Manitoba Mining and Minerals Convention 2008:
Orogenic Gold Short Course

Orogenic gold deposits in the Superior Province of Manitoba

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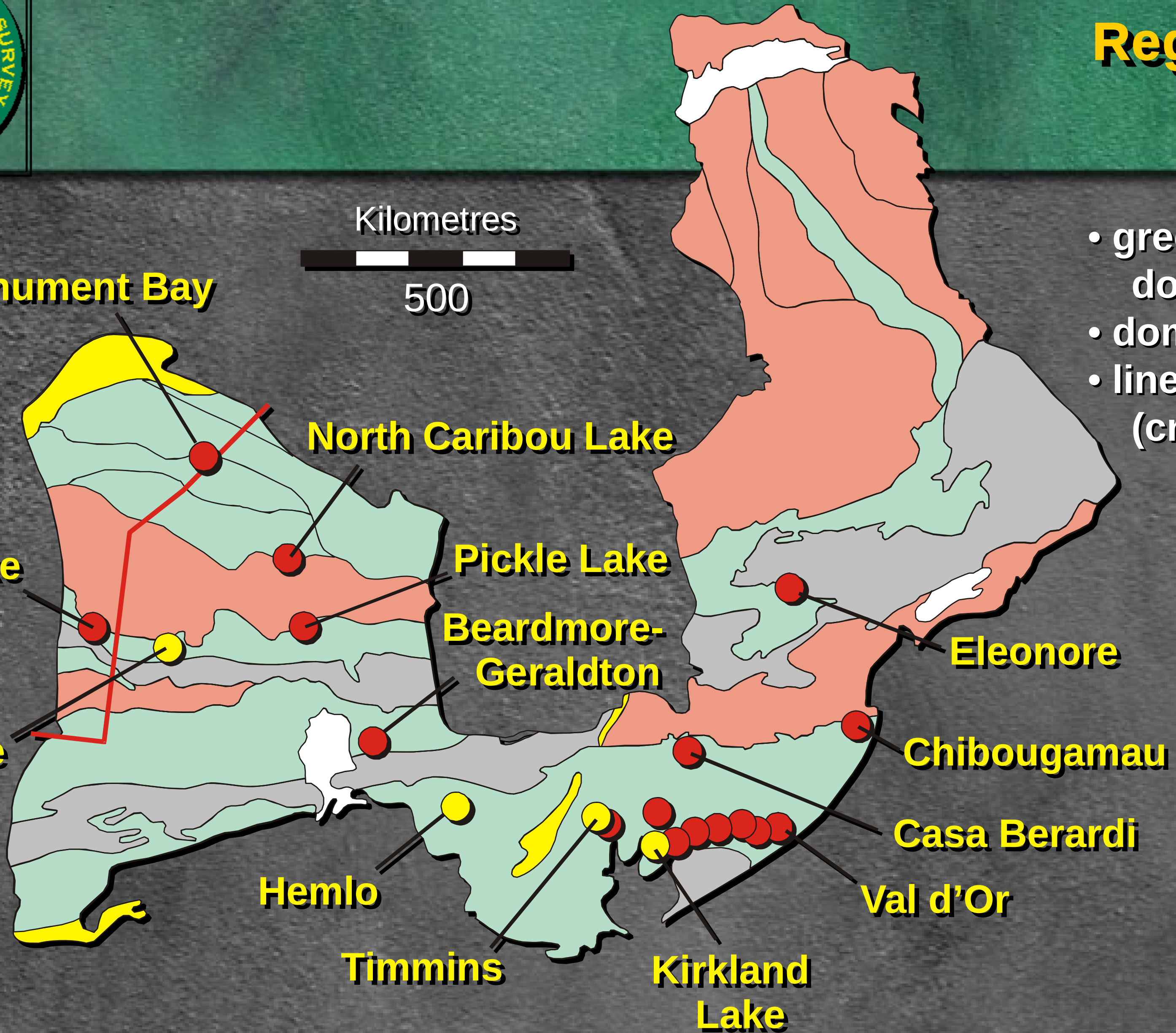
Headframe, Rice Lake mine

Main vein, High Rock Island deposit

Regional setting:
Superior Province

- greenstone-granitoid domains
- domain margins
- linear distribution (crustal-scale faults)



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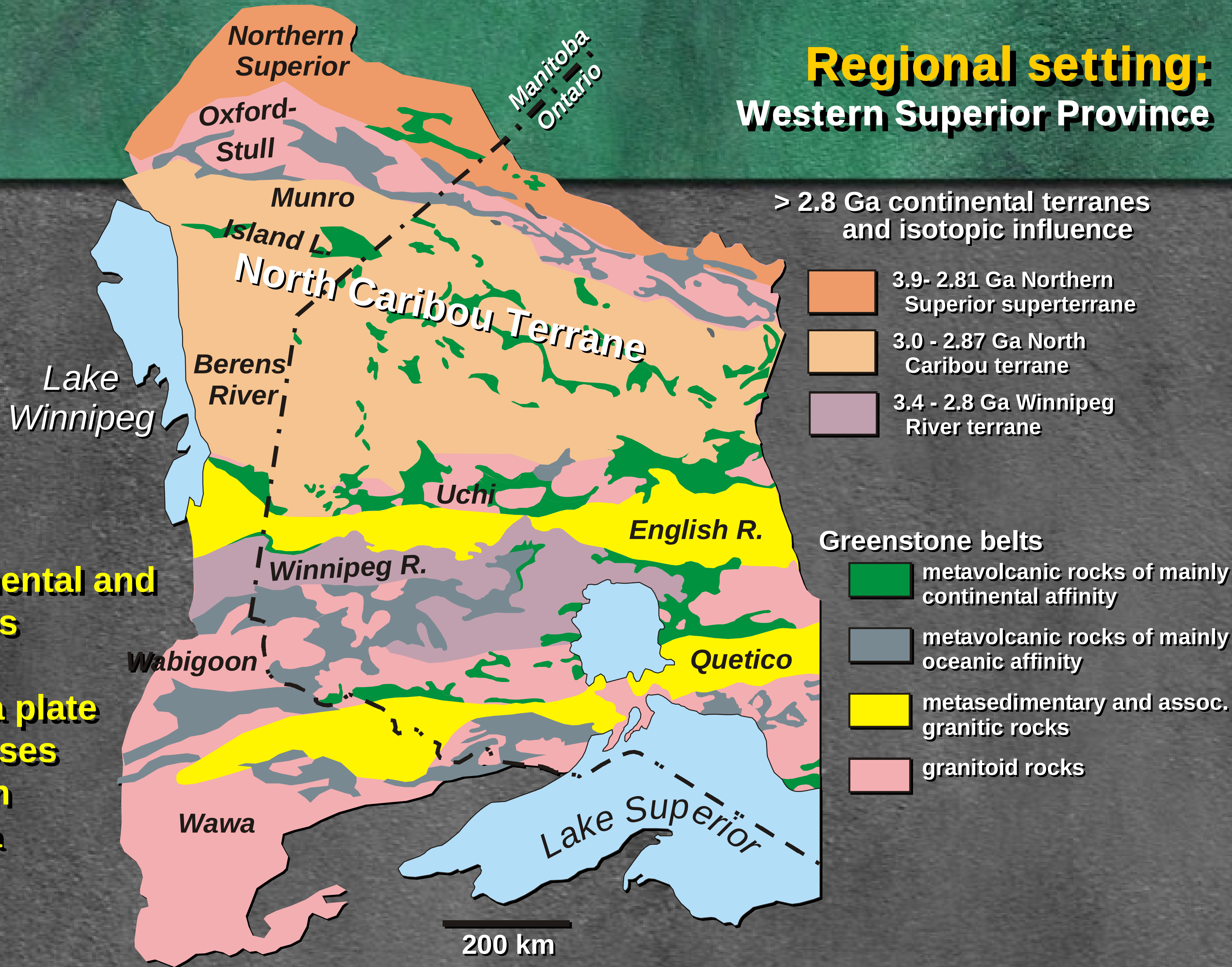
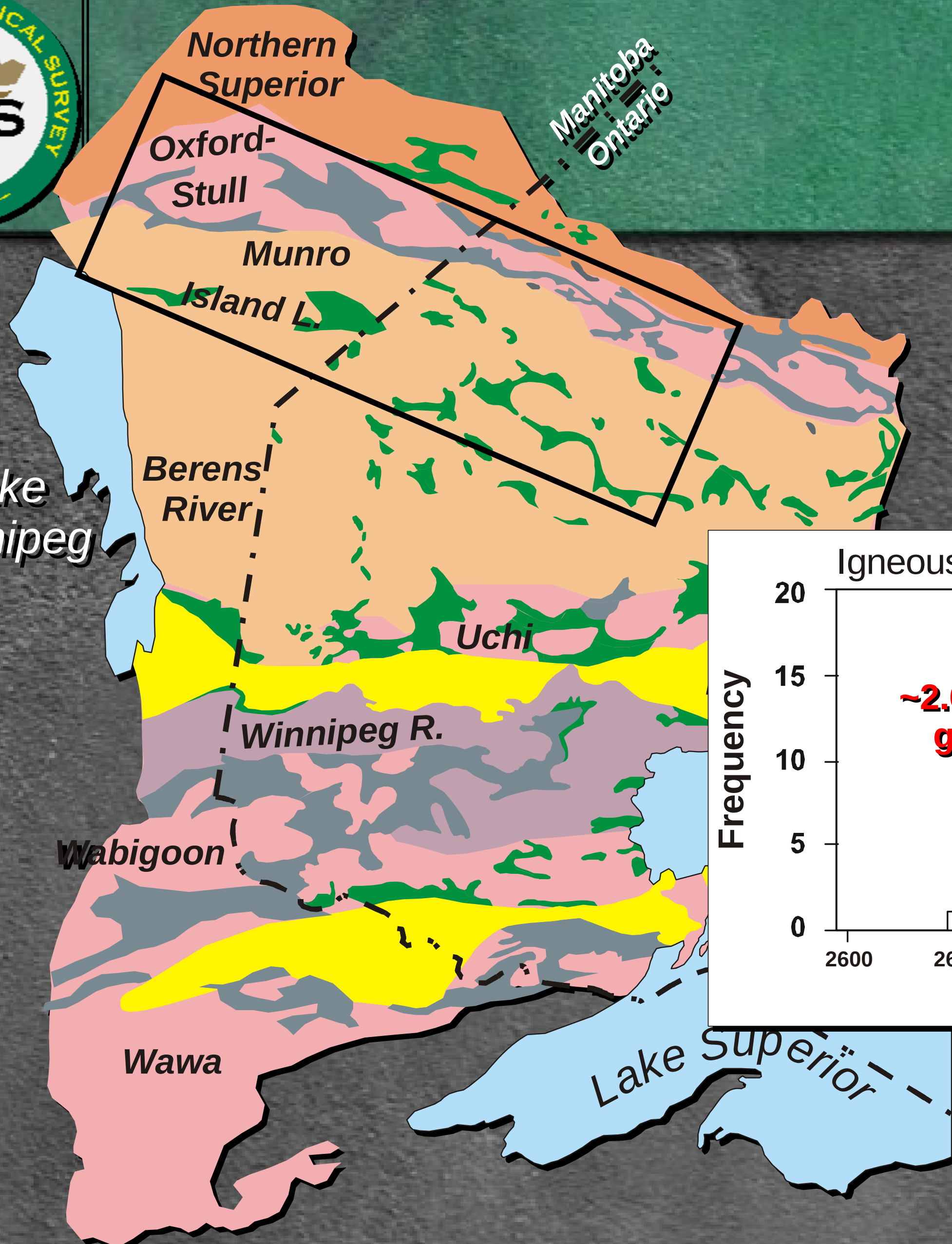
Regional setting:
Western Superior Province

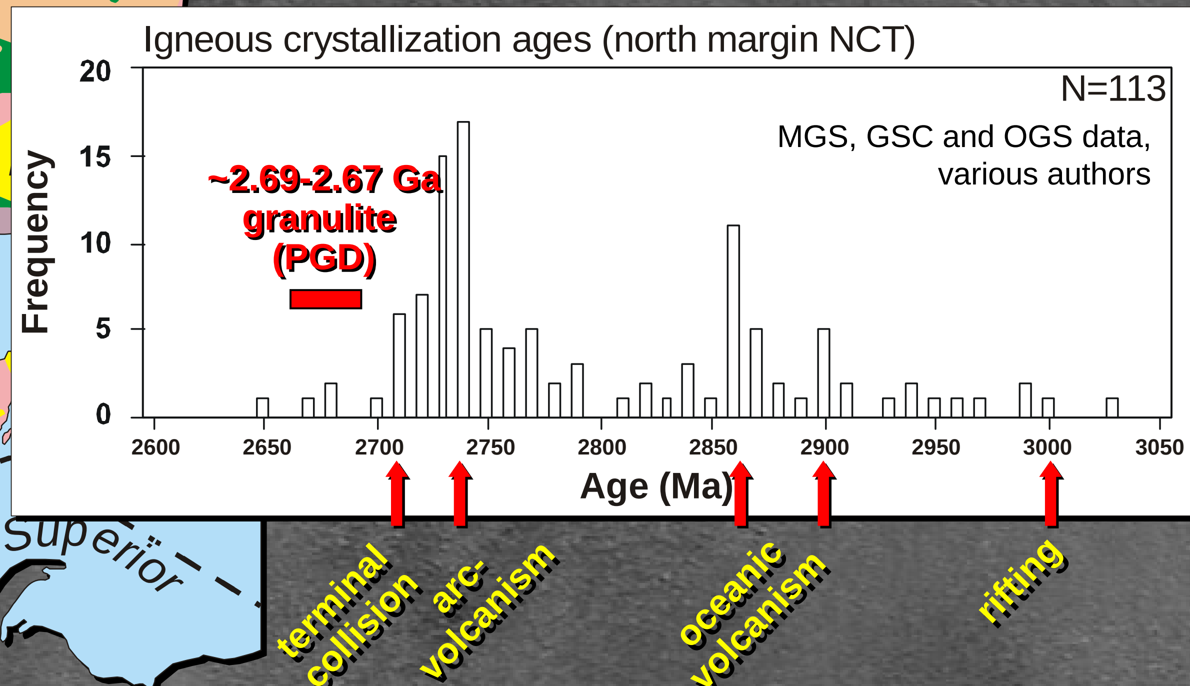


- collage of continental and oceanic terranes (ca. 3.9-2.7 Ga)
- amalgamated via plate tectonic processes
- terminal collision ca. 2.69-2.67 Ga

North margin of NCT:
tectonomagmatic evolution

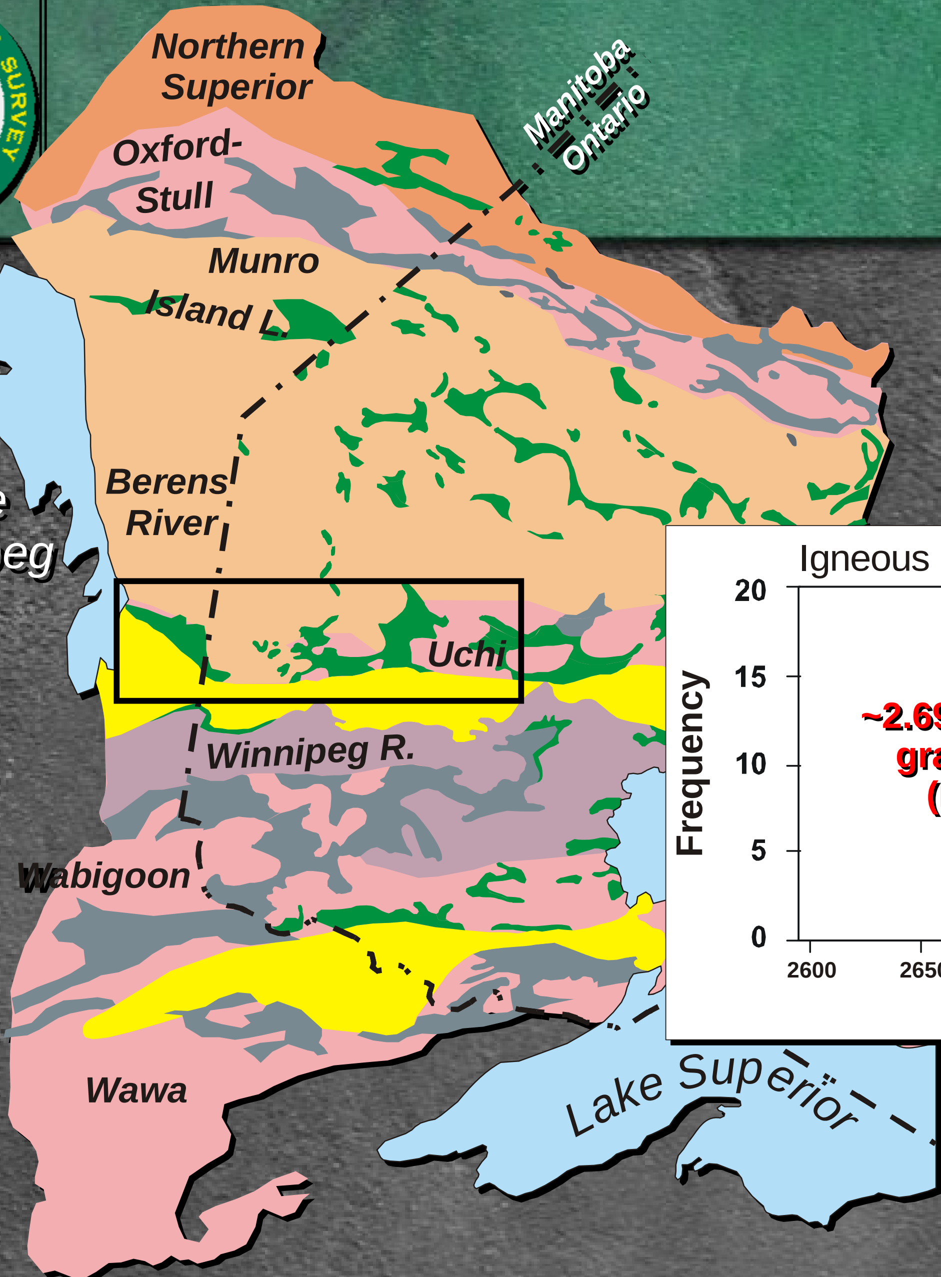


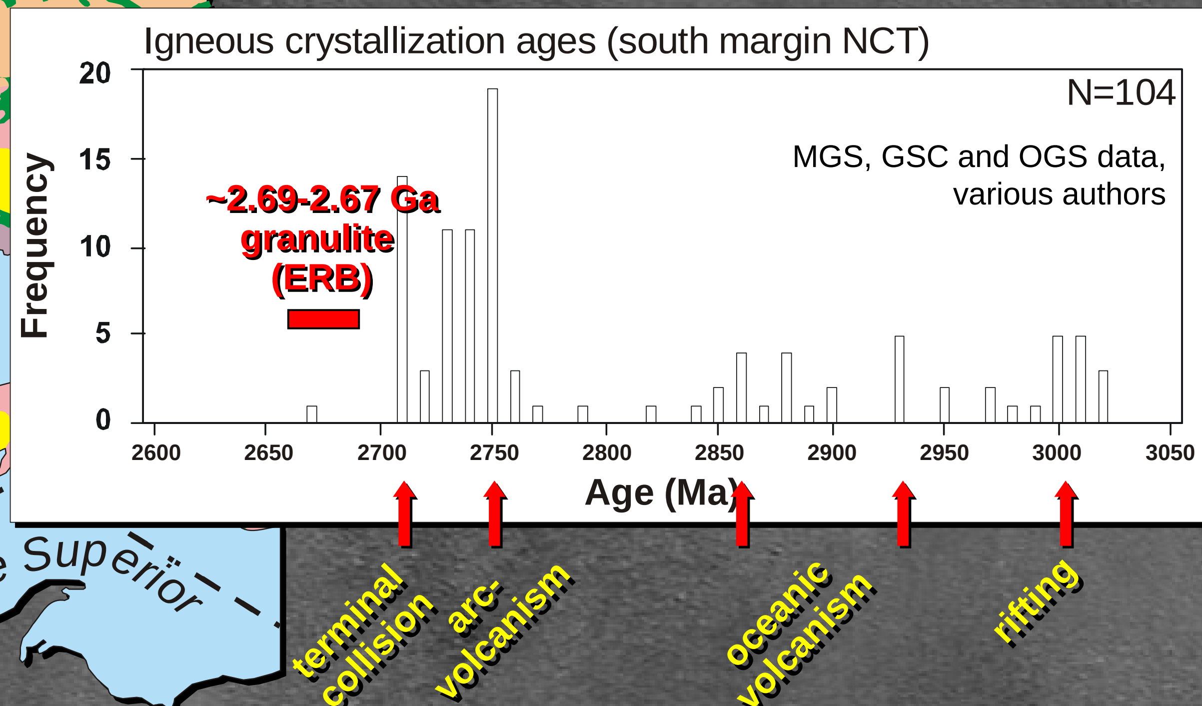
- magmatic history spans ~380 my
- major additions of crust at ~2.86 and 2.74-2.73 Ga
- subduction-accretion complex



South margin of NCT:
tectonomagmatic evolution

- magmatic history spans ~350 my
- major addition of crust at ~2.71-2.75 Ga
- subduction-accretion complex

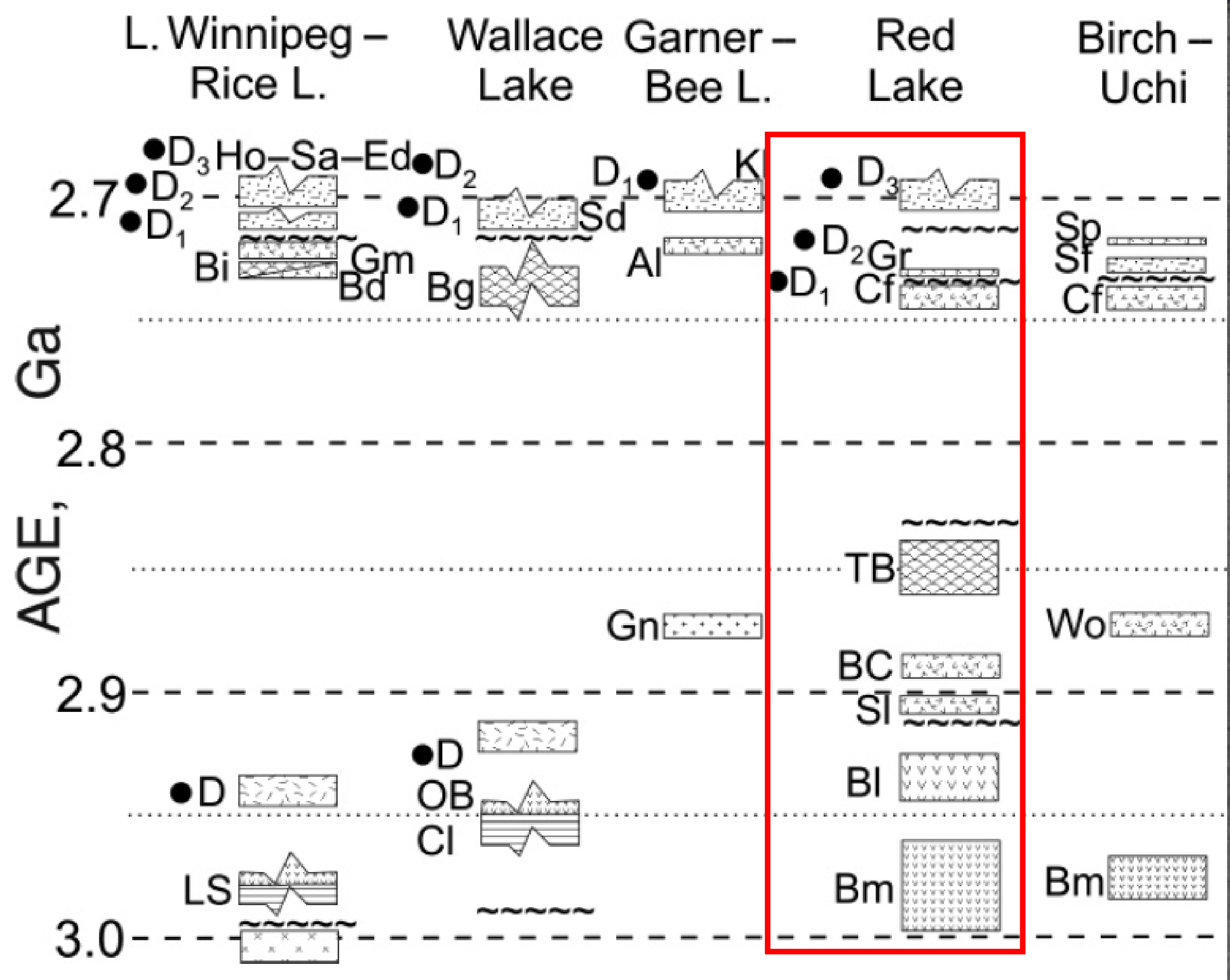




Percival et al., 2006;
CJES, v. 43, p. 1085-1117

South margin of NCT:

tectonic evolution and regional correlation



Collisional orogenesis

Orogenic sedimentation

Oceanic and continental-arc magmatism

Oceanic and continental-arc magmatism

Continental rifting, plume-magmatism

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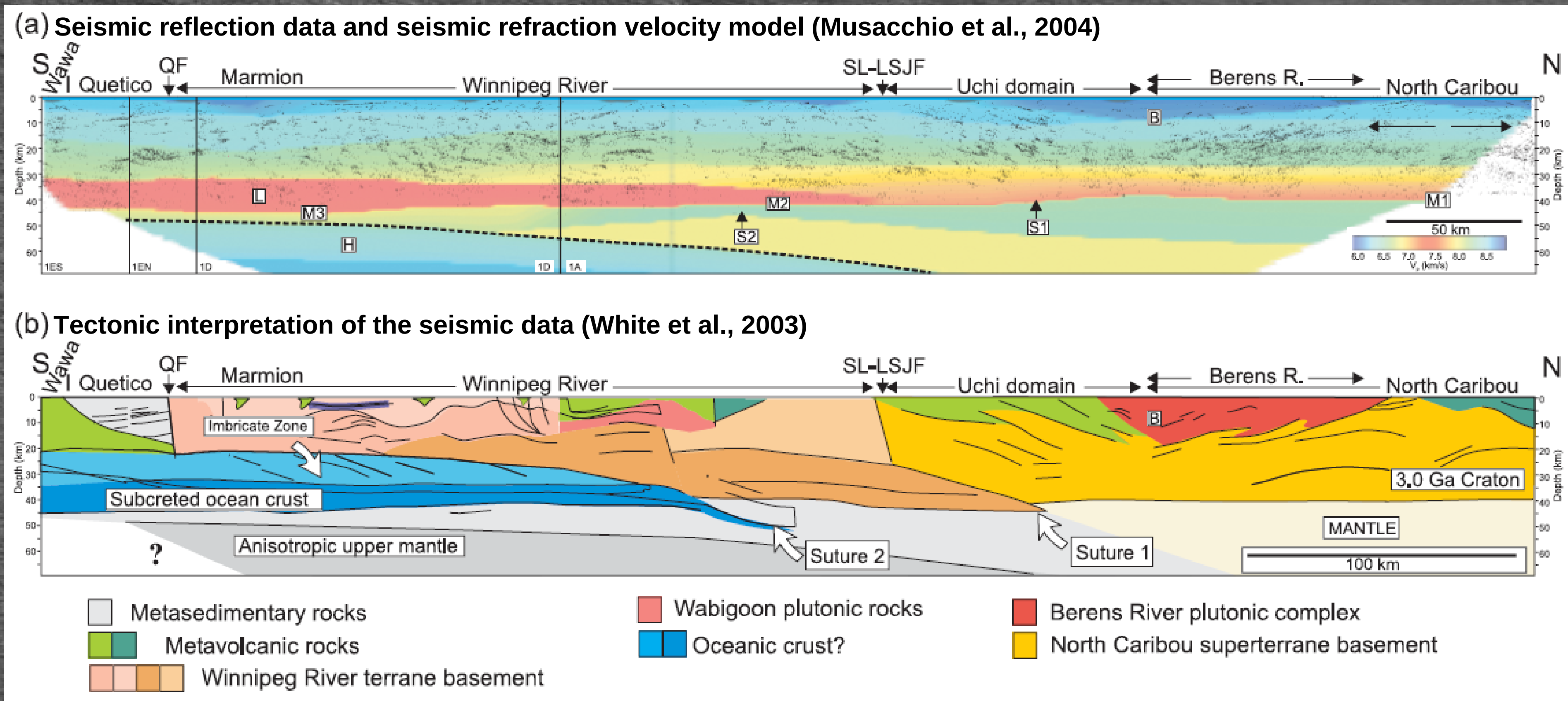
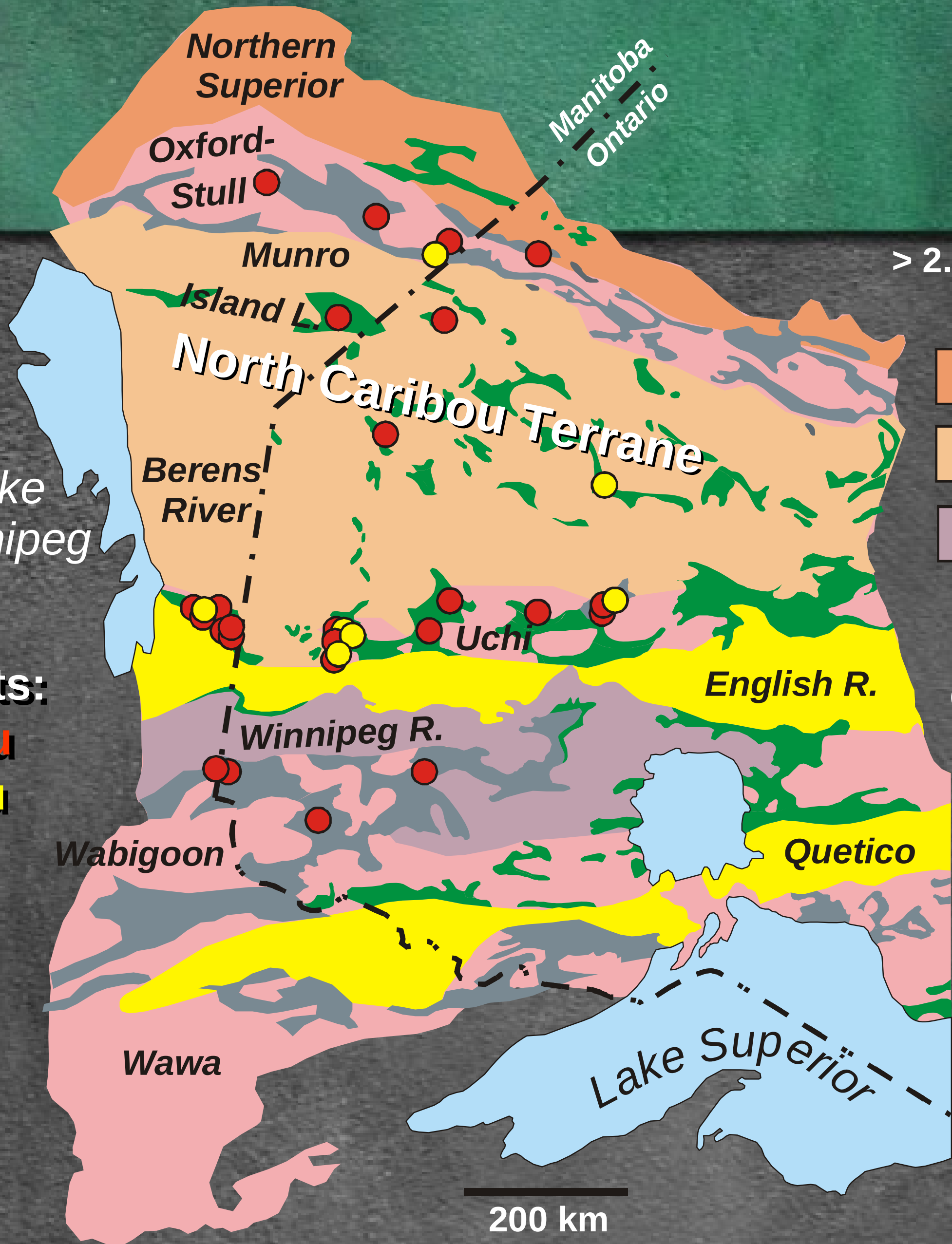
- Accretionary orogens on NCT margins
- Crustal-scale structures
- Favourable geodynamic settings for OGD

Western Superior Province:
lithospheric structure



- **Western Superior Lithoprobe transect** Percival et al., 2006; CJES, v. 43, p. 1085-1117

Western Superior Province: gold deposits (>50k ounces Au)



Gold deposits:
>50k oz. Au
>1M oz. Au

> 2.8 Ga continental terranes and isotopic influence

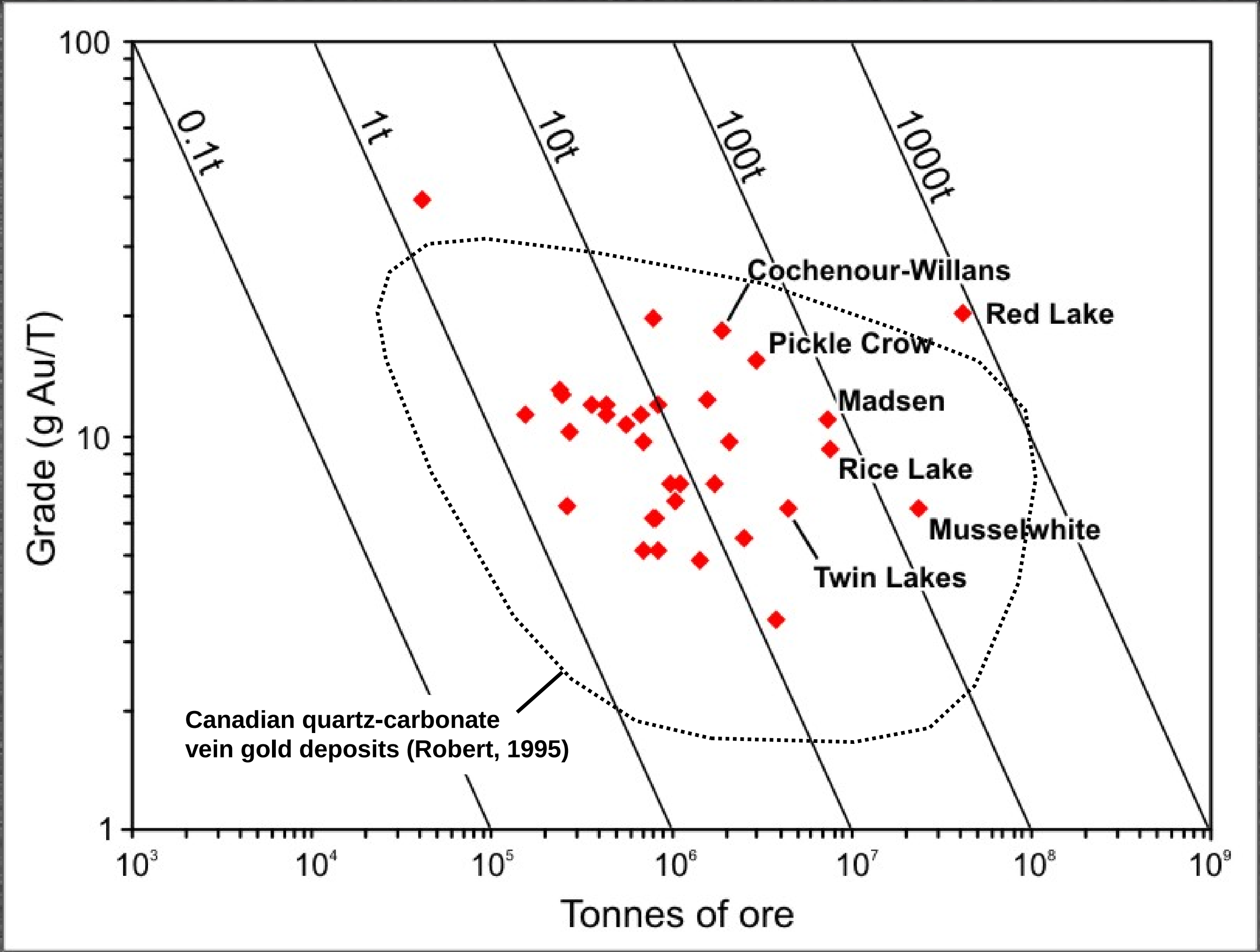
- 3.9- 2.81 Ga Northern Superior superterrane
- 3.0 - 2.87 Ga North Caribou terrane
- 3.4 - 2.8 Ga Winnipeg River terrane

Greenstone belts

- metavolcanic rocks of mainly continental affinity
- metavolcanic rocks of mainly oceanic affinity
- metasedimentary and assoc. granitic rocks
- granitoid rocks

34 deposits
>47.6 million ounces Au

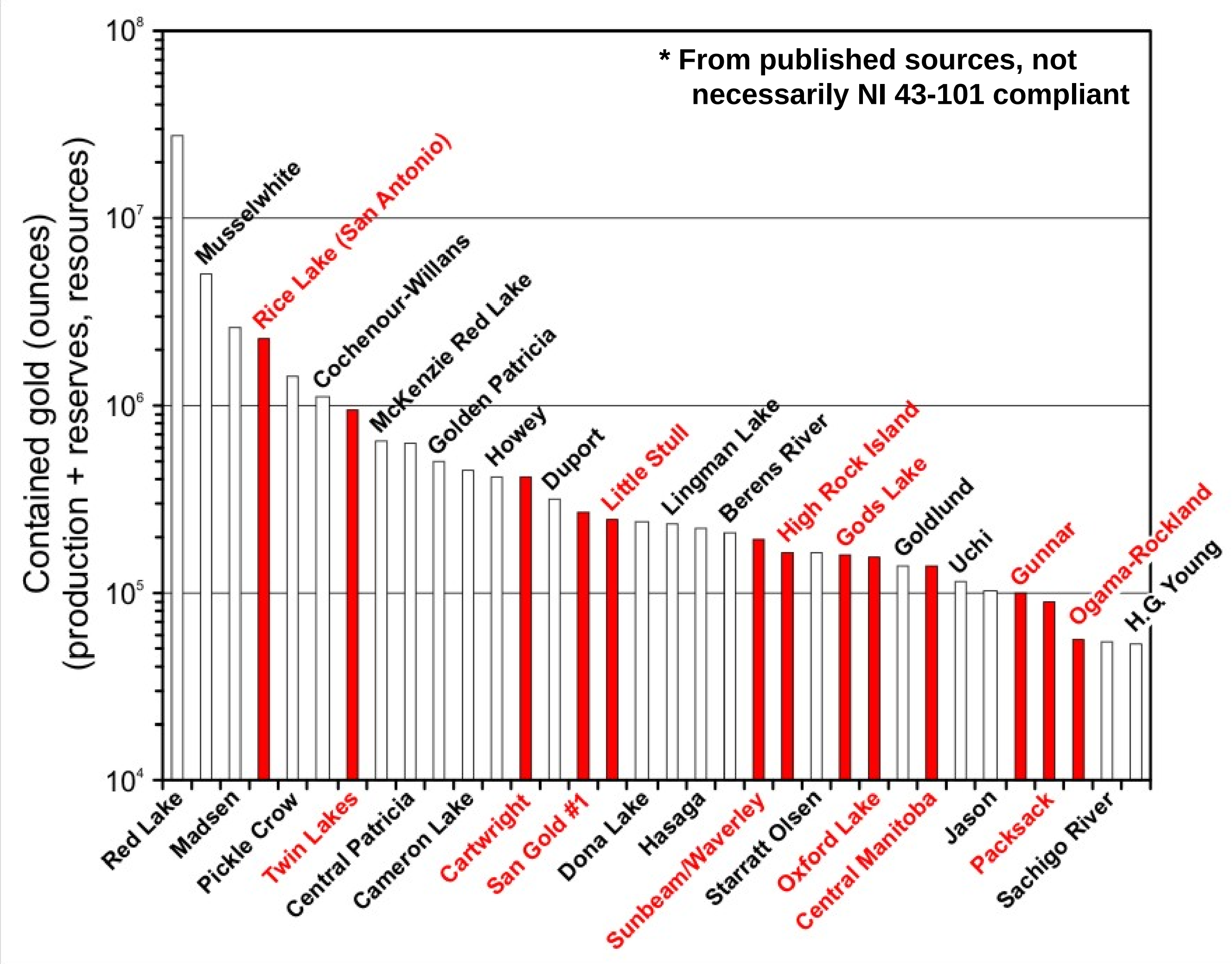
Western Superior Province gold deposits:
tonnage vs. grade



- relatively high-grade
- median grade: 10.0 g Au/T
- median tonnage: 836,000 T
- two 'world-class' deposits (>100 tonnes Au)

Note: Twin Lake resource expanded to 1.2M ounces Au

Western Superior Province gold deposits:
contained gold



- Production + reserves and resources
- Manitoba deposits in red
- Large deposits rare, but account for most of the gold endowment

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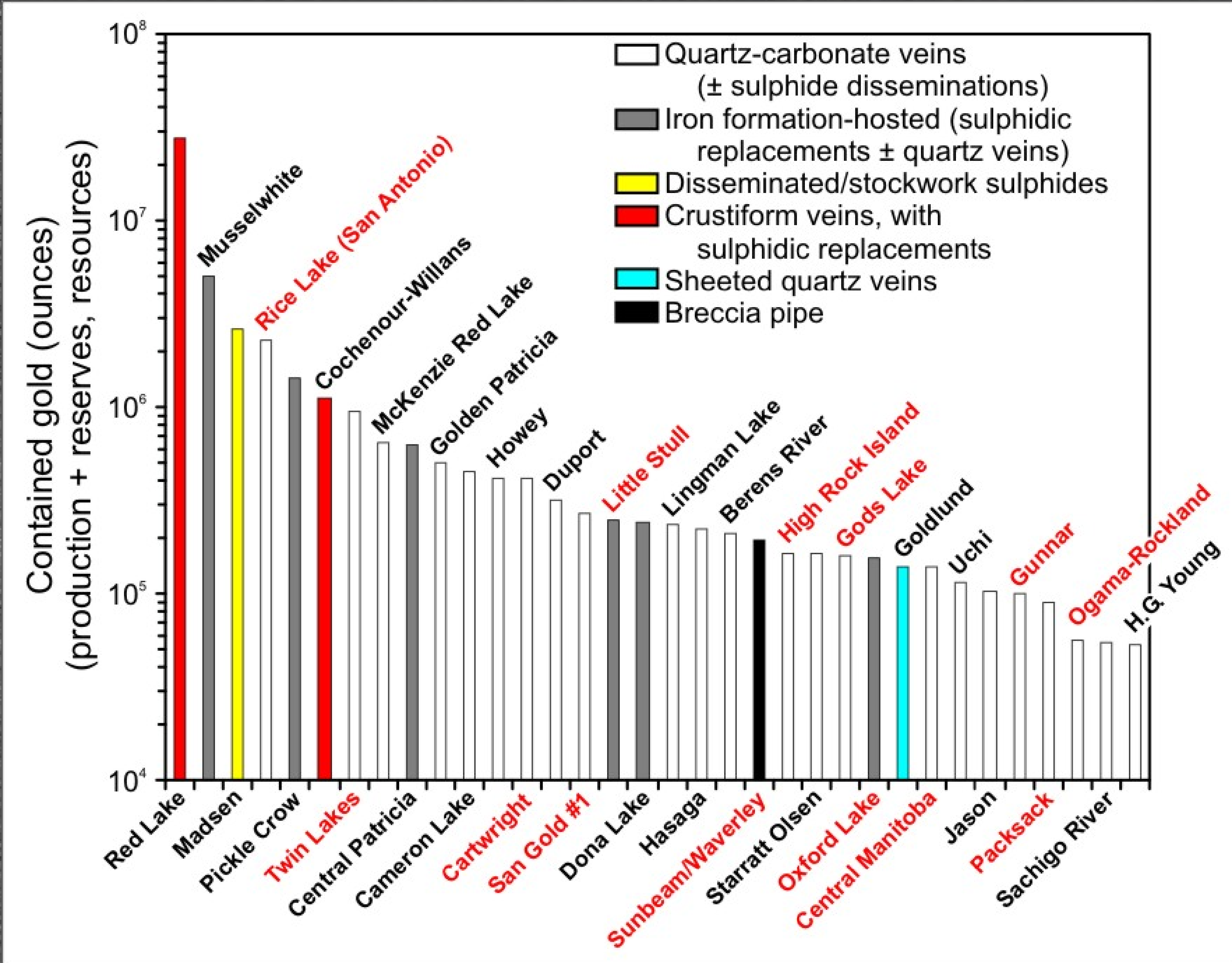
Western Superior Province gold deposits:
style of mineralization

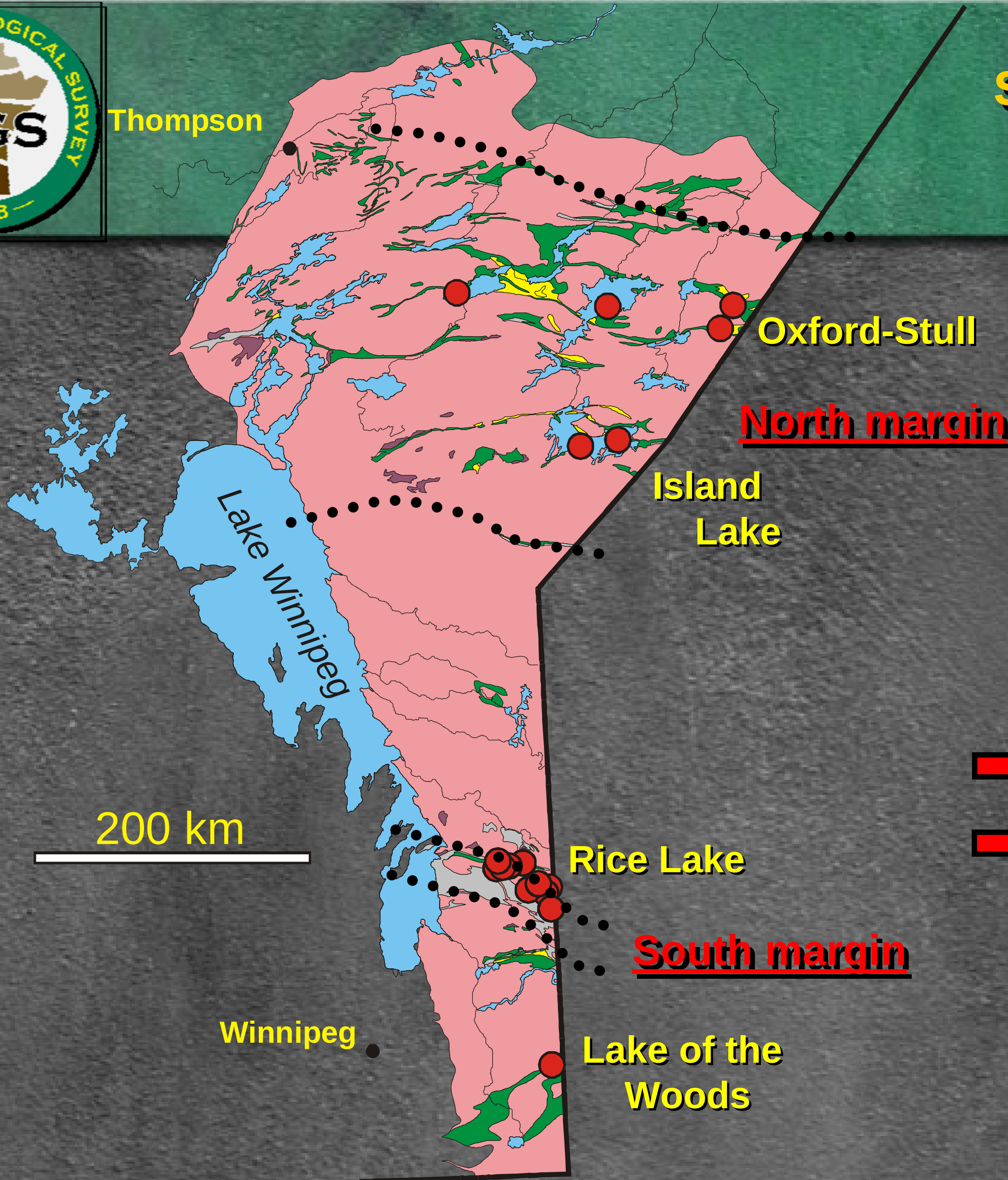


- 23 quartz-carbonate vein
- 6 iron formation-hosted
- 2 crustiform vein/sulphidic replacement
- 1 disseminated/stockwork sulphide
- 1 sheeted quartz veins
- 1 breccia pipe

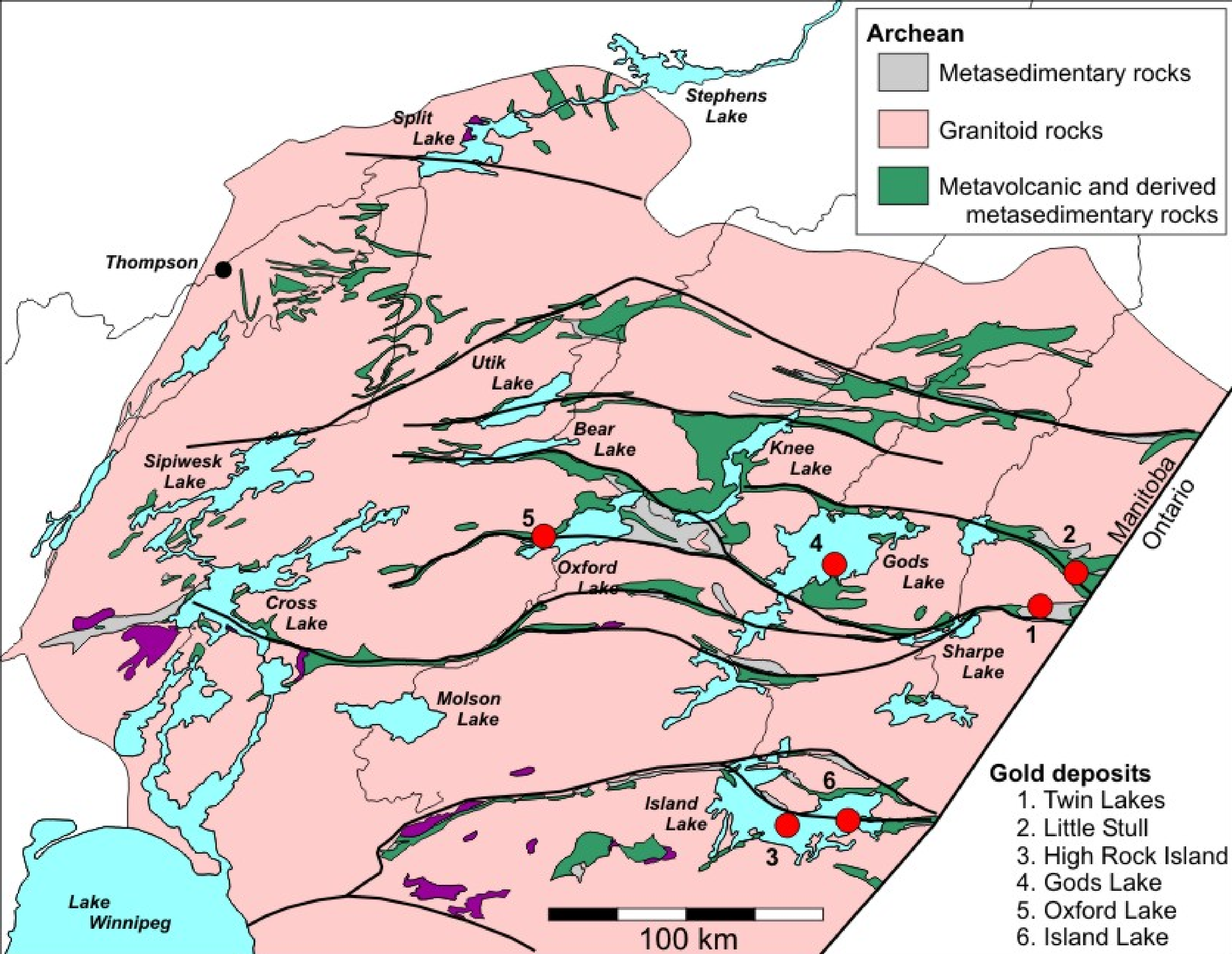
- significant diversity of styles. particularly for larger deposits

- nature, setting and style of mineralization indicate dominantly ‘orogenic’ gold

Superior Province of Manitoba: gold deposits



- 17 significant deposits (>5000 ounces Au)
- >5.3 million ounces discovered to date
- four main gold 'trends':
  - Oxford-Stull
  - Island Lake
  - Rice Lake
  - Lake of the Woods
- common affiliations:
  - greenstone terranes
  - crustal-scale faults



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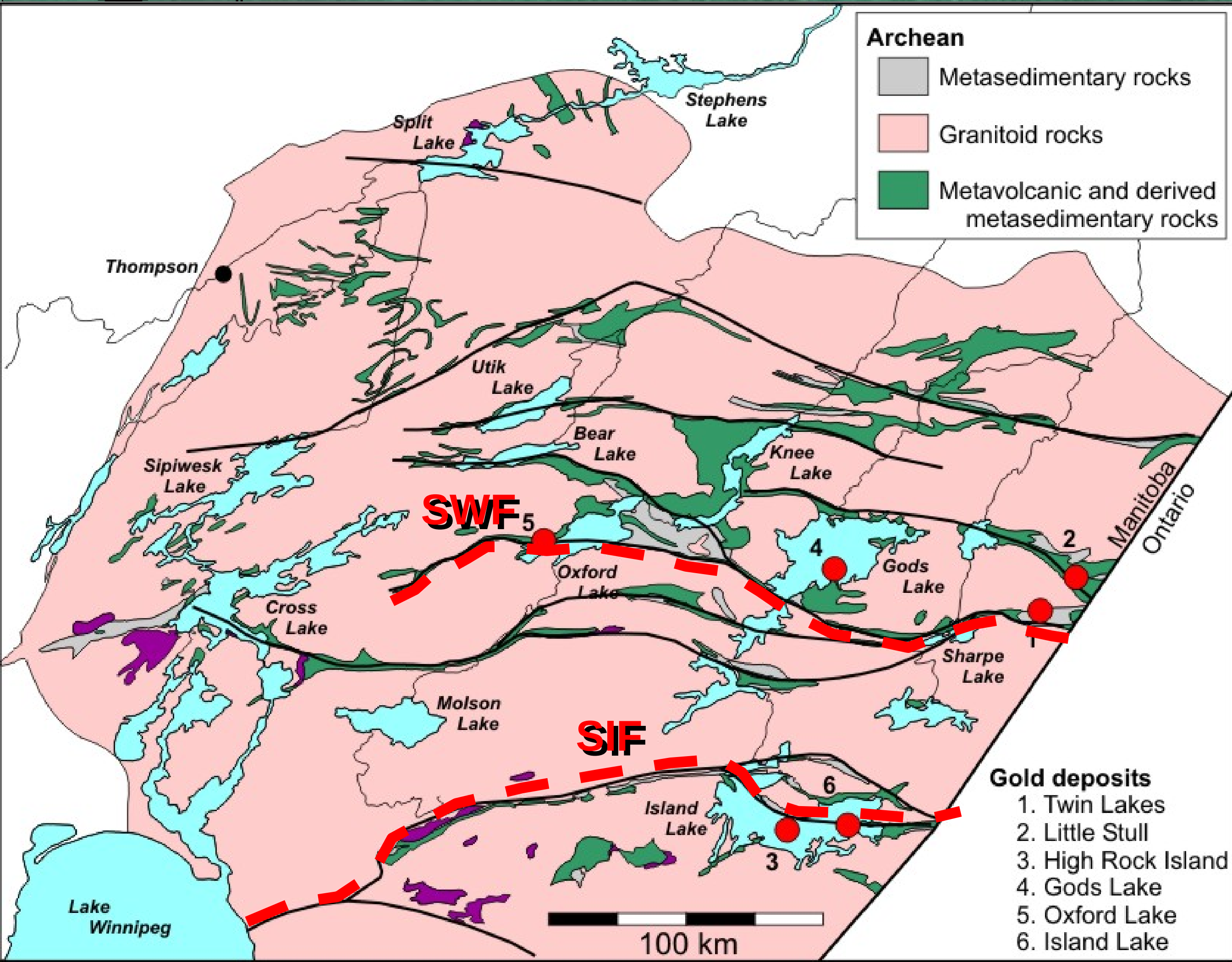
North margin NCT: gold deposits

- six significant deposits
- >1.9M oz. contained Au
- two past-producers

Deposit name	Discovery	Greenstone belt	Grade (oz./t)	Total Au (oz.)	Host-rock	Mineralization style	Sulphide mineralogy	Structure	Alteration
Twin Lakes	1989	Stull Lake	0.19	944,000	Felsic volcanic	QC veins, DS	as,py	SZ	sil,alb,ser,carb
Little Stull	1986	Stull Lake	0.33	248,000	Basalt, iron formation	QC veins	py,as	SZ	carb,sil,chl
High Rock Island	1934	Island Lake	0.35	165,000	Mafic volcanic, diabase	QC veins	py,cp,ga	SZ	chl,carb
Gods Lake	1932	Gods Lake	0.28	161,000	Chert, wacke, basalt	QC veins	po;py,as,ga,cp	SZ	sil
Oxford Lake	1986	Oxford Lake	0.18	154,000	Iron formation, wacke, basalt	QC veins, DS		SZ	sil,carb
Island Lake	1928	Island Lake	0.61	6,000	Greywacke	QC veins	py,po;ga,as,sp	SZ	sil,carb

1) Spatially associated with two crustal-scale faults

North margin NCT:
gold deposits



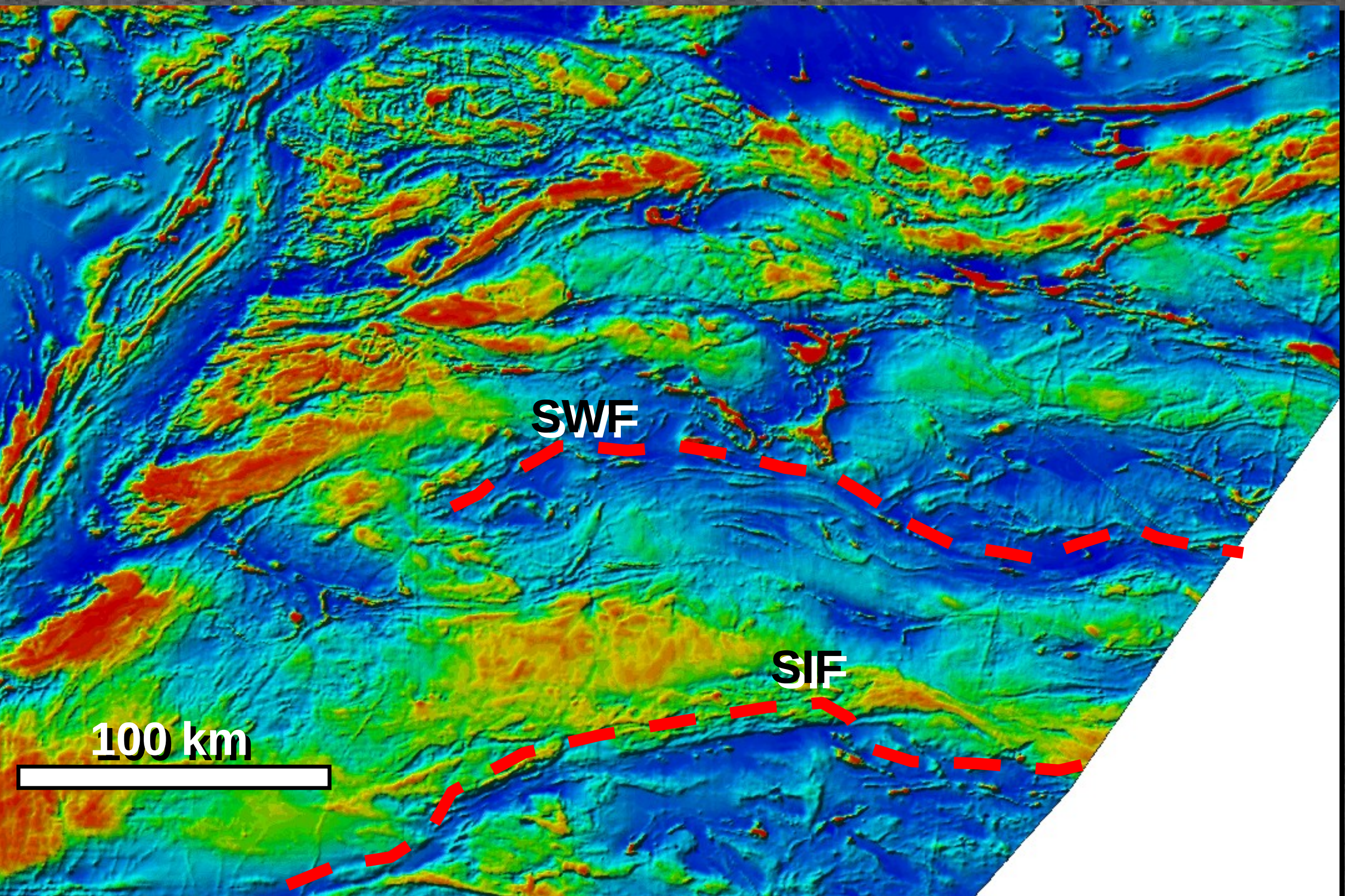
Stull-Wunnummin Fault
- Oxford-Stull terrane (north) (juvenile oceanic)
- Munro Lake domain (south) (evolved cratonic)

Savage Island Fault
- Island Lake domain (north)
- N.Caribou terrane (south) (continental arc?)

Two orogen-scale metallotects

North margin NCT: gold deposits

1) Spatially associated with two crustal-scale faults



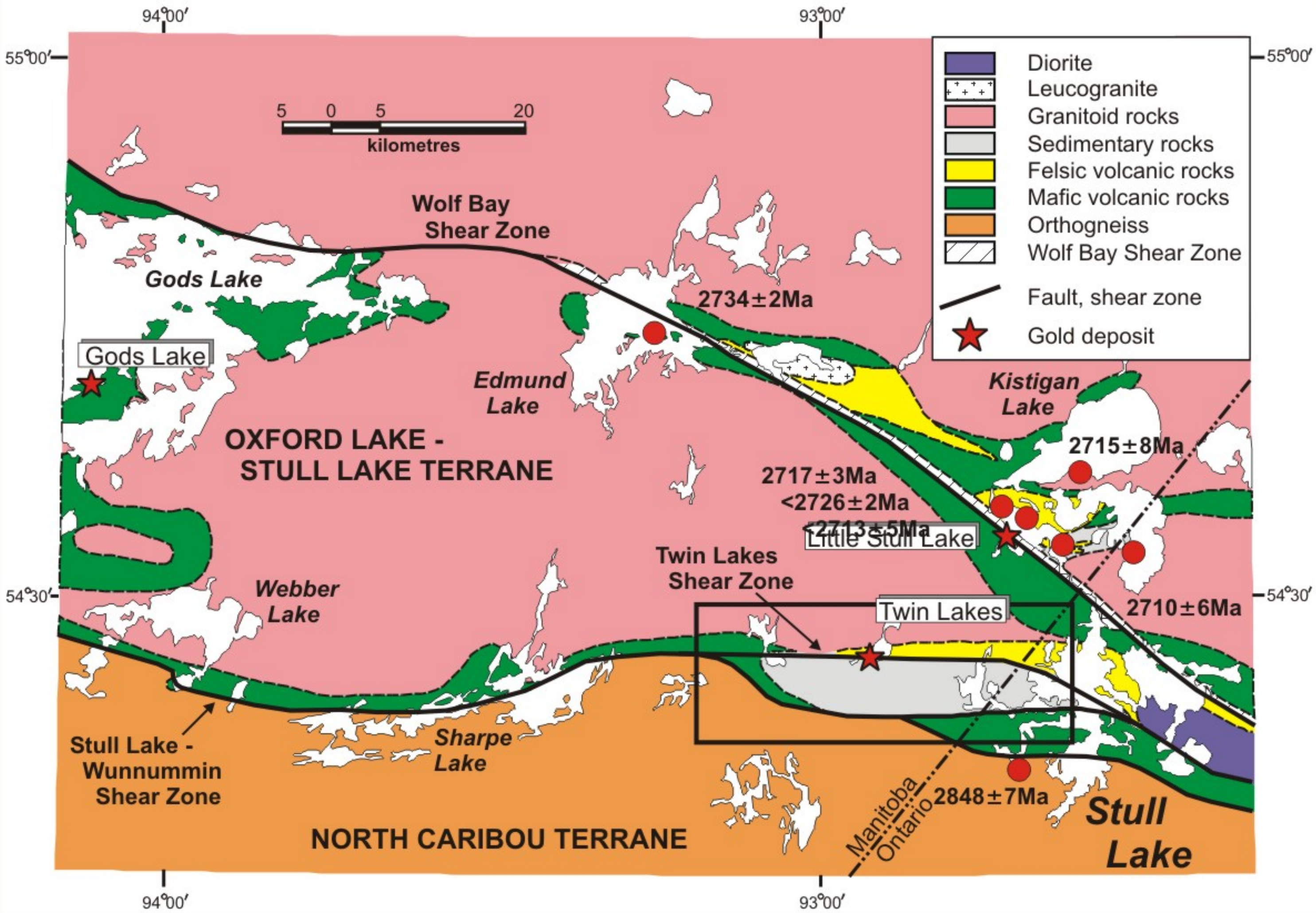
Stull-Wunnummin Fault
- Oxford-Stull terrane (north) (juvenile oceanic)
- Molson domain (south) (evolved cratonic)

Savage Island Fault
- Molson domain (north)
- Island Lake (intracratonic rift?)

- two major metallotects identified to date

2) At least two distinct styles of mineralization

North margin NCT:
gold deposits



Main-stage orogenic:

('Twin Lakes type')

- hosted by major shear zones or first-order splays

2) At least two distinct styles of mineralization

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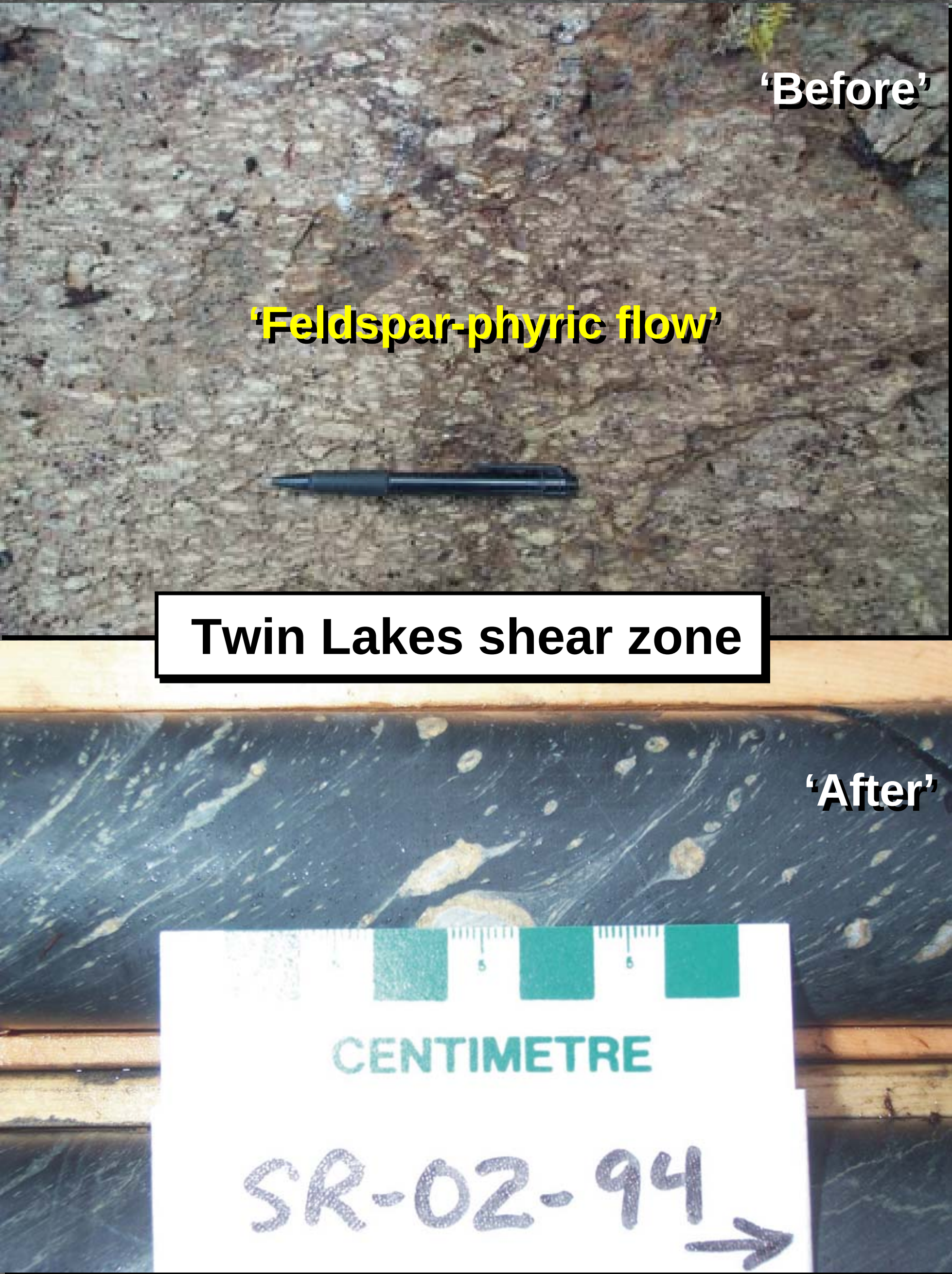

North margin NCT:
gold deposits

Main-stage orogenic:
('Twin Lakes type')
- **hosted by major shear zones or first-order splays**

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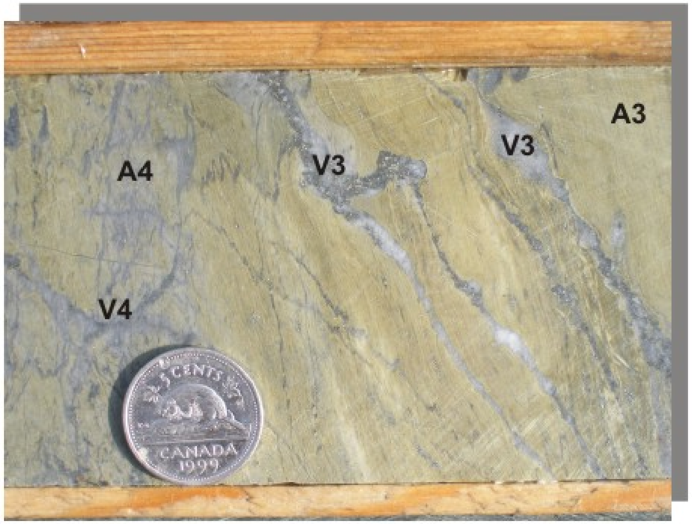
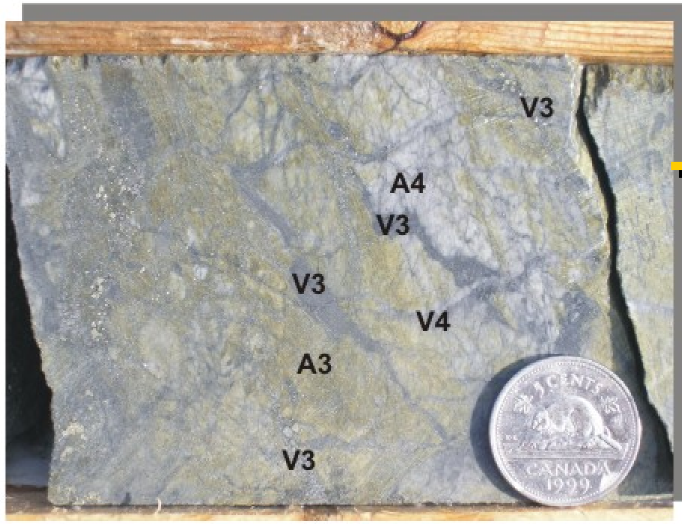
Twin Lakes deposit: mineralization

Main-stage orogenic:
('Twin Lakes type')
- hosted by major shear zones or first-order splays
- evidence of synkinematic emplacement…

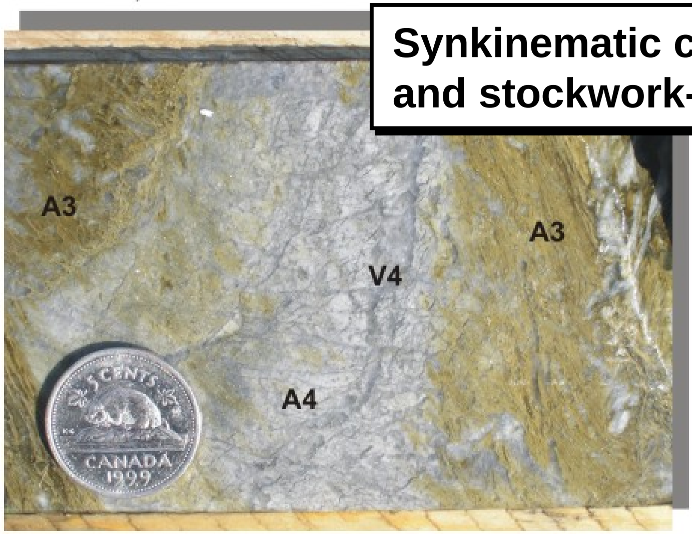


Transposed quartz-ankerite-arsenopyrite veins (V3) cutting strongly foliated sericite-ankerite-albite alteration (A3). Note the weak mauve alteration (A4), with well-developed stockwork quartz veins (V4). TL-04-190, 266.4 m. A-zone.

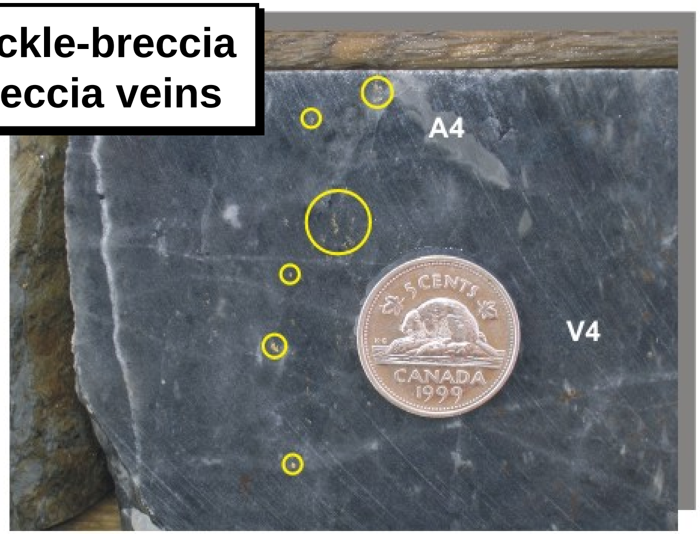


Multiphase stockwork of quartz-ankerite-arsenopyrite (V3) and quartz (V4) veins cross-cutting proximal sericite-ankerite-albite (A3) and mauve quartz-albite alteration (A4). TL-04-190, 266.1 m. A-zone.

Synkinematic crackle-breccia and stockwork-breccia veins

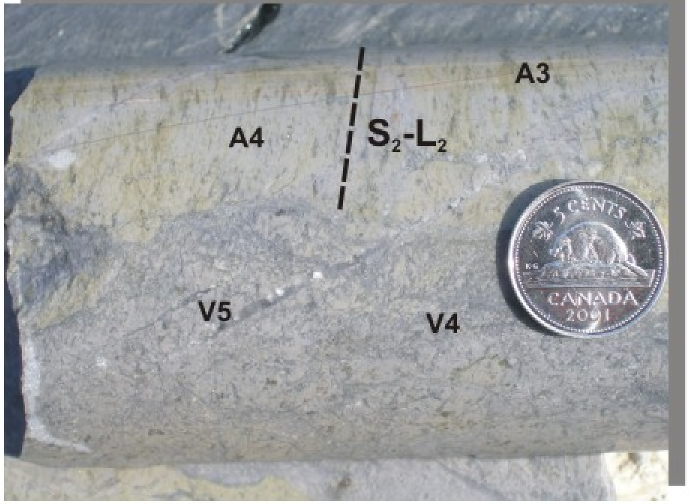


Discrete zone of mauve quartz-albite alteration (A4), overprinting sericite-ankerite-albite alteration (A3). A4 alteration contains well-developed stockwork quartz veins (V4). Note that the V4 stockwork is transposed into the sericite foliation. TL-04-190, 396.3 m. C-zone.



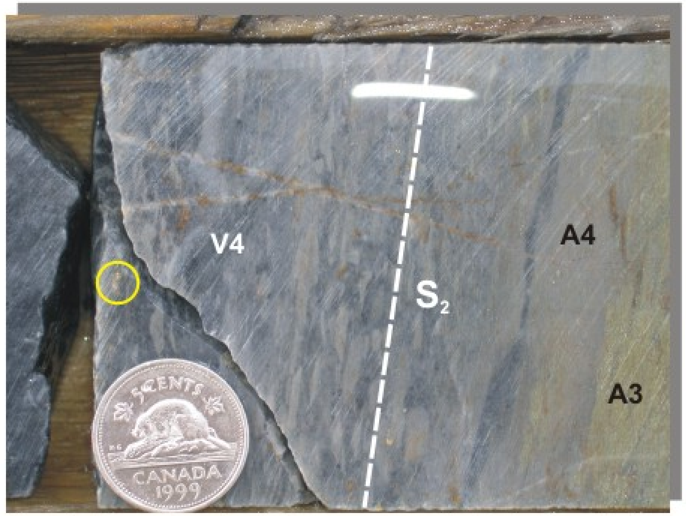
Very high-grade quartz breccia vein (V4), containing coarse visible gold (circled) and angular fragments of quartz-albite alteration (A4). GSC-04-05, 110.2 m. B-zone.

Twin Lakes deposit:
timing of mineralization

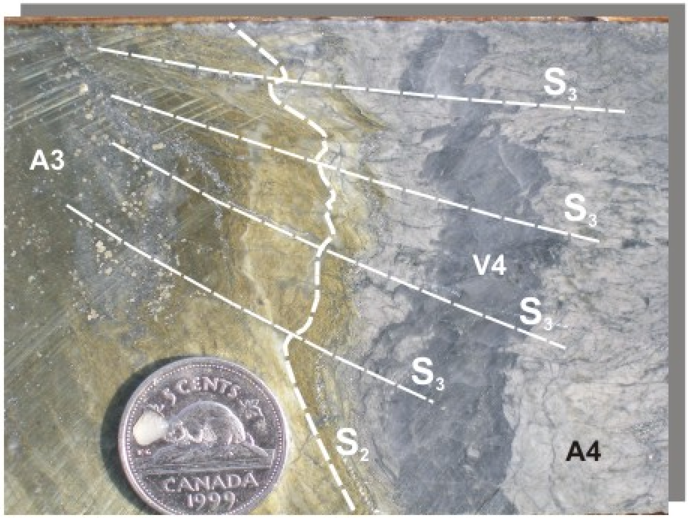


Penetrative S_2-L_2 fabric in altered wallrock (A3 - A4), overprinted by micro-stockwork quartz veins (V4) and late quartz-calcite tension gashes (V5). TL-04-190, 333.7 m. B1-zone.

Late- to post-D_2 mineralization.

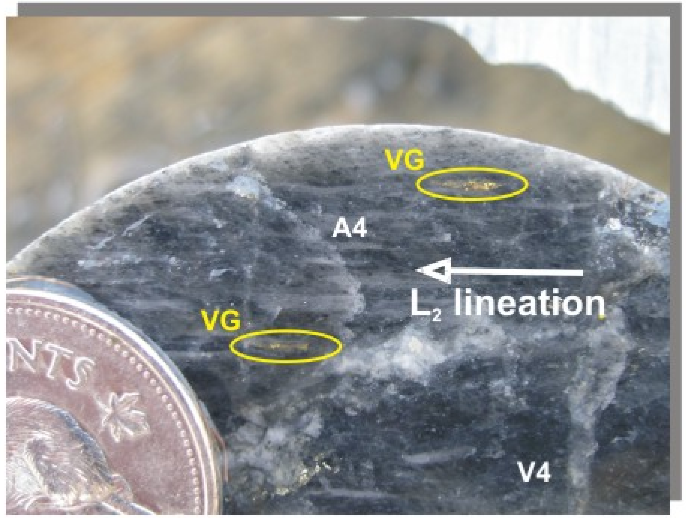


Quartz breccia vein (V4; coarse gold circled), which contains a strong S_2 foliation defined by inclusions of mauve quartz-albite alteration (A4). GSC-04-05, 110.5 m.



Open F_3 folds and spaced S_3 crenulation cleavage overprinting the upper contact of the A-zone (V4-A4) and the S_2 foliation. TL-04-190, 265.3 m.

Pre-D_3 mineralization.



S_2 foliation plane in the quartz breccia vein (V4), showing L_2 lineation defined by elongate inclusions of mauve quartz-albite alteration (A4) and grains of coarse gold (VG). GSC-04-05, 110.5 m.

Pre- or syn-D_2 gold mineralization.

Main-stage orogenic:

('Twin Lakes type')

- hosted by major shear zones or first-order splays
- evidence of synkinematic emplacement… …with significant structural overprint

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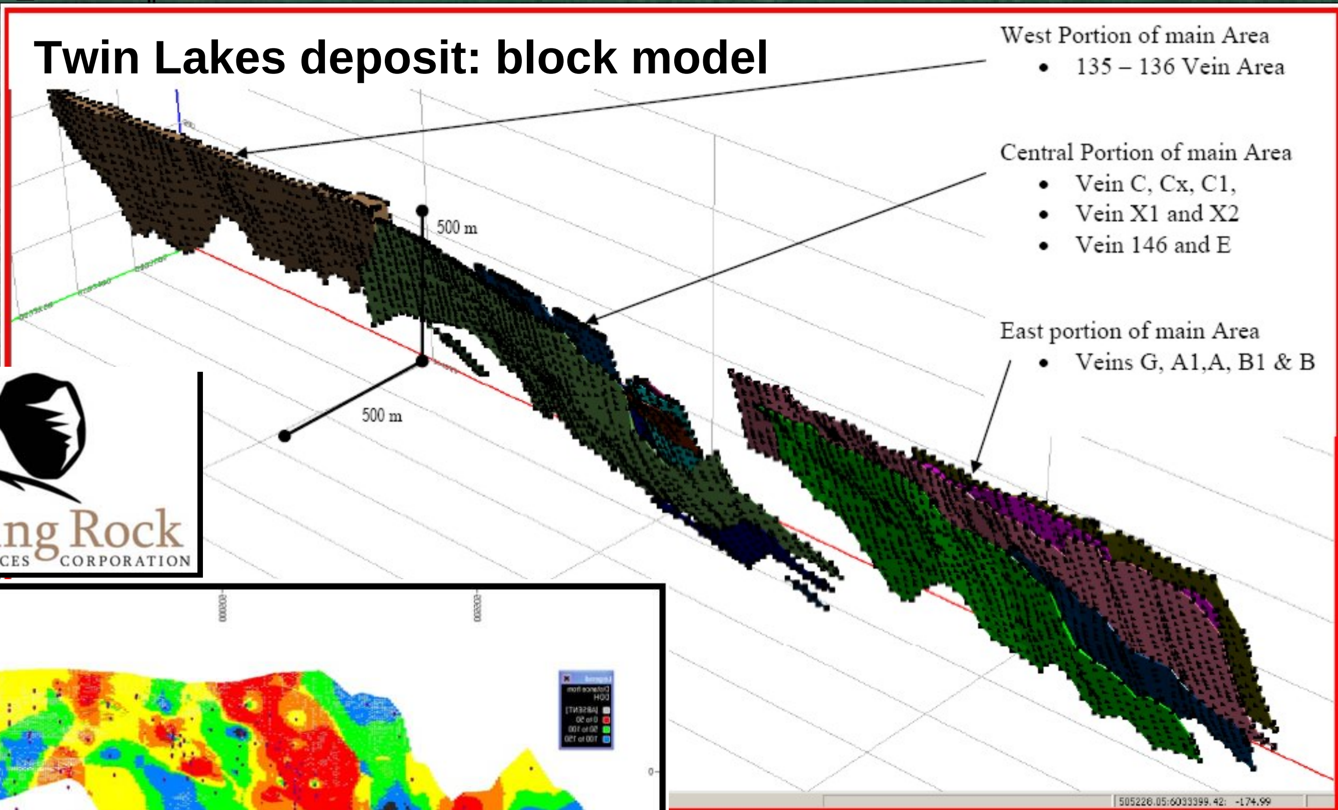
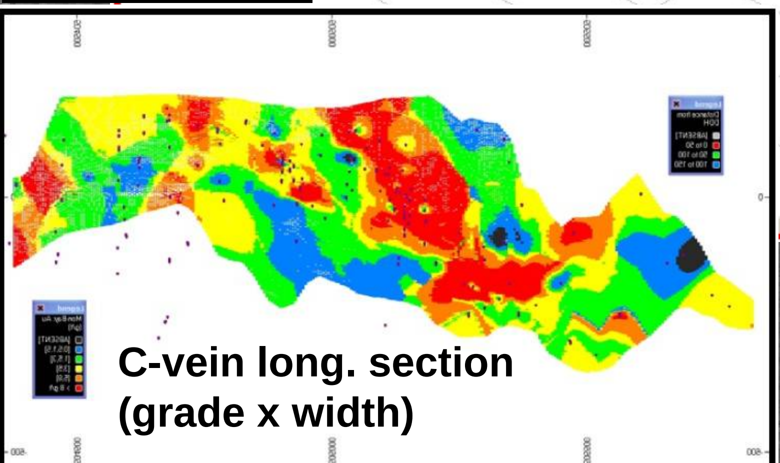
Twin Lakes deposit:
timing of mineralization





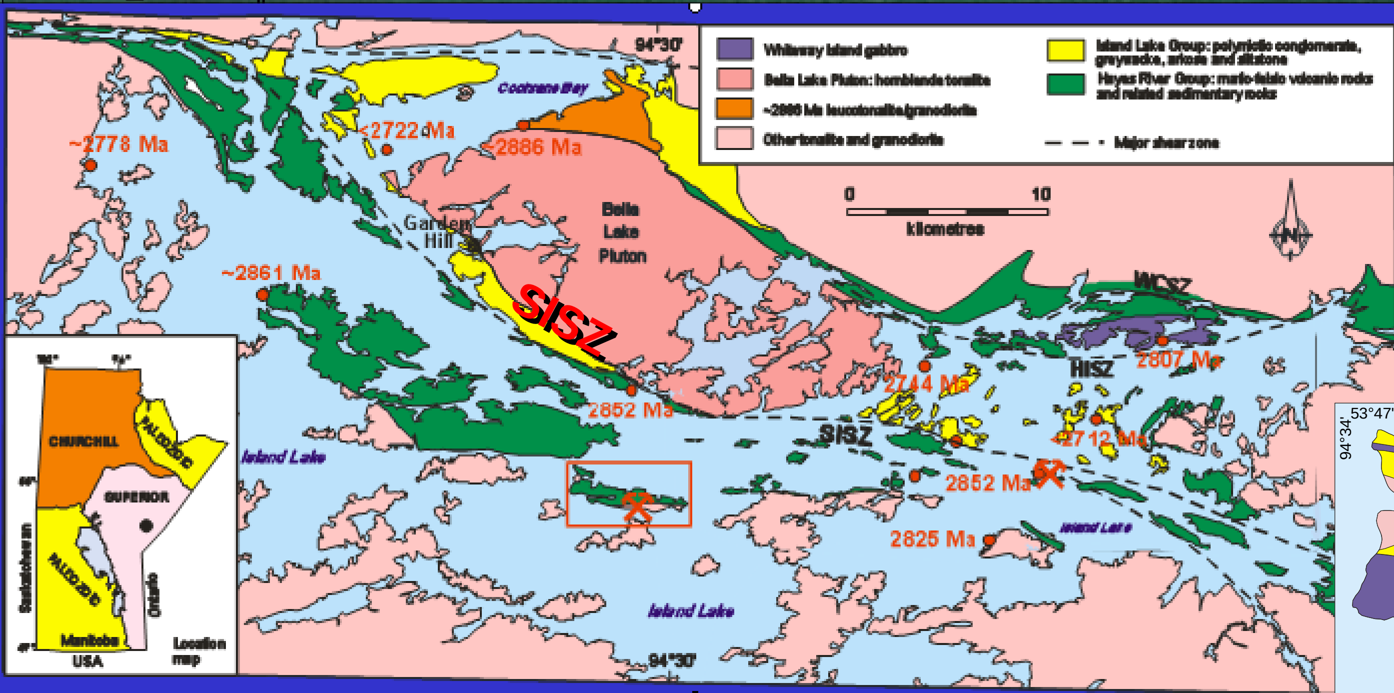
Twin Lakes C-vein

Main-stage orogenic:
('Twin Lakes type')

- hosted by major shear zones or first-order splays
- evidence of synkinematic emplacement… …with significant structural overprint
- complex geometry

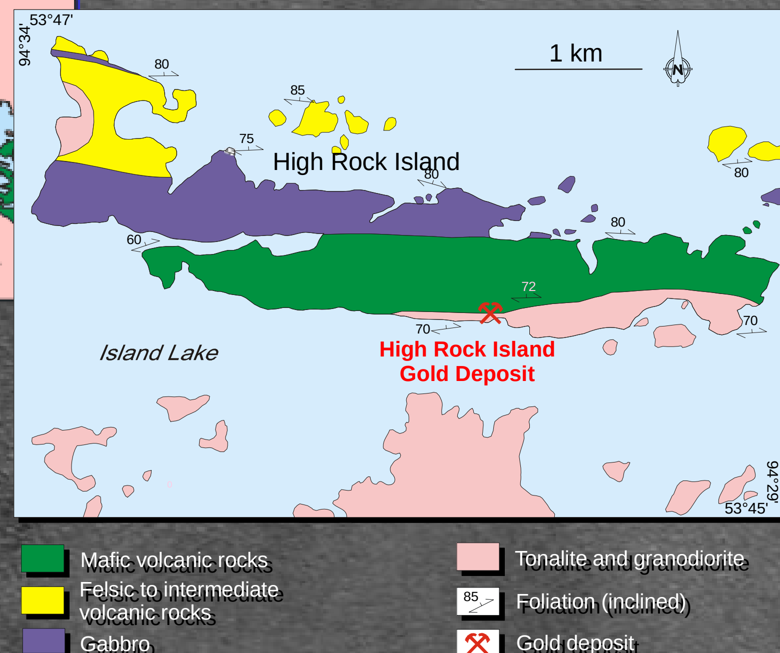
2) At least two distinct styles of mineralization

North margin NCT: gold deposits



Lin and Corfu, 2002; Econ. Geol., v. 97, p. 43-57.

Late-stage orogenic:
('High Rock Island type')
- peripheral to major shear zones or first-order splays



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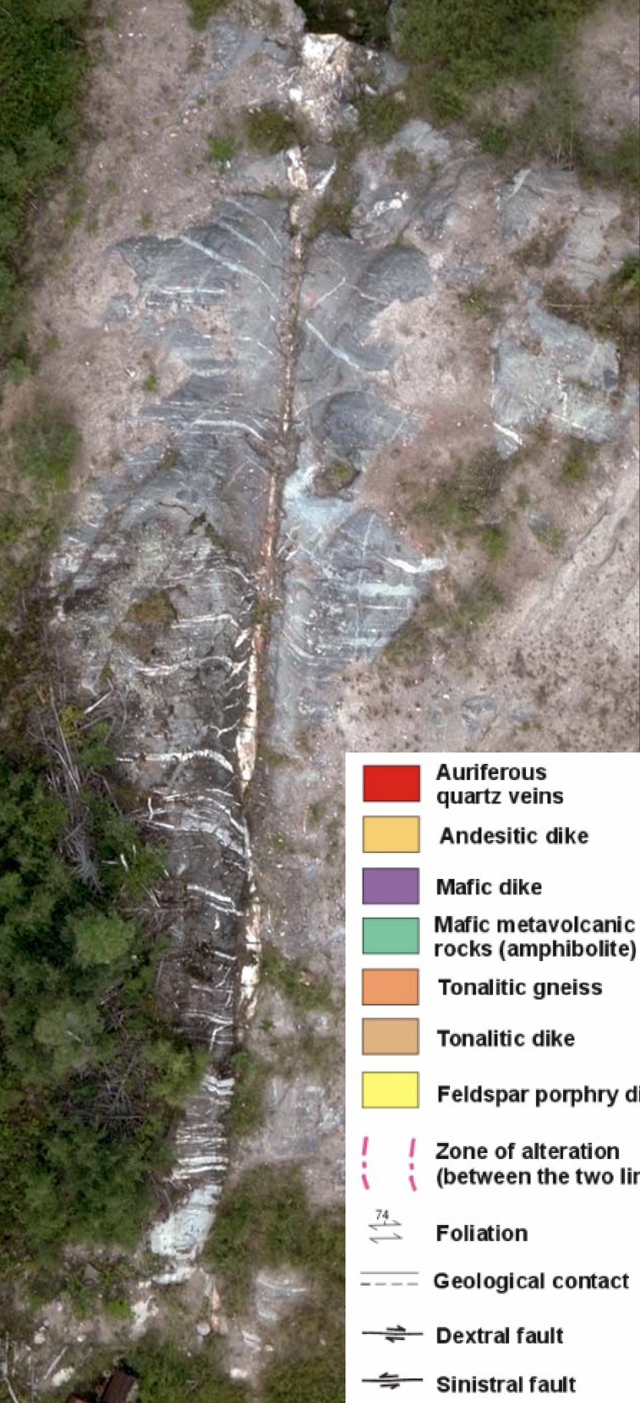
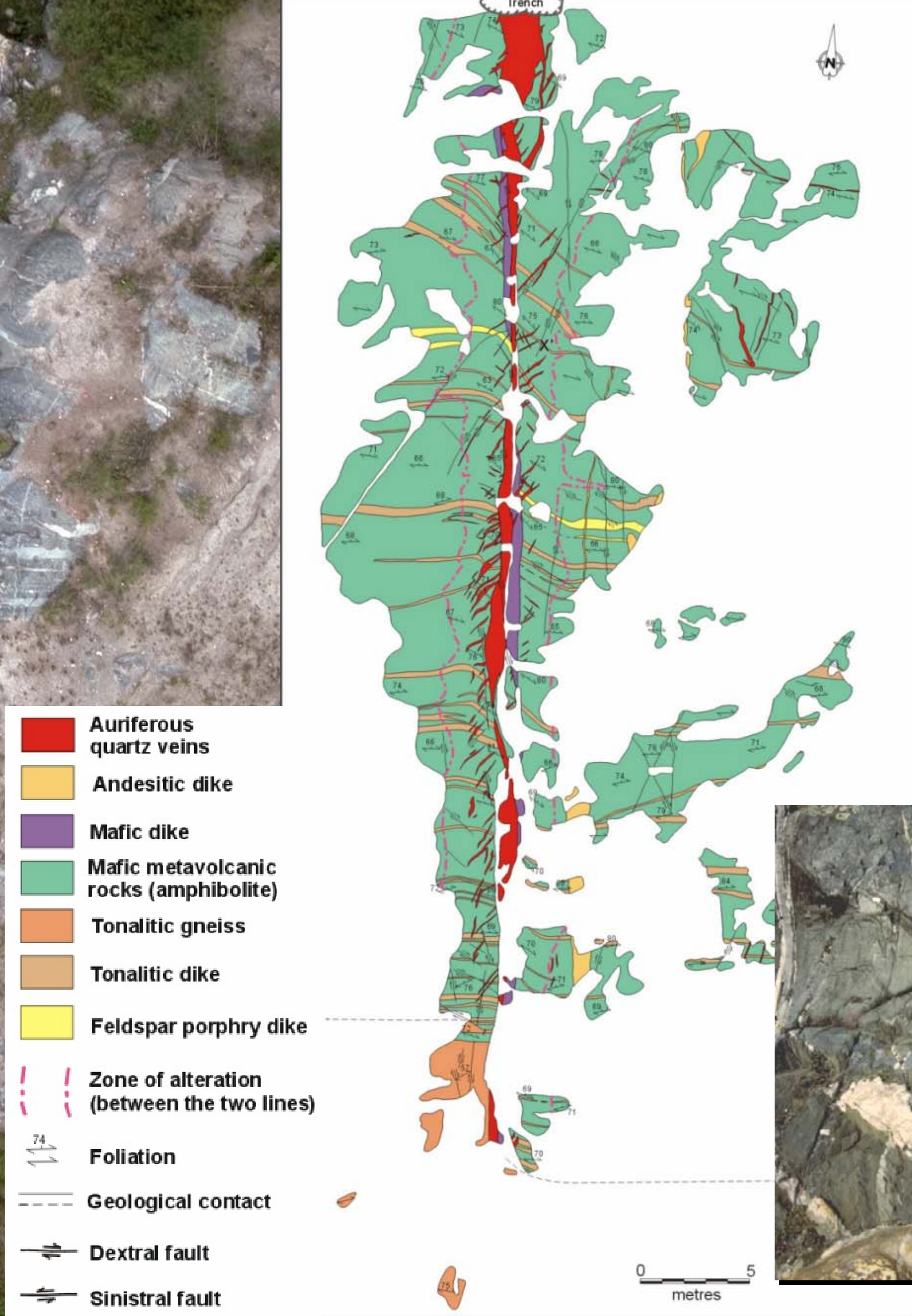
North margin NCT: gold deposits





<u>**Late-stage orogenic:**</u>

('High Rock Island type')

- **peripheral to major shear zones or first-order splays**
- **post-date main-phase structures in wall-rock**

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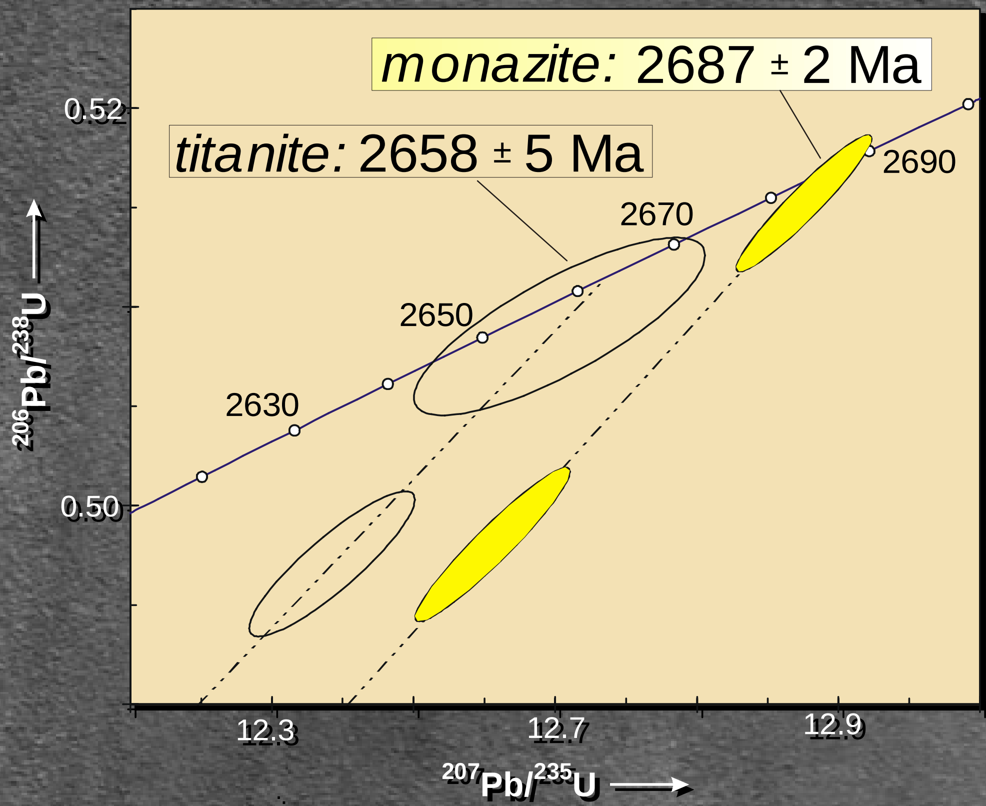
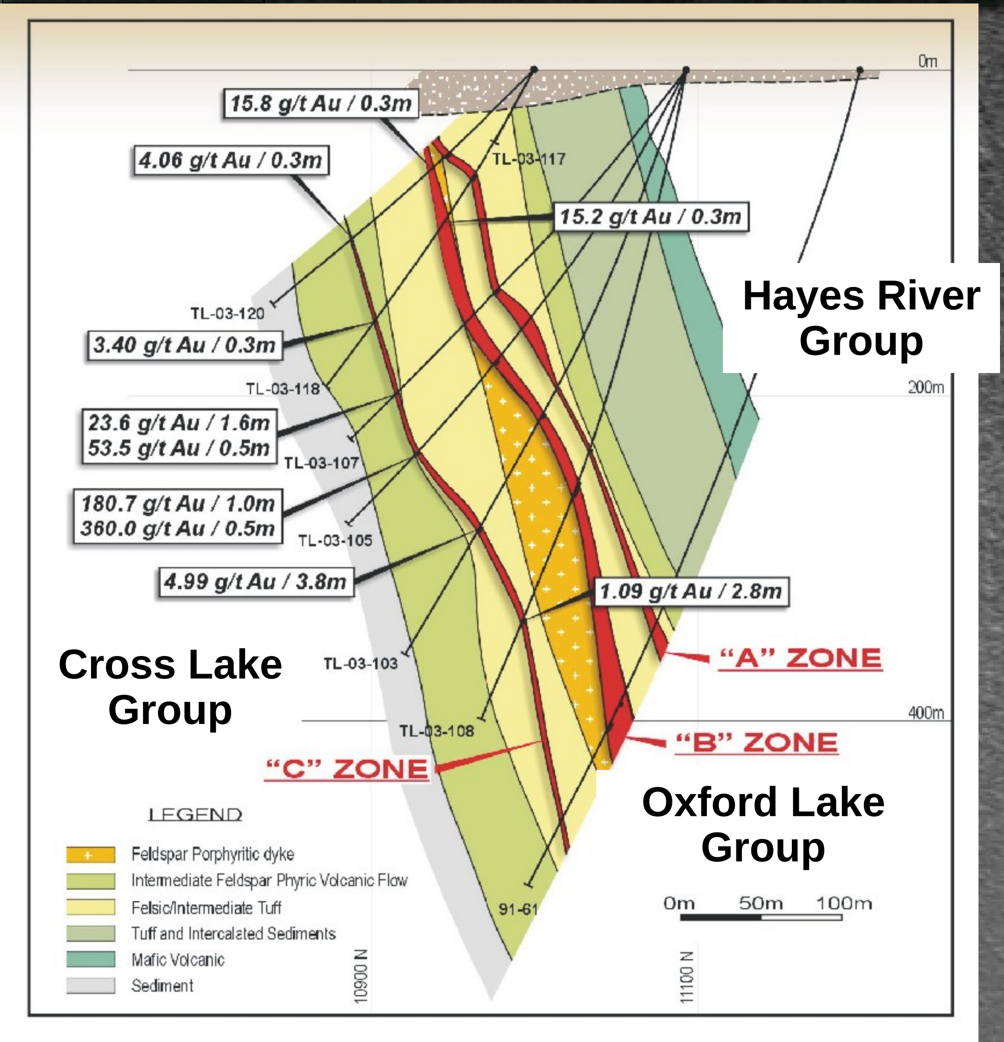
High Rock Island:
absolute age of mineralization



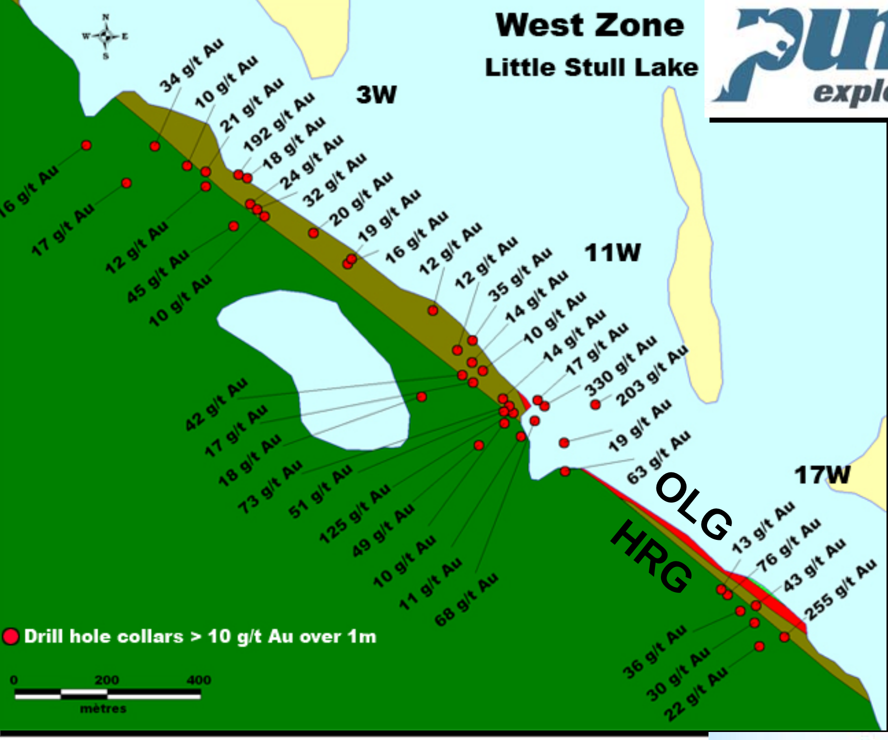
- U-Pb geochronology on titanite and monazite from vein quartz
- ca. 2687 Ma monazite: emplacement of the 'main vein' (± Au)
- ca. 2658 Ma titanite: reactivation, Au mineralization

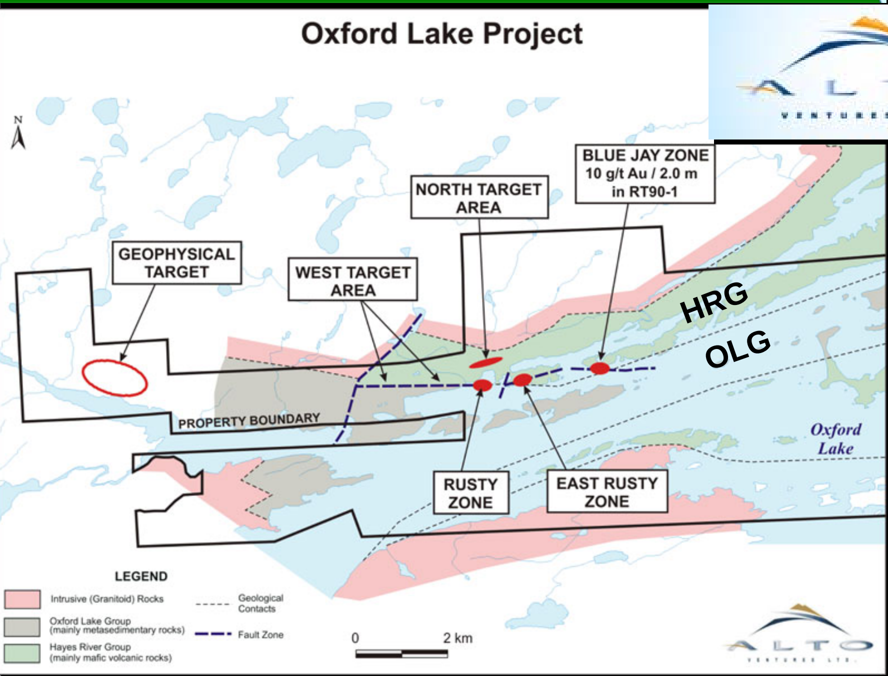
3) Recurring stratigraphic affiliation

North margin NCT:
gold deposits



- significant gold deposits occur at interface between pillowed basalt and orogenic sedimentary rocks
- contact traditionally mapped as contact between ca. 2.83 Ga 'Hayes River Group' and <2.707 Ga 'Cross Lake Group'
- contact zone occupied by distinctive lithostratigraphic association:
  - felsic volcanic-volcaniclastic rocks;
  - syn-volcanic felsic dikes;
  - intermediate porphyry flows;
  - iron formation
- locally dated at ca. 2.72 Ga – 'Oxford Lake Group'





North margin NCT:
gold deposits

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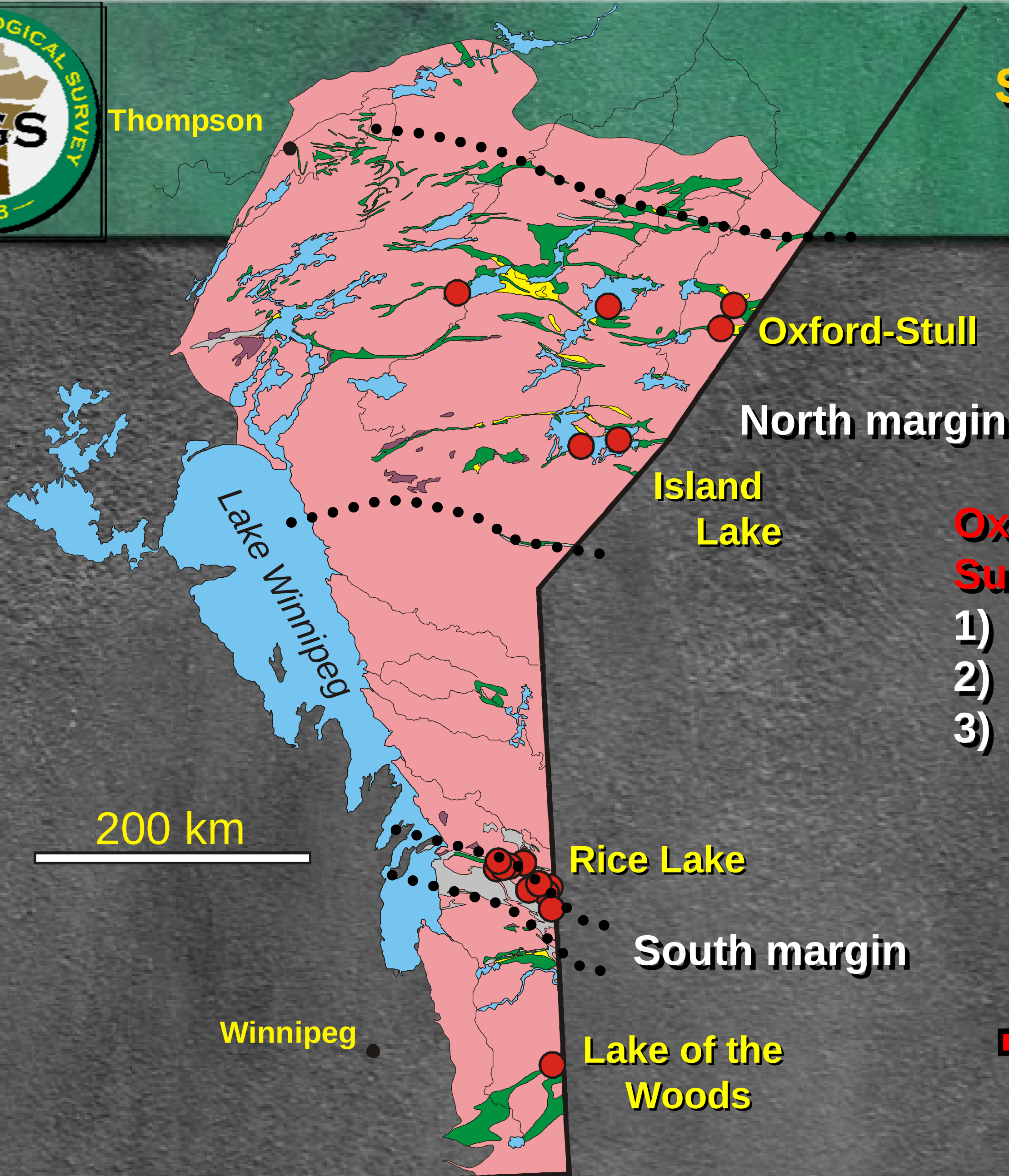
- locally dated at ca. 2.72 Ga – 'Oxford Lake Group'

Possibly reflects strain localization in response to pronounced competency contrasts and strength anisotropy in OLG

Superior Province of Manitoba: gold deposits



Oxford-Stull and Island Lake Summary:

1) Association with SWF and SIF
2) Syn- and late-kinematic Au
3) Recurring affiliation with OLG at HRG- CLG interface

Four main gold 'trends':

- Oxford-Stull
- Island Lake
- Rice Lake
- Lake of the Woods

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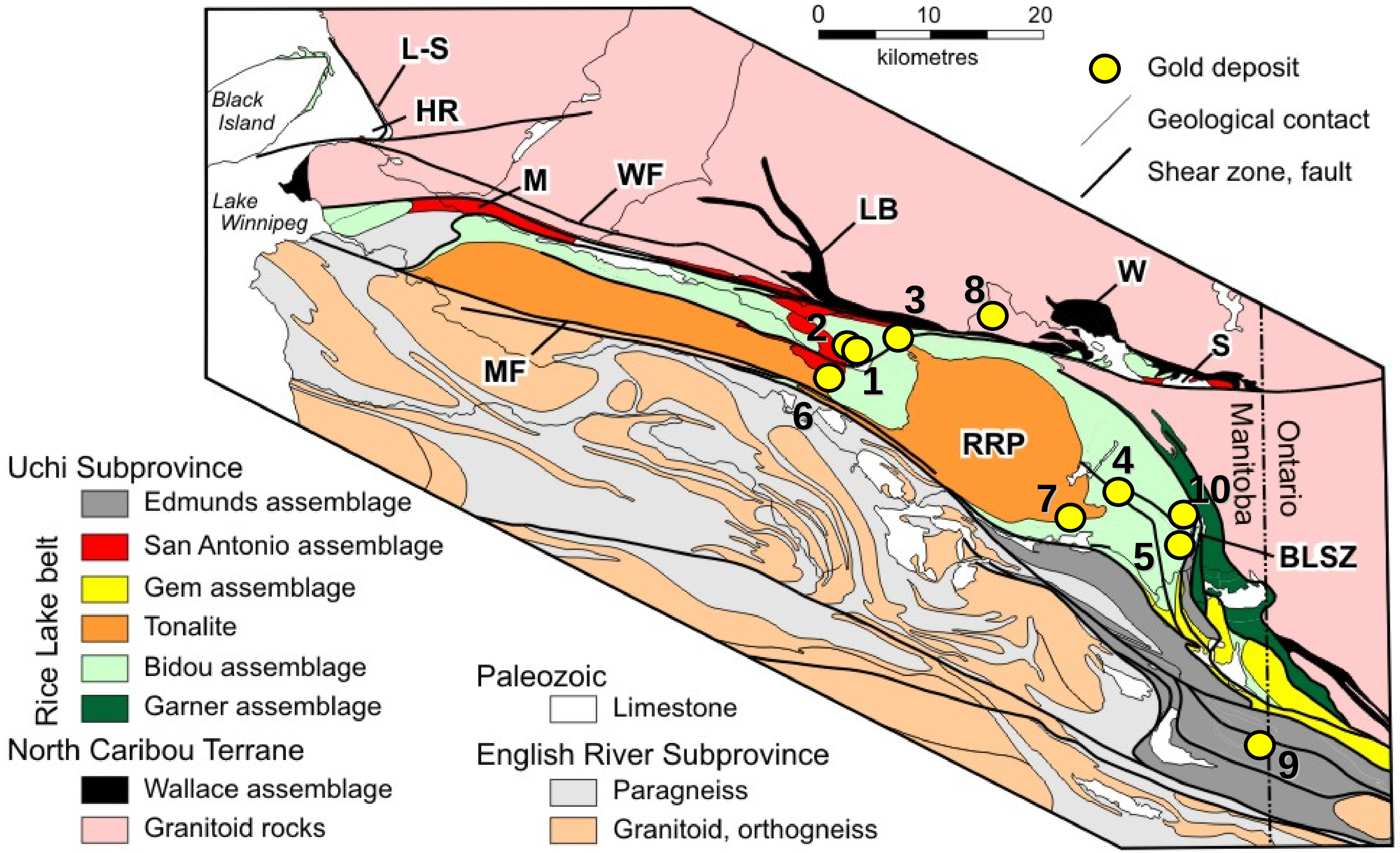
Gold deposits: Rice Lake belt



- 10 deposits
- >3.4M ounces contained Au
- two producers: Rice Lake and SG#1
- seven past-producers
- uniform characteristics

	Deposit	Discovery	Grade (oz./t)	Total Au (oz.)	Host-rock	Mineralization style	Sulphide mineralogy	Structure	Alteration
1	Rice Lake (San Antonio)	1911	0.28	2,264,000	Gabbro	QC veins, DS	py; ga,cp,sp	SZ; STWK-BX	carb,ser,ab,sil,chl
2	Cartwright	1911	0.22	419,000	Gabbro	QC veins	py	SZ	ser,carb,sil
3	San Gold #1	1944	0.22	269,000	Felsic volcanic, basalt	QC veins, DS	py	SZ	ser,carb,sil
4	Central Manitoba	1915	0.35	138,000	Chert, wacke, basalt	QC veins, DS	py,cp,po	SZ	sil,ser,carb
5	Gunnar	1921	0.38	100,000	Basalt, QFP	QC veins	py,cp;sp,ga	SZ	sil,ser,carb
6	Packsack	1917	0.30	90,000	Felsic volcanic	QC veins	py;cp	SZ	chl,carb
7	Ogama-Rockland	1915	0.33	57,000	Tonalite	QC veins	py,cp;po,sp	SZ	sil,ser,carb
8	Jeep	1934	0.76	14,000	Gabbro	QC veins	py,as	SZ	carb,chl
9	Diana	1926	0.33	8,000	Gabbro, basalt	QC veins	py,cp,po,ga	SZ	chl,carb
10	Solo-Oro Grande	1919	0.33	5,000	Gabbro, basalt	QC veins	py,cp,sp,po	SZ	chl,carb

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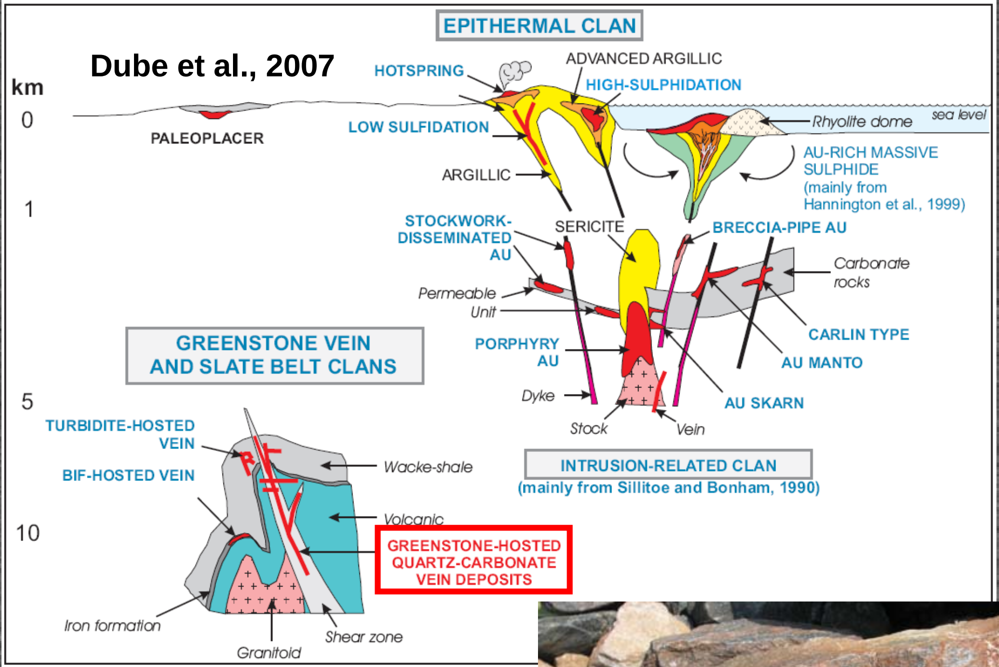
Rice Lake belt

- first discovery of gold in Manitoba (1911)
- several significant deposits
- Rice Lake and SG-1 mines (San Gold Corp.)
- Rice Lake deposit >2.3 million ounces Au (production + reserves, resources)

RLB gold mineralization:
general characteristics

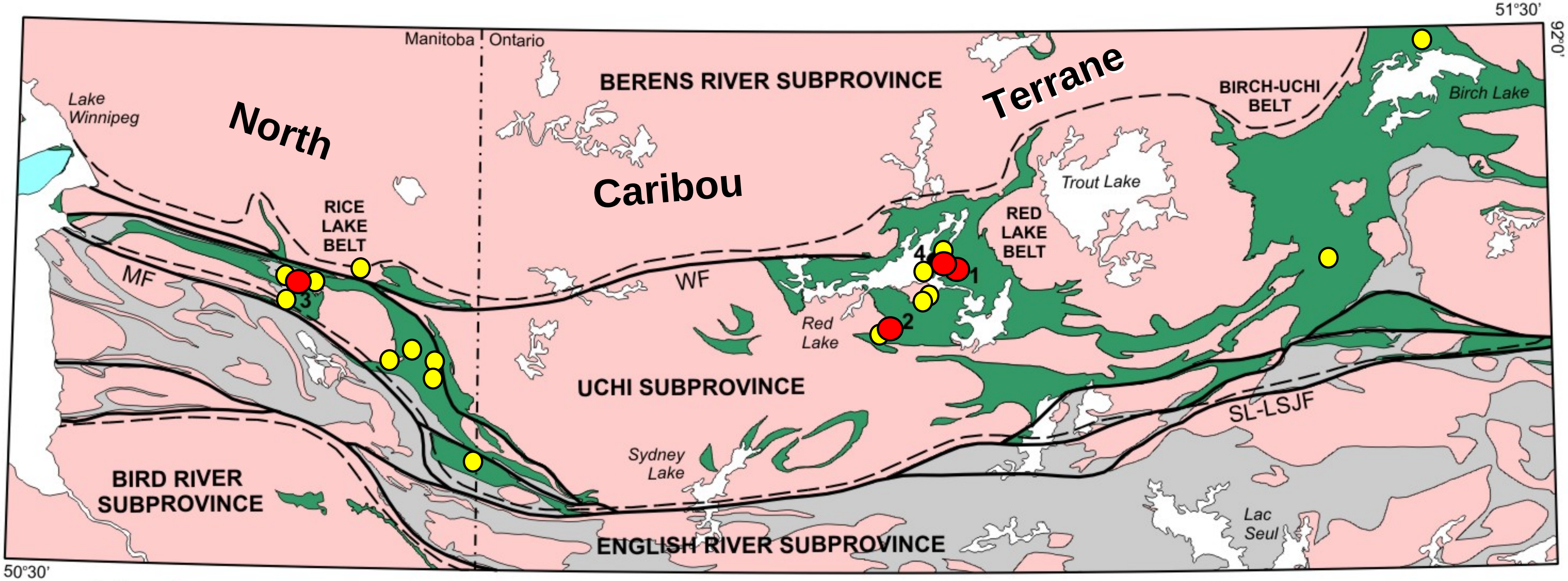


AKA: ‘Mesothermal’
‘Shear-hosted’
‘Mother-lode’
‘Orogenic’

- quartz-carbonate veins
- shear zone or fracture control
- quartz, subordinate carbonate (ank>cal), albite, chlorite, sericite
- low sulphide content (<5%)
- pyrite; other sulphides negligible
- free gold, assoc. with pyrite
- high Au:Ag (>5:1)
- low base metals and pathfinder elements (e.g., As, Bi, B, Sb, W)
- narrow, zoned wall-rock alteration
  proximal: ankerite-albite-sericite-pyrite
  distal: chlorite-calcite
- evidence of wall-rock sulphidation
- considerable depth extent (>2 km), yet negligible variation (RLM)

1) Largest deposits associated with crustal-scale Wanipigow Fault

South margin NCT: Uchi Subprovince



Paleozoic
- Limestone, sandstone

Archean
- Metasedimentary rocks
- Granitoid rocks
- Metavolcanic and derived metasedimentary rocks

0 — 100 kilometres

Major fault/deformation zone

Subprovince boundary

Gold deposits (>1 million oz. Au)
1. Campbell - Red Lake
2. Madsen
3. Rice Lake (San Antonio)
4. Cochenour - Willans

Gold deposits (>5000 oz. Au)

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2) Largest deposits (Red Lake, Madsen, Rice Lake) exhibit significant diversity…. ….a cautionary tale for model-driven exploration

South margin NCT: Uchi Subprovince

	Rice Lake	Red Lake	Madsen
Host sequence	Gabbro, felsic volcaniclastic rocks	Basalt, komatiite, rhyolite	Basalt, komatiite, gabbro
Host-rocks	Gabbro	Basalt	Pillowed and fragmental basalt
Host-rock chemistry	Transitional tholeiitic-calcalkalic	Fe-tholeiitic	Fe-Tholeiitic
Host-rock age	ca. 2.72 Ga	2.99-2.96 Ga	2.99-2.96 Ga
Mineralization style	Fault-fill, stockwork and breccia quartz-carbonate veins	Colloform-crustiform ankerite veins and replacements	Stratabound, disseminated, replacements
Gangue (non-sulphide)	Quartz, carbonate, albite, sericite, chlorite	Ankerite, quartz	Andalusite, amphibole, biotite, garnet, quartz, calcite
Gangue (sulphide)	Pyrite	Arsenopyrite	Pyrrhotite, pyrite, arsenopyrite
Alteration assemblage	Ankerite-albite-sericite-pyrite	Ankerite-biotite-arsenopyrite	Andalusite, garnet, staurolite, biotite, chloritoid, amphibole
Chemical signature	weak As,Cu,Pb	strong As±Sb	strong As±Zn,Sb,Cu,Hg
Coeval intrusions	None known	Lamprophyre dikes	None known
Mineralization age	<2.705 Ga	>2.712 (main stage) (Dube et al., 2004)	<2.744 Ga; >2.699 Ga (Dube et al., 2000)

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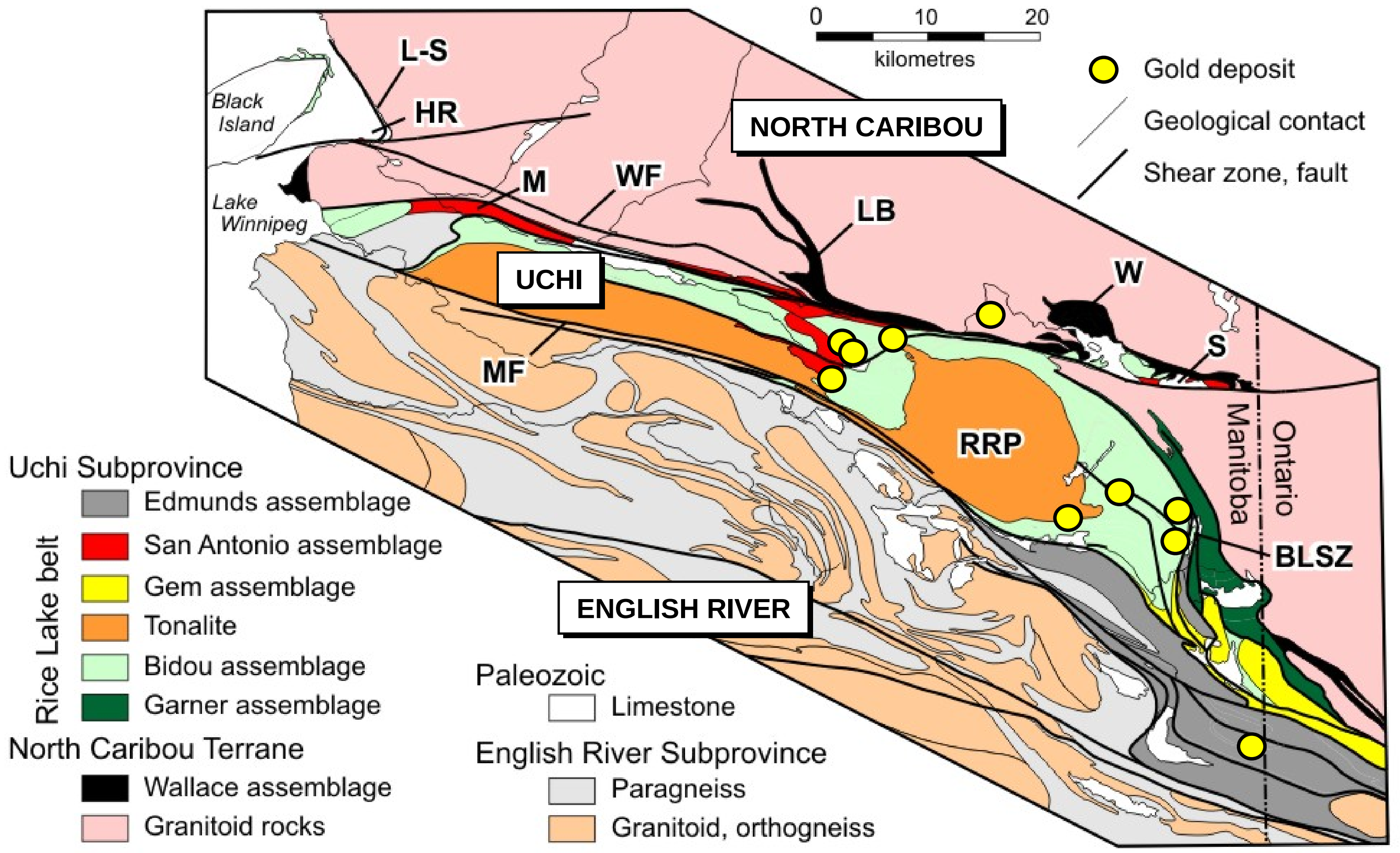
MGS

3) Rice Lake belt deposits cluster around margins of the Ross River Pluton… …but proximity does not indicate genesis

South margin NCT: Uchi Subprovince



Several authors have proposed genetic link between RRP and Au

(e.g., Cooke, 1922; Reid, 1931; Wright, 1932; Stockwell, 1940)

But…

At odds with field relationships, style of mineralization, and structural timing

RLB gold mineralization:
style

- brittle-ductile shear zones
- shear and tensile fracture arrays
- competent rock types, with strength anisotropies
- shear-hosted veins – massive, laminated and brecciated
- evidence of ‘fault-valve’ (Sibson et al., 1988) behaviour
- extension-vein stockworks – intensify into hydraulic breccia
- subhorizontal extension veins

- high degree of structural control
- synkinematic vein emplacement
- brittle-ductile (mid-crustal) conditions
- high fluid pressure (transiently supralithostatic)

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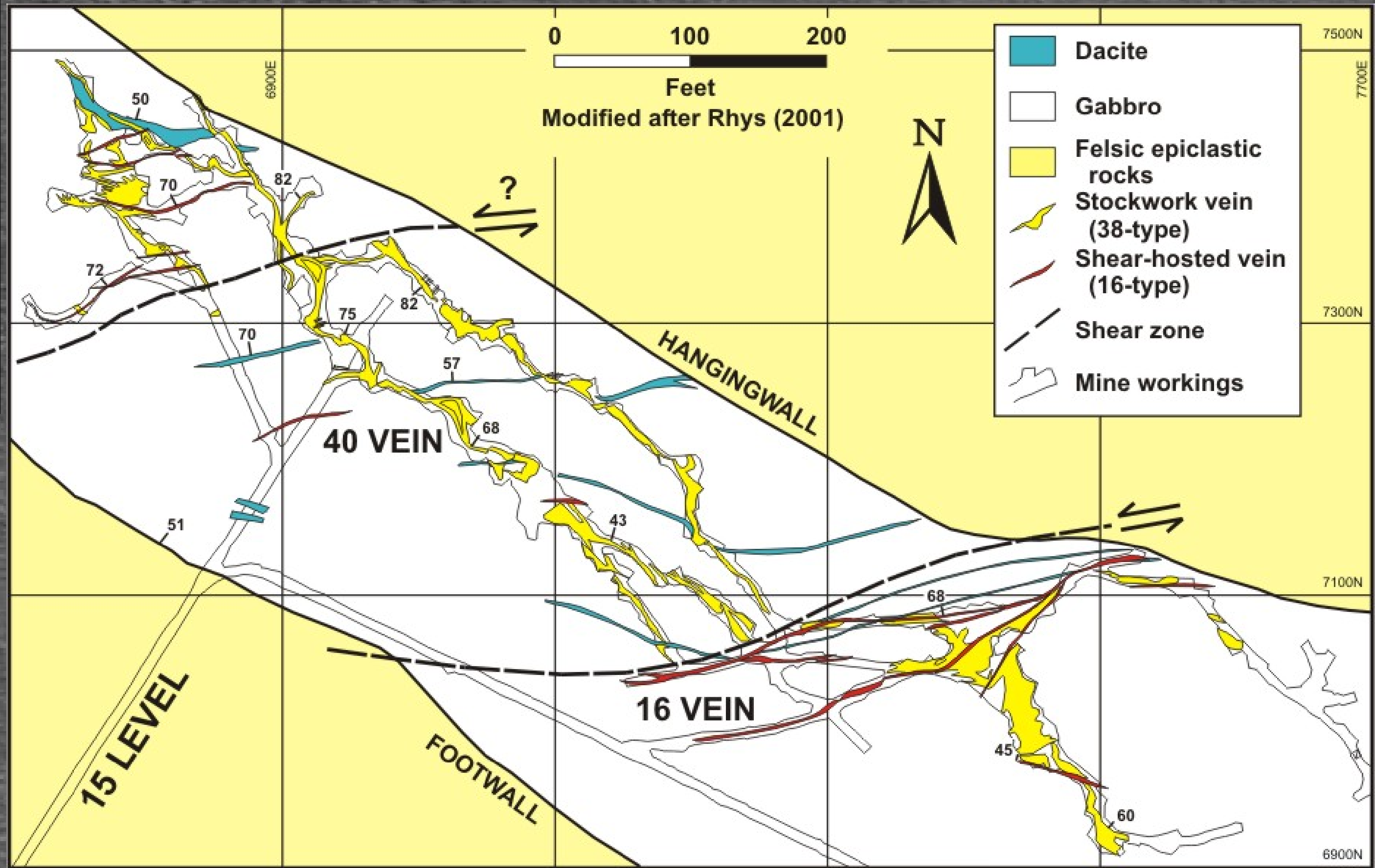
Rice Lake mine: styles of mineralization

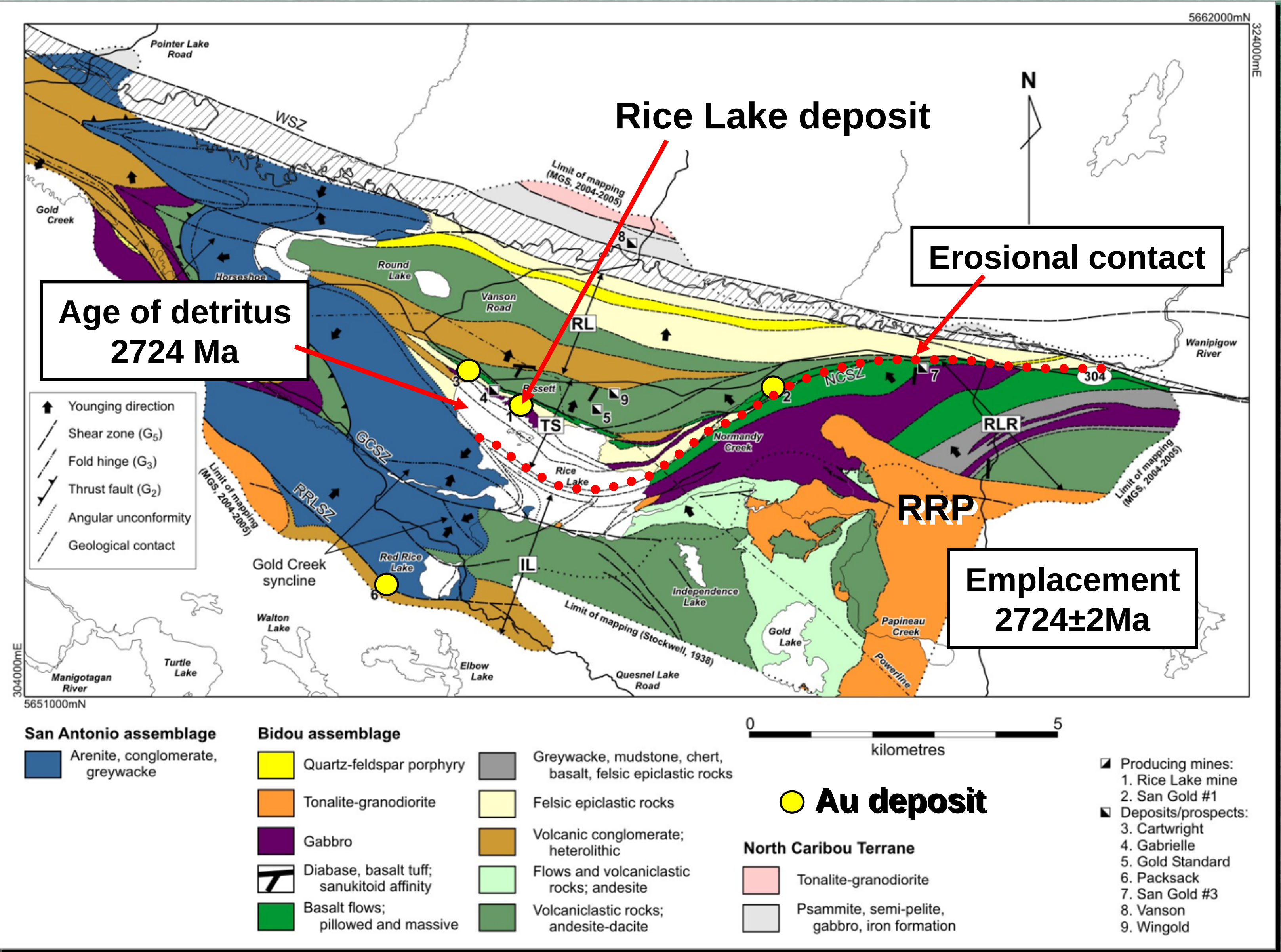
- Gold mineralization hosted by two distinct types of vein within the differentiated 'SAM' sill
- High degree of structural control
- Brittle-ductile conditions, with high-fluid pressures
- Alteration overprints regional g.schist assemblage (Ames, 1988; Ames et al., 1991)

Stockwork-breccia vein
3098W

Fault-fill vein
3096E



Local geology: Rice Lake area



Deposit genesis constrained by field relationships and U-Pb zircon geochronology

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4) Orogenic model provides best explanation for Au deposition in the Rice Lake belt

Rice Lake belt: summary of deformation

Generation	Shortening direction[a]	Mesoscopic structure	Macroscopic structure	Deformation episode and inferred tectonic significance
G_1	?	Penetrative to finely-spaced S_1 foliation in phyllite fragments in clastic dikes	Synvolcanic subsidence structures (normal faults)	D_1 : arc-extension; initiation of back-arc spreading?
	?	None observed	Early tilting of the Bidou assemblage	D_2 : arc-accretion and back-arc basin inversion?
G_2	?	Local, weak, layer-parallel S_2 foliation in San Antonio assemblage	Thrust fault at top of San Antonio assemblage	D_3 : basin inversion; continued accretion and/or initial crustal thickening
G_3	NNE-SSW	Regional WNW-trending S_3; steep L_3 stretching lineation; upright F_3 folds	Macroscopic folds (HLA, GCS); sinistral-reverse shear in WSZ	D_4 : collisional tectonics; crustal thickening
G_4	NW-SE	Regional, WSW-trending, S_4 crenulation cleavage; F_4 Z-folds		Early-D_5 : onset of terminal collision; dextral transpression
G_5	NNW-SSE	Regional S_5 shear-band cleavage; mylonitic S_5 in NW-trending high-strain zones; shallow L_5 lineation; F_5 Z-folds	Main-stage dextral shear in WSZ and subsidiary zones; coaxial flattening in NCSZ	Main-D_5 : terminal collision; dextral transpression
G_6	E-W	Open, north-trending F_6 crenulations	Open fold in the Bidou assemblage at Rice Lake	Late-D_5 : butress effect on Ross River pluton; continued dextral transpression

Abbreviations: GCS, Gold Creek syncline; HLA, Horseshoe Lake anticline; NCSZ, Normandy Creek shear zone; WSZ, Wanipigow shear zone

[a] inferred trend of maximum principal far-field stress axis; based on *present* orientation of associated fabric elements

- structures indicate complex sequence of deformation
- belt geometry mainly reflects regional D_4 and D_5

D_4

D_5

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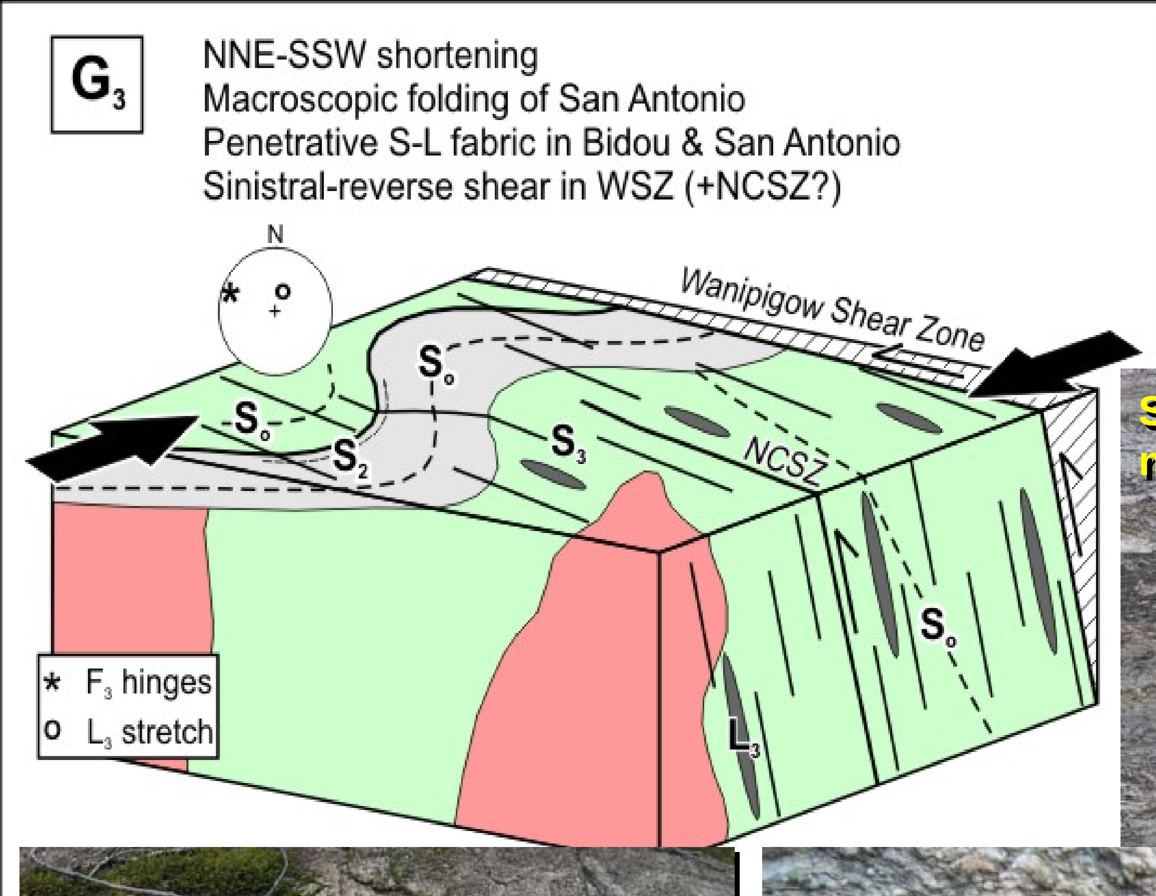
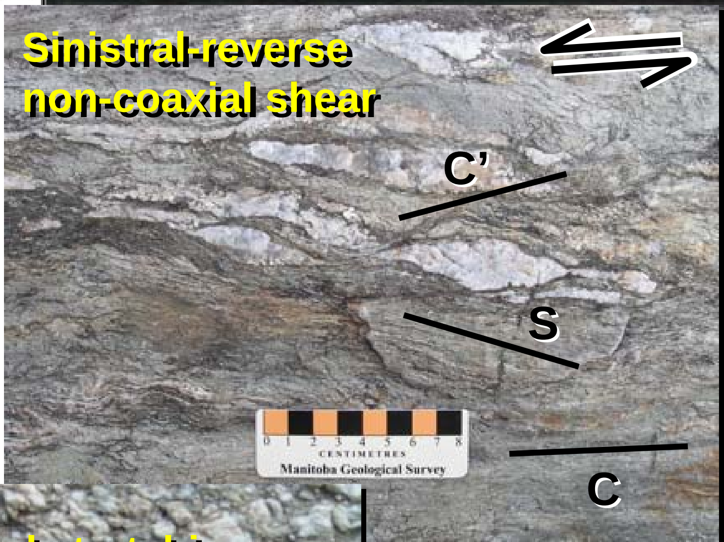
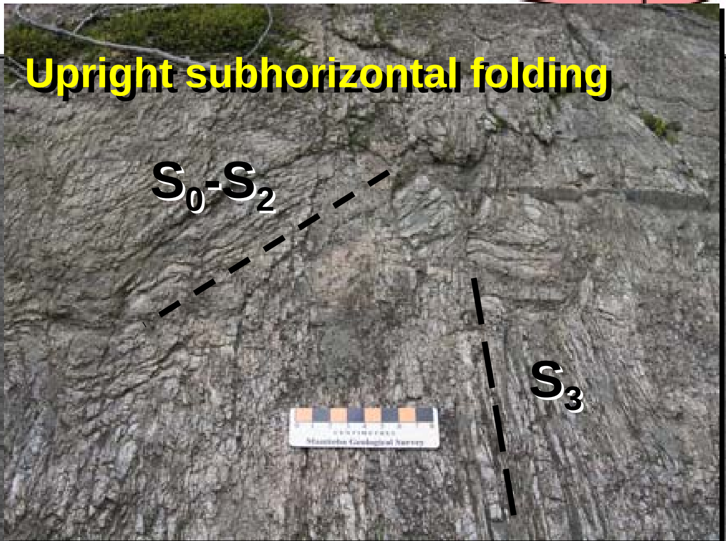
D_4 deformation
sinistral transpression
(ca. 2.69-2.68 Ga?)







- first 'regional' deformation
- greenschist-facies regional metamorphism
- NE-SW shortening strongly partitioned in three distinct macroscopic domains

Crustal thickening

RLB gold mineralization:
kinematic framework

Section view (looking east)

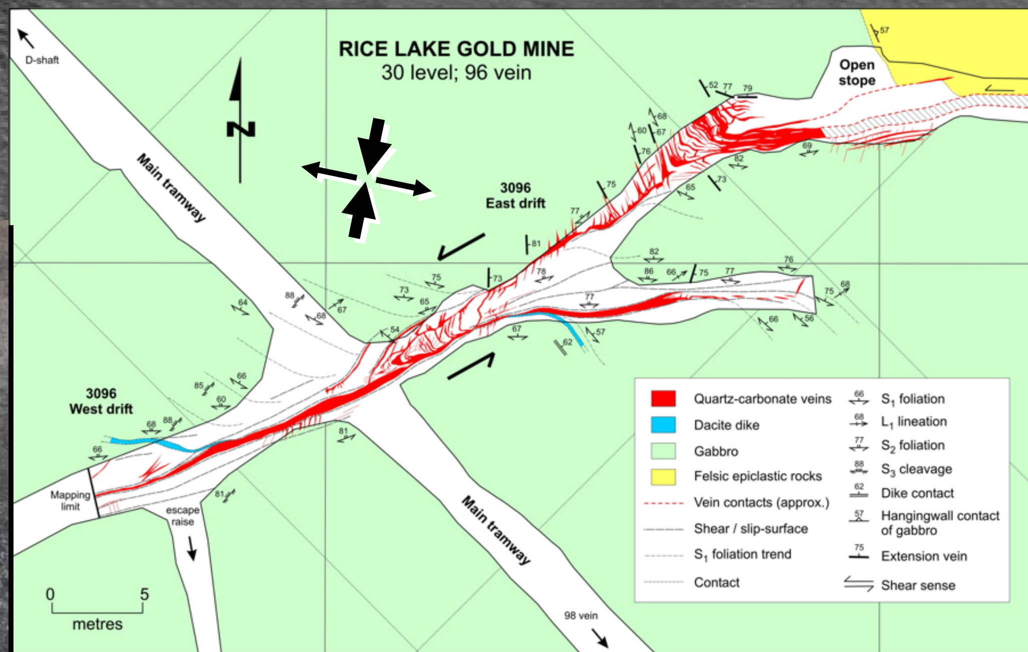
- subhorizontal σ_1
- subvertical σ_3
- supralithostatic P_f

- far-field NE-SW, subhorizontal shortening (*see also* Davies, 1953; Lau, 1988; Lau and Brisbin, 1996; Brommecker, 1991)

Plan view

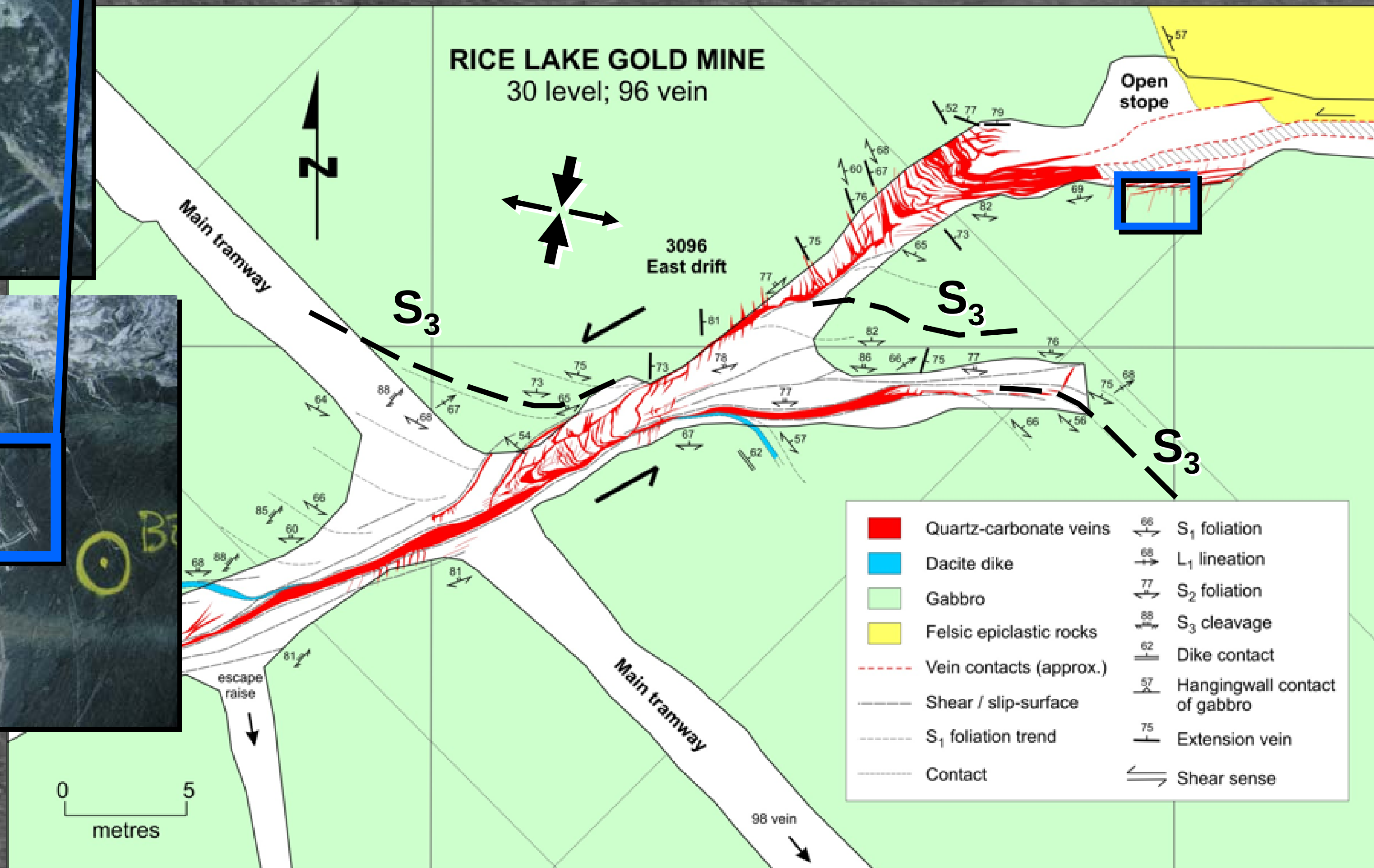
Pencils point north

- near-field σ_1 roughly NNE-SSW



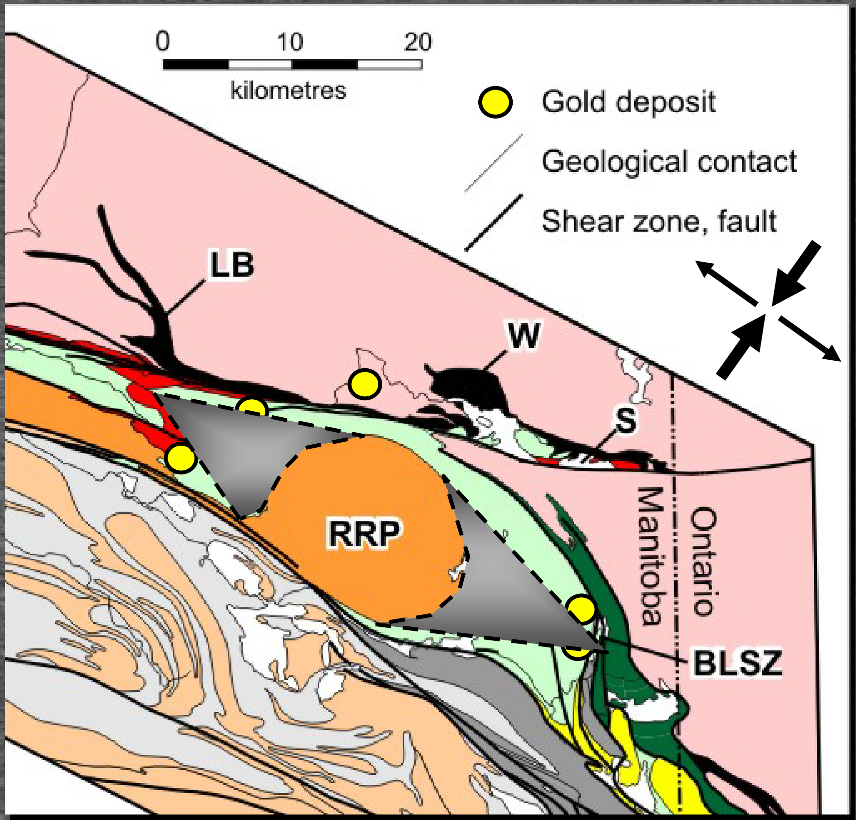
RLB gold mineralization:
late D_4 structural timing

- post-dates at least initial increments of regional D_4
- post dates arc magmatism by >10 million years
- precludes syngenetic Au



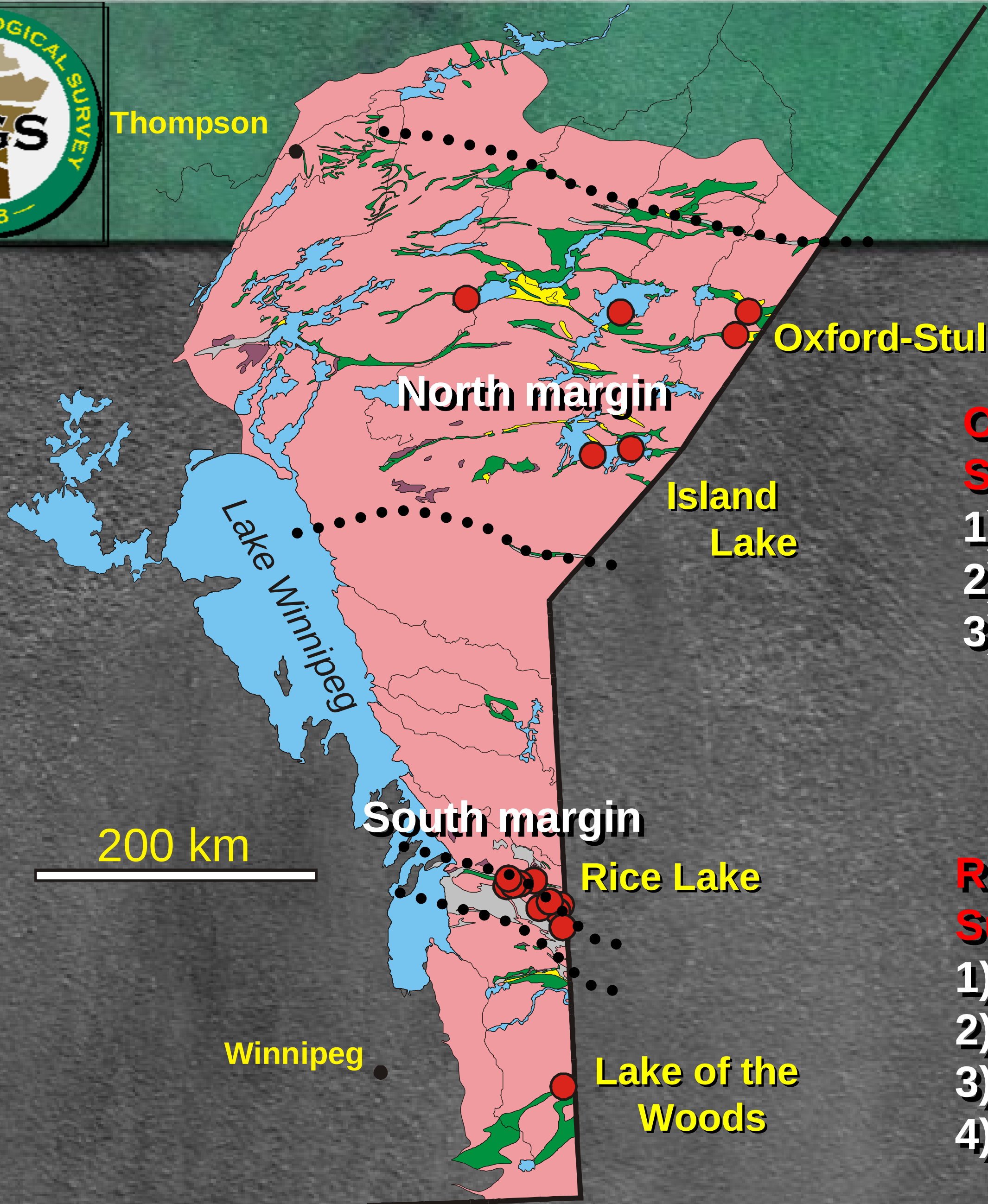
South margin of NCT:
metallogenic model

4) Orogenic model provides best explanation for Au deposition in the Rice Lake belt



- ca. 2.69-2.67 Ga collisional orogenesis
- crustal thickening
- prograde metamorphism
- dehydration reactions at depth
- high fluid pressures
- regional NE-SW compression
- structural anisotropy (RRP)
- domains of low mean stress
- shear and hydraulic fracturing of competent rock-types
- enhanced permeability
- channeling of auriferous metamorphic fluids
- decompression-induced Au precipitation

Superior Province of Manitoba: gold deposits



Oxford-Stull and Island Lake Summary:

1) Association with SWF and SIF
2) Syn- and late-kinematic Au
3) Recurring affiliation with OLG at HRG- CLG interface

Rice Lake Summary:

1) Association with WF and MF
2) Regional diversity of styles
3) Syn-kinematic Au (not syngenetic!)
4) Regional NE-SW compression

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