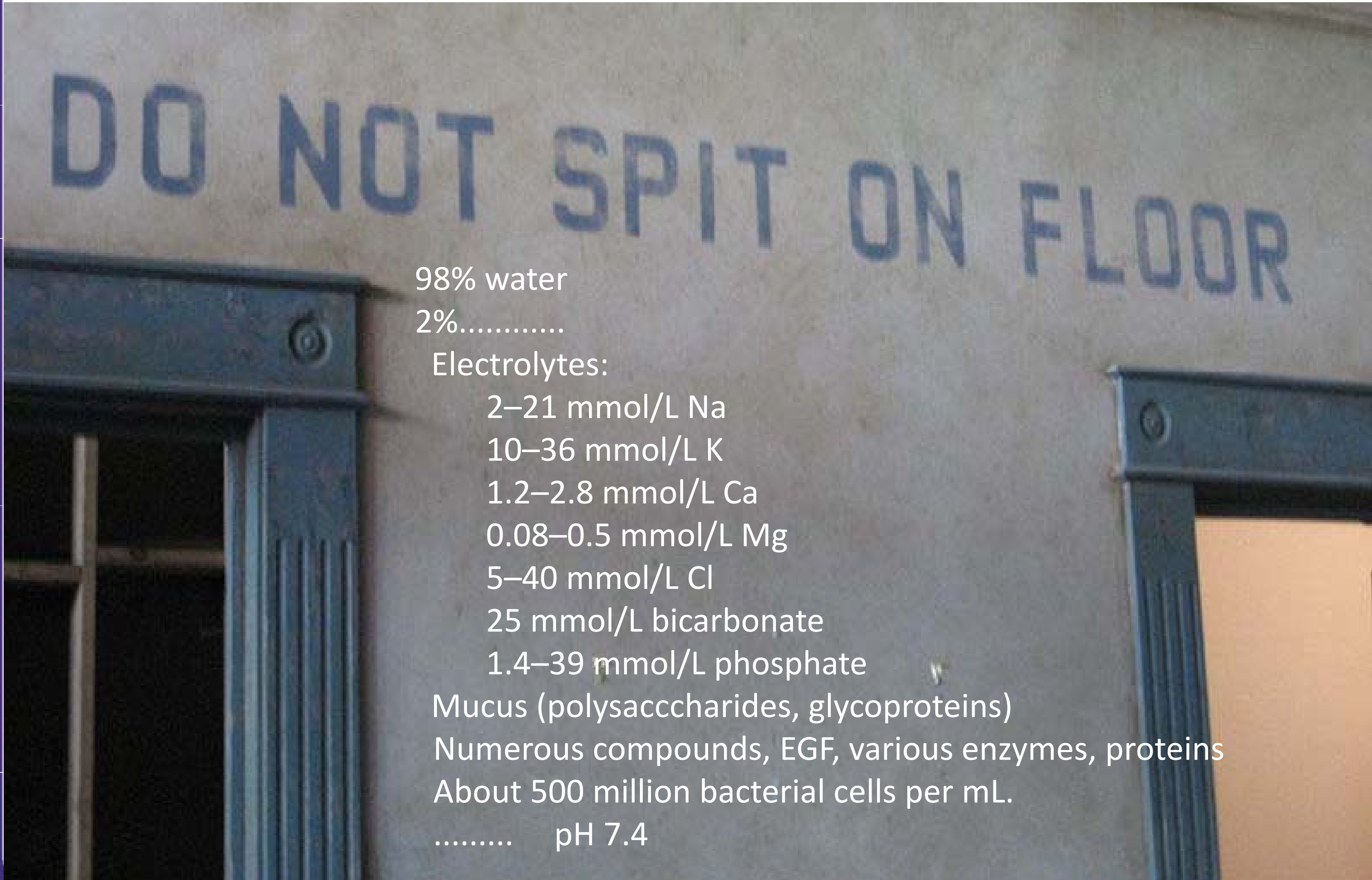
Composition of saliva



98% water

2%............

- Electrolytes:
  - 2–21 mmol/L Na
  - 10–36 mmol/L K
  - 1.2–2.8 mmol/L Ca
  - 0.08–0.5 mmol/L Mg
  - 5–40 mmol/L Cl
  - 25 mmol/L bicarbonate
  - 1.4–39 mmol/L phosphate
- Mucus (polysacccharides, glycoproteins)
- Numerous compounds, EGF, various enzymes, proteins
- About 500 million bacterial cells per mL.
- ....   pH 7.4

The Rumen Model – true or tripe?

- Anoxic/oxygen-depleted and high fluid environment
- Methane-rich
- Highly saline/sodium (added in saliva)
- No light (no photosynthesis)
- Abundant microbial activity and 'floating' biomass
- Sulphidic - Sulphate is reduced to sulphide (also occurs in rumen)
- Settling and mixing in fluid column
- pH – near neutral to slightly acid (buffered by saliva)
- 'Fixing' of cobalt in vitamin B12 by bacteria in rumen

Note that there is likely a spectrum of deposits between shale-hosted basins (cyanobacteria) and 'rumen-like' deposits since the latter may form at the same time and at depth beneath the former in dark, anoxic environment at the AOTZ (eg Finland's Talvivaara Ni-Zn-Cu-Co graphitic schist hosted deposit has characteristics of both)

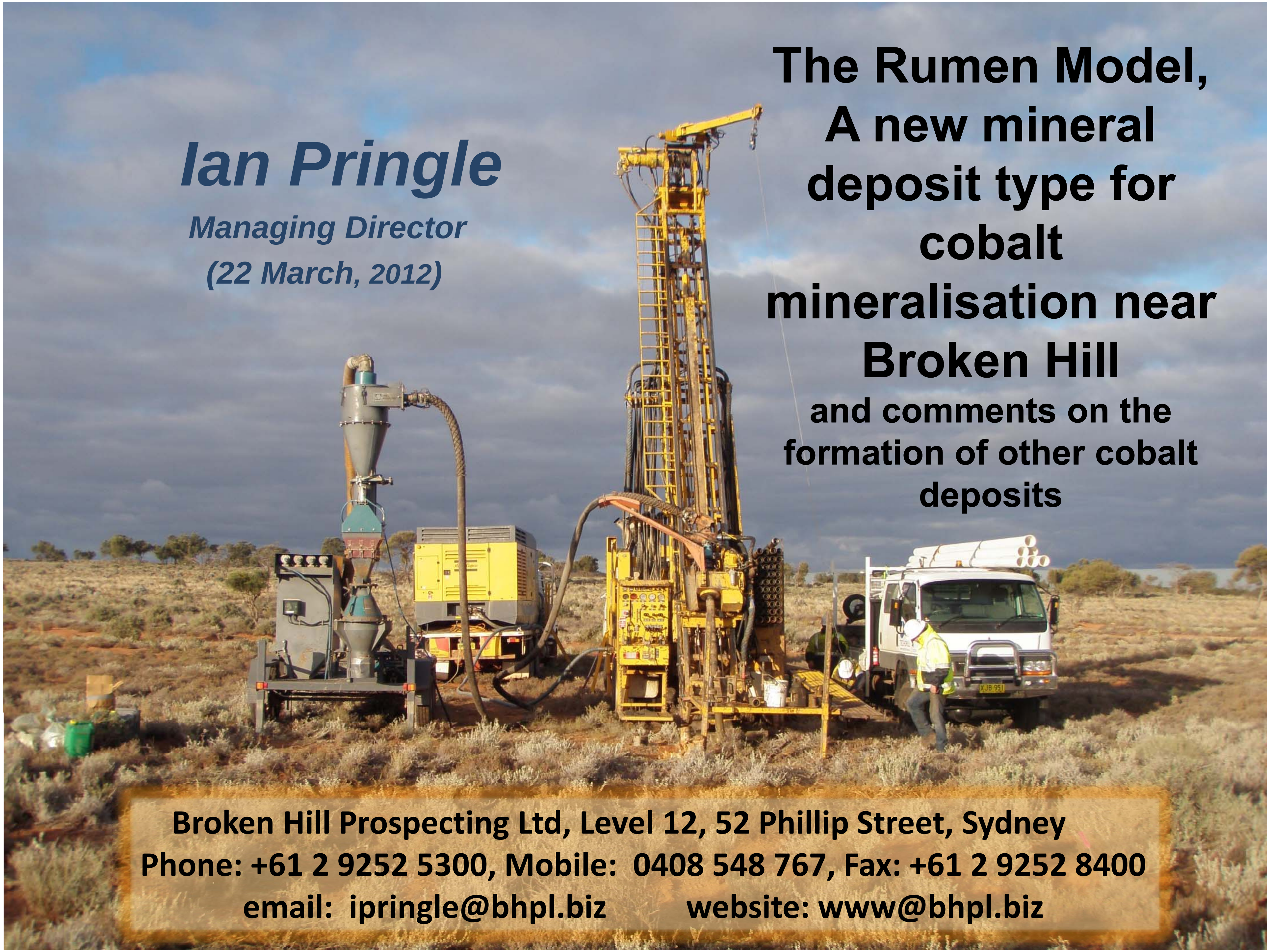
Some stats on cobalt, future uses....

- DRC (Congo) +50% Co res, +60% of total world production in 2011
- Most used in **superalloys** and **catalysts**, but huge growth in........
- **Batteries** was 11% Co consumption in 2002, and is now 27%
  - **3.6g Co in each mobile phone (2005, 2 billion phones; 2011, 5.8 billion)**
  - **Laptop/tablets increased 35% since 2009 and expected to double over next 5 years (will need +11,000t Co)**
  - **4kg Co for each hybrid car, 6kg for each electric car**
  - **12-13 million hybrid/electric vehicles by 2020 will need 30,000t Co**
  - **80 million electric bicycles in China by 2015 (plus more in India?)**
- **Superalloys** in jet engines/turbines
  - **Southwest Airlines have ordered 208 aircraft from Boeing (largest commercial deal in history, $19 billion)**
  - **Boeing forecast demand for 33,500 new aircraft in next 20 years**
  - **Airbus plans 6,000 new jets in US and 8,500 in Asia in next 20 years**

(data mostly from Resource Investor, Philip Burgert report “Supply disruption threats looming for cobalt”, 9 February, 2012)

Summary

- IP geophysics, mapping has defined ++4km strike of sediment-hosted stratabound mineralisation of quartz-albite-cobaltiferous pyrite (20%).
- Pyrite Hill has an Inferred Resource of 16.4mt of 1.83lb/t Co and potential for 14-24Mt of similar grade. Can be upgraded to pyrite concentrate with 0.5% Co.
- Nearby Big Hill has an Inferred Resource of 4.4mt of 2.0lb/t Co.
- Mapping and IP show considerable extensions of cobalt mineralisation outside the drill areas and this has located excellent along-trend drill targets along a +4km strike.
- Preferred deposit model is syngenetic sulphide (greigite) formation by sulphate reducing bacteria at the oxic-anoxic transition zone (OATZ) in a saline brine basin. Magnetotactic bacteria incorporate cobalt to assist in movement using earths magnetic field. Greigite/cobaltiferous pyrite settles to basin floor and displays textures typical of sea floor sedimentation. Regional metamorphic overprinting and recrystallisation, tilting/tectonism.
- Closest modern analogues are saline basins with active and highly concentrated magnetotactic bacterial colonies located at the OATZ and active sulphidic production.
- Model end-member Proterozoic sedimentary basin-hosted base metal deposits are proposed:
  - Carbonaceous - cyanobacteria (photosynthetic) produce carbon which settles to basin floor to form laminated/graded sediment where diagenetic pyrite formation dominates. Low-latitudes, sunlight/ice free and an O2 atmosphere favour these deposits.
  - Pyritic – anoxic magnetotactic bacteria (magnetite or sulphide) selectively fix metals within colony/blooms located at the OATZ. Syngenetic sulphides settle to saline basin floor. High latitudes, ice cover, eroding BIFs and low oxygen/high sulphur environments favour these deposits. (RUMEN MODEL)
- Bacterial concentration of cobalt in the stomachs of rumenants show similarities with the pyritic end member model.
- A role for bacteria is suggested for cobalt-rich (limonitic) laterite deposits such as Syerston in NSW.
- Comparison is made with Cu-Co Deposits in central Africa which, although are more than 1 billion years younger, were formed during comparable episodes of continental break-up, ice cover and rising levels of atmospheric oxygen.
- Mn-Co sea floor nodules and crusts are likely bacteria film deposits and analogies with ulcer causing bacteria may be not be unreasonable


The Rumen Model,
A new mineral
deposit type for
cobalt
mineralisation near
Broken Hill
and comments on the
formation of other cobalt
deposits
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