Structural controls on nickel sulfide deposits: examples from China and Russia inform models for Voisey's Bay

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Project review | Interpretation | Strategy | Training

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Richard W Hutchinson (1928-2016)

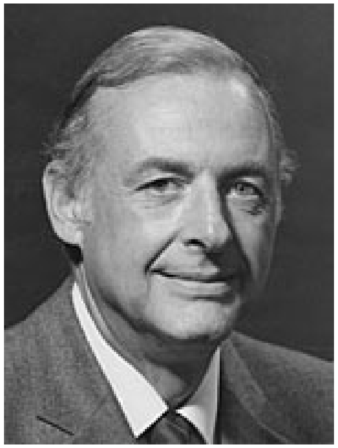
- *BSc (Western, 1950), MSc and PhD (Univ Wisconsin, 1951, 1954)*
- *Three decades in academia (Western and Colorado School of Mines)*
- *Inducted to Canadian Mining Hall of Fame 2006*
- *Numerous awards (including the Barlow, Duncan Derry, Penrose Gold and SEG Silver medals)*

Field observations
Process-based models for ore deposits
Tectonic controls on metallogeny
Application to exploration

- *Syngenetic models for VMS – New Brunswick and Cyprus, (e.g. Econ. Geol., 1973)*
- *Precambrian gold metallogeny – Abitibi and Witwatersrand (e.g. OGR, 1993; Econ Geol, 1997)*
- *Rare metals in pegmatites – NWT and Mozambique (e.g. Econ Geol, 1959)*
- *Evaporites and potash (e.g. GSA, 1968)*

Training, mentoring, and inspiring students with practical geoscience skills

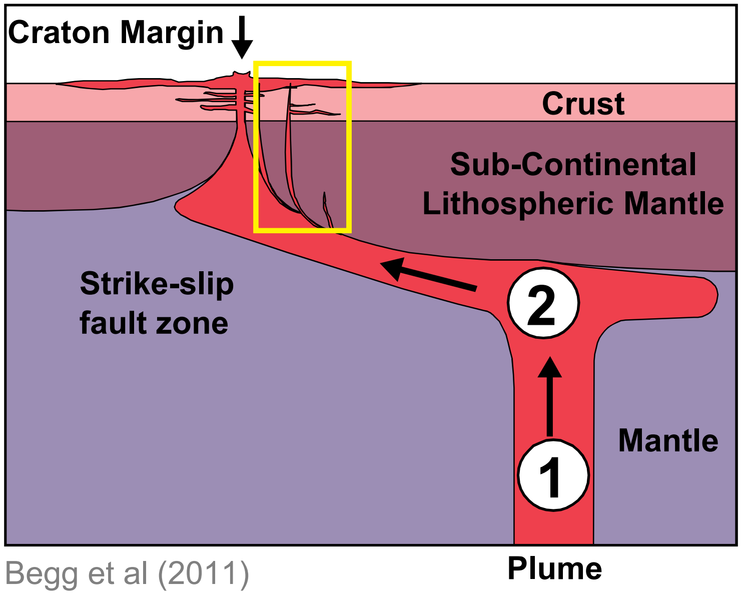
- *"An army of geological disciples now spread around the globe" (Poul Emsbo, 2005)*



A complete bibliography of Dick's papers will be available from: WWW.LIGHTFOOTGEOSCIENCE.CA

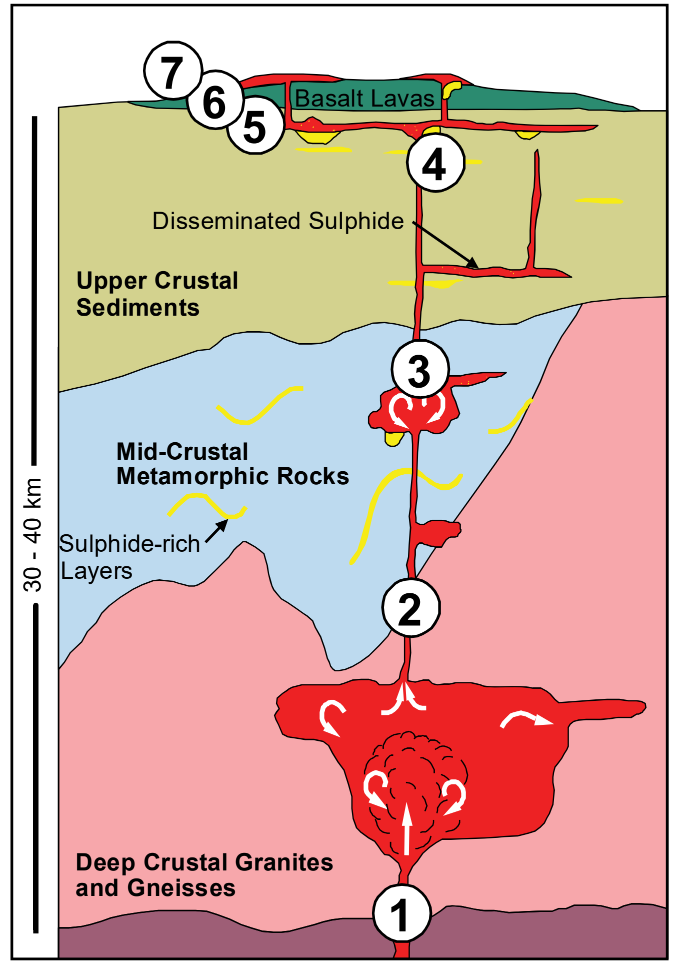
Traditional view of Process Controls in the Formation of Nickel Sulfide Ore Deposits

Tetonic Setting



Begg et al (2011)

Crustal Architecture



After: Lightfoot (2007) and Naldrett (2010)

Key Process Controls

7. Syn-tectonic and post-tectonic modification
6. Sulphide segregation
5. Sulphide saturation and metal endowment
4. Emplacement
3. Fractionation and contamination
2. Ascent of magma
1. Generate ultramafic magma from metal endowed source

Extensional spaces in transform fault systems act as “magma highways” from mantle to surface and control many small differentiated intrusions with nickel sulfide deposits

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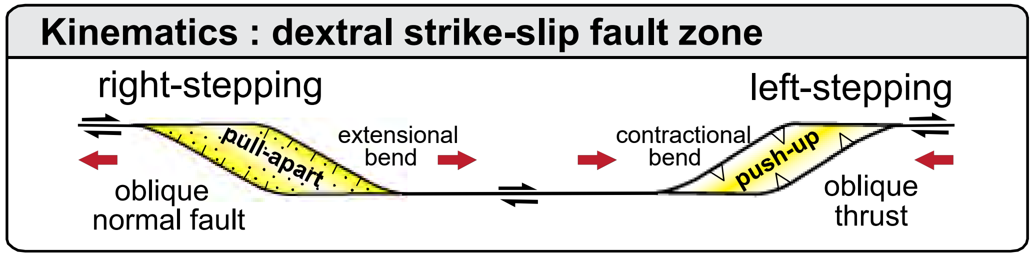
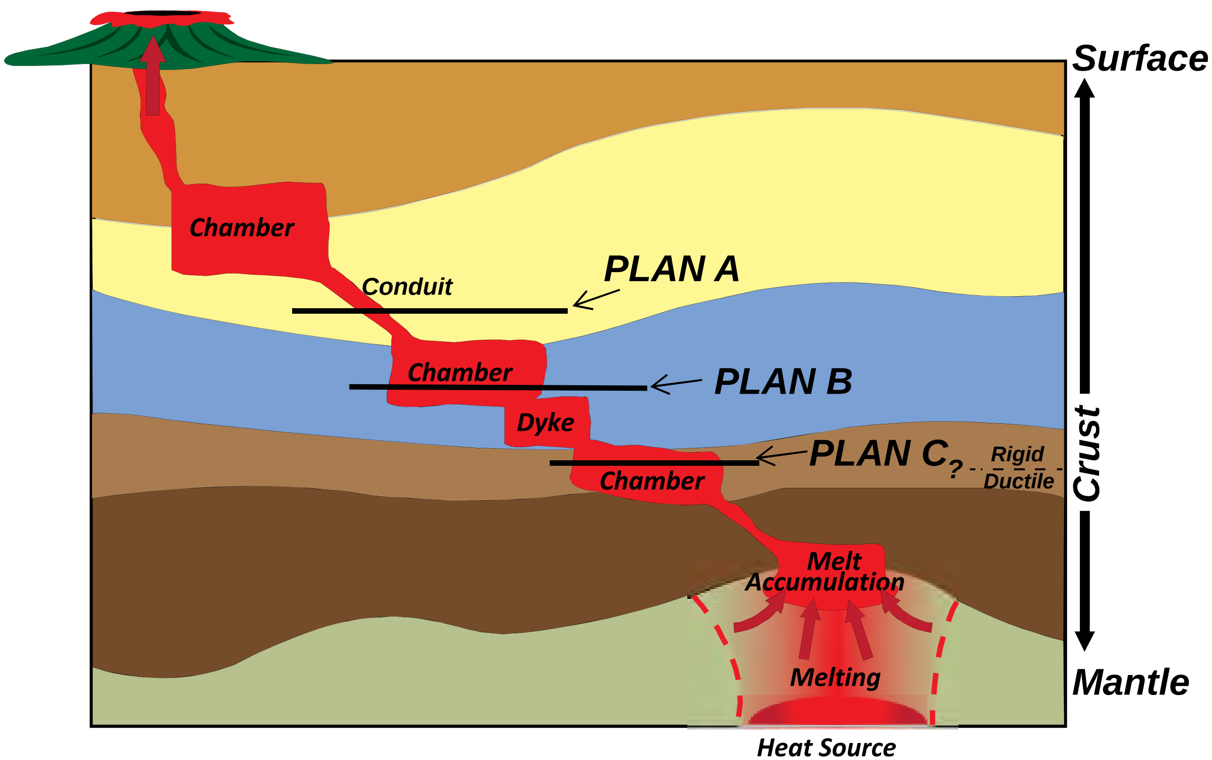
Magma Conduits (chonoliths)

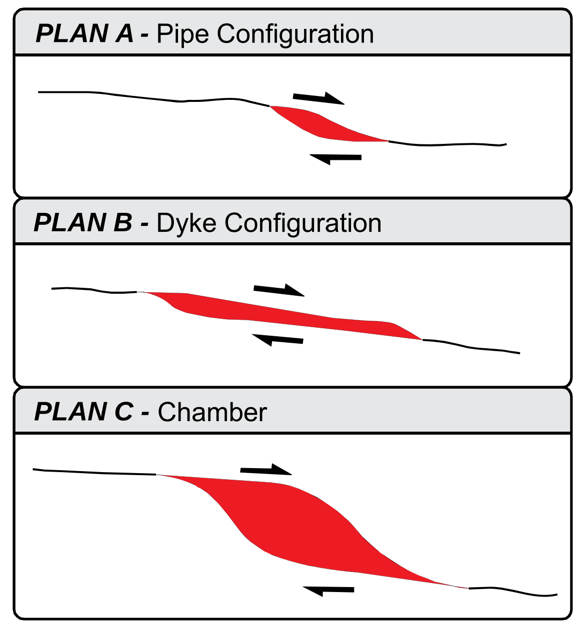


View Along Plane of Stike-Slip Shear Zone



Plan View

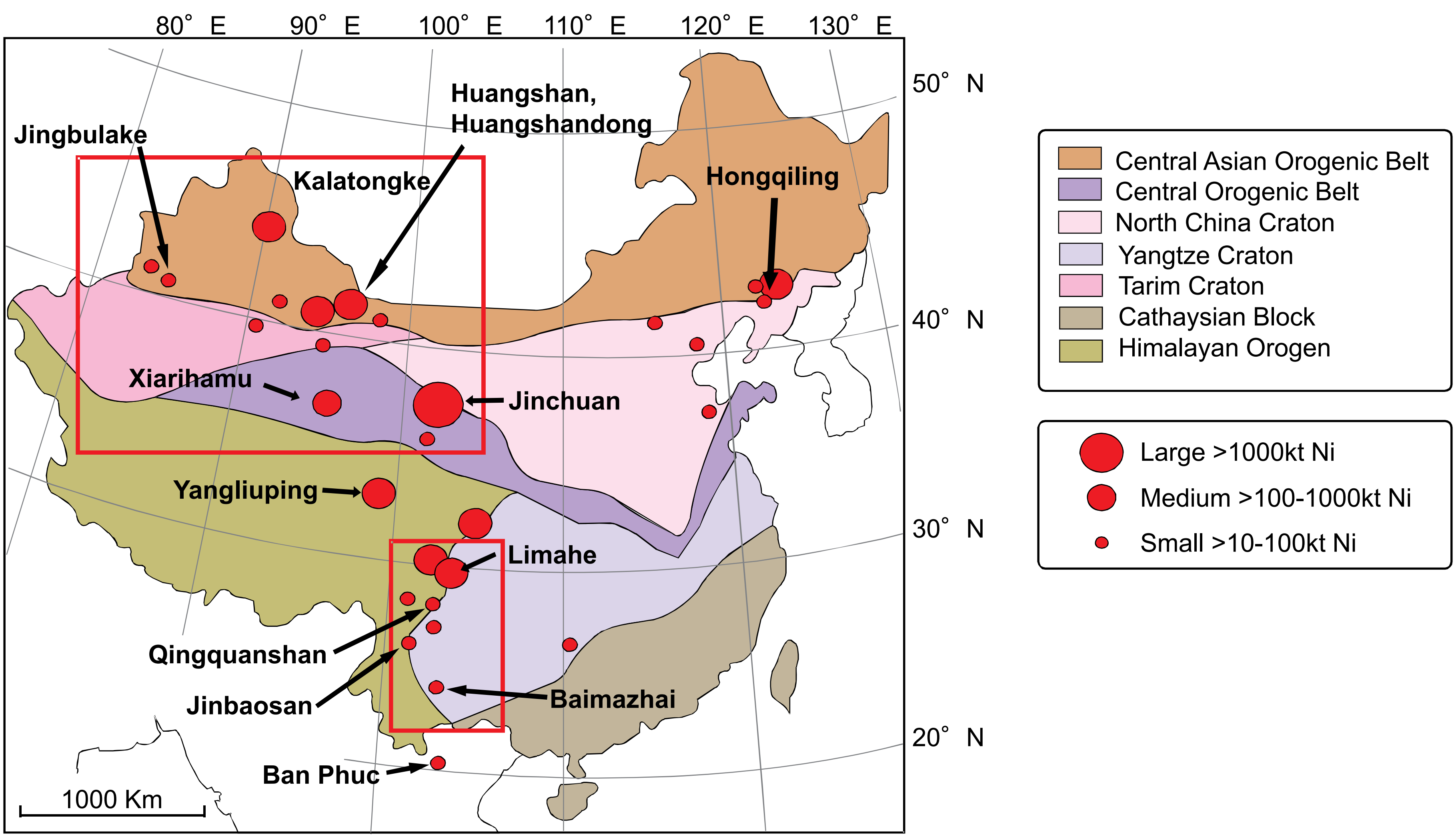
Magma Conduits (pipes, dykes, chambers) at different crustral levels



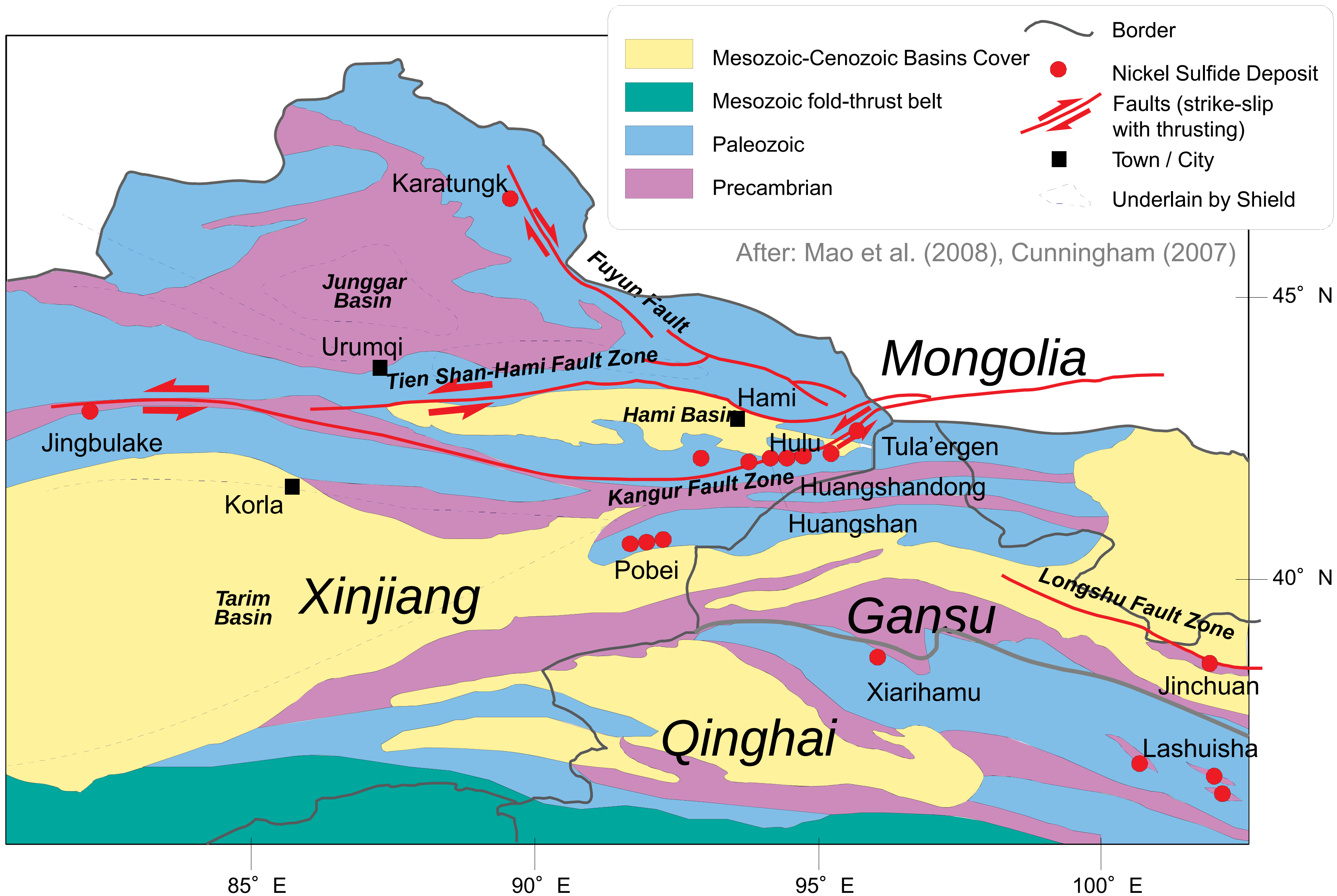
Take-away points

- Widespread importance of strike-slip structures on emplacement of small differentiated intrusions with transported sulphide:
  - Vertical champagne glass-shaped chonoliths (e.g. Huangshan, Huangshandong, Jingbulake, Limahe, Hong Qi Ling…)
  - Accumulations within sub-horizontal chonoliths (e.g. Noril'sk-Talnakh, Karatungk, Nkomati, Babel-Nebo…)
- A common model for nickel sulfide formation in the roots of large igneous provinces in craton-margin structures
- Case studies of Chinese deposits and Norli'sk help to understand Voisey's Bay
- Chamber geometry, ore distribution, and transport of magmatic sulfide controlled by dilational space created in a right-lateral fault zone

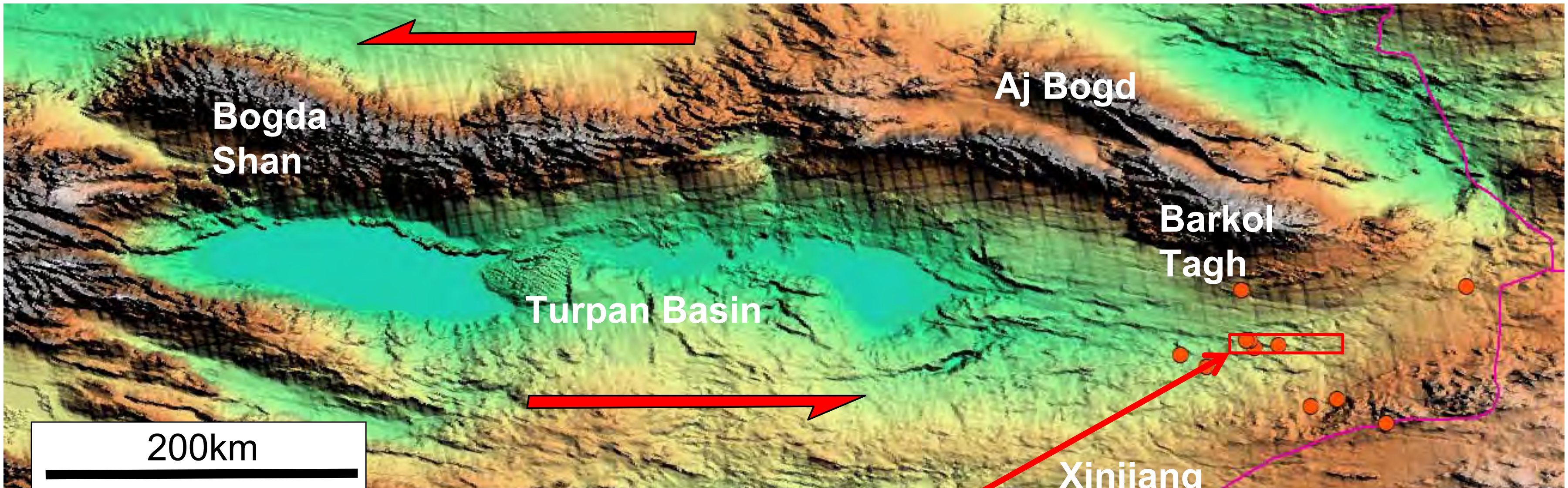
Distribution and scale of Ni sulfide deposits in China



Distribution of nickel deposits in Western China



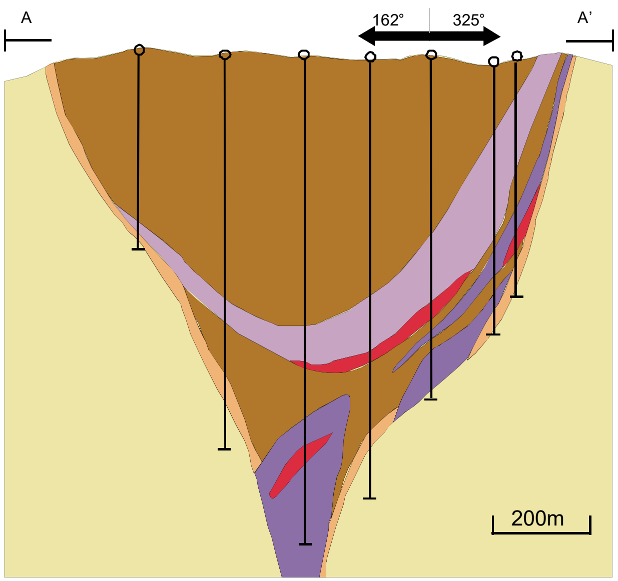
Restraining bends and pull-apart basins along the Gobi-Tien Shan fault system in Eastern Xinjiang, China

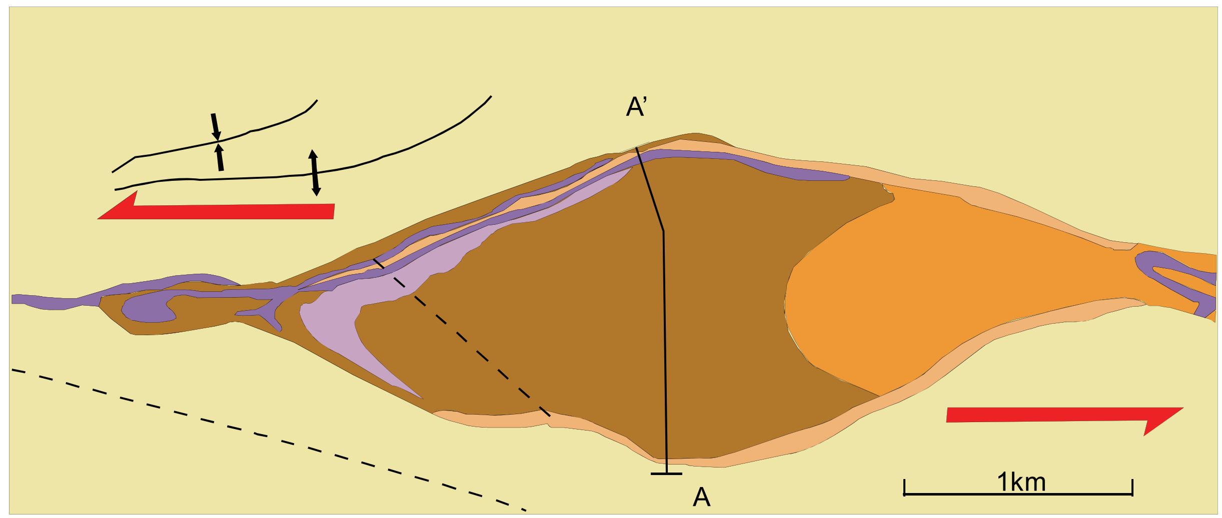


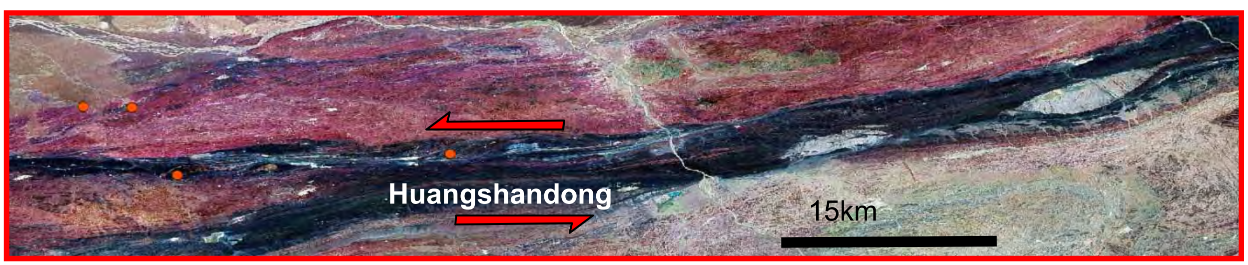
After: Mann, (2007)

Lightfoot, Evans-Lambswood, (2007)

Geology of the Huangshandong Intrusion and the location of Cu-Ni Sulfide mineralization







- Gabbronorite
- Ni-Cu sulphide mineralization
- Peridotite
- Gabbro to olivine gabbro
- Gabbro Diorite
- Diorite
- Country rocks
- Faults
- Synform
- Antiform
- Boreholes

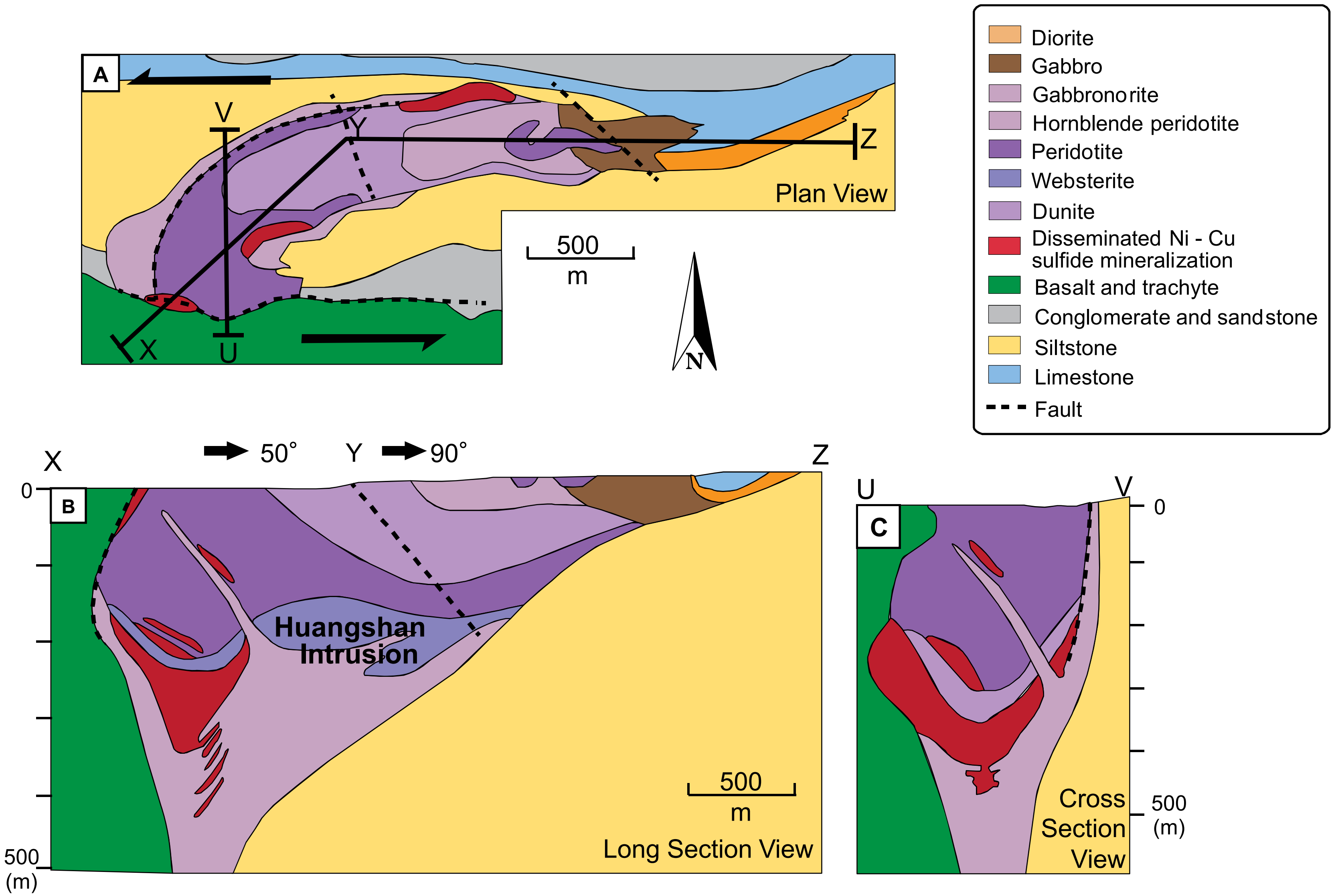
Xinjiang: Hami Belt – shaft on Huangshandong

Photograph: Peter Lightfoot, 2001

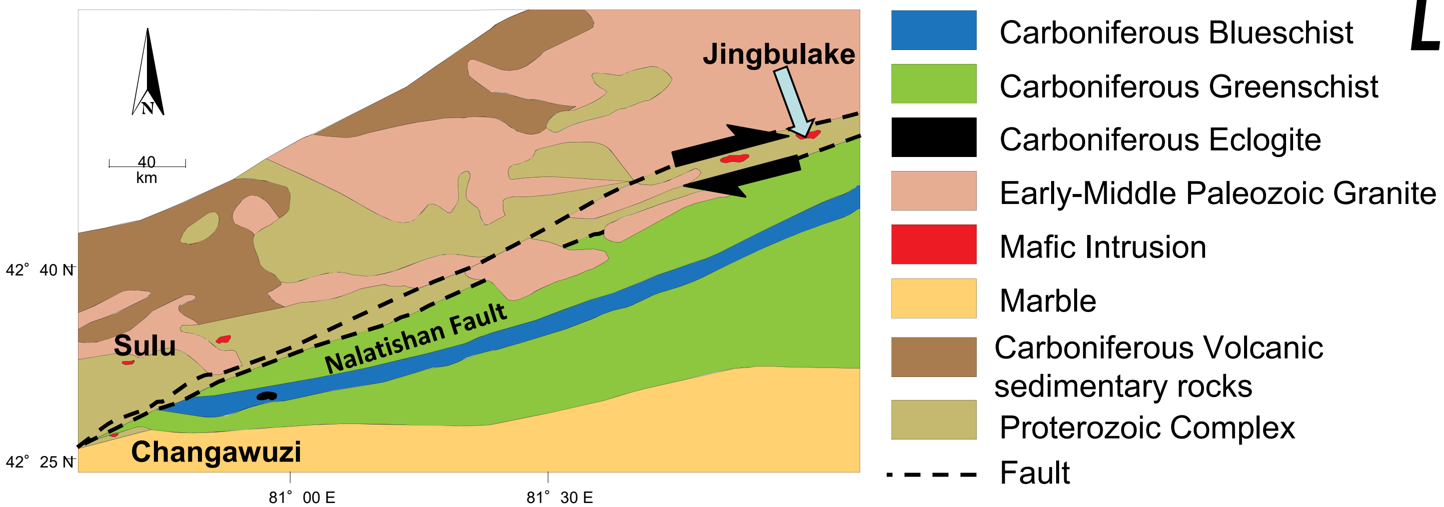
Xinjiang: Hami Belt – exploration under Chairman Mao's 5 Year Plans

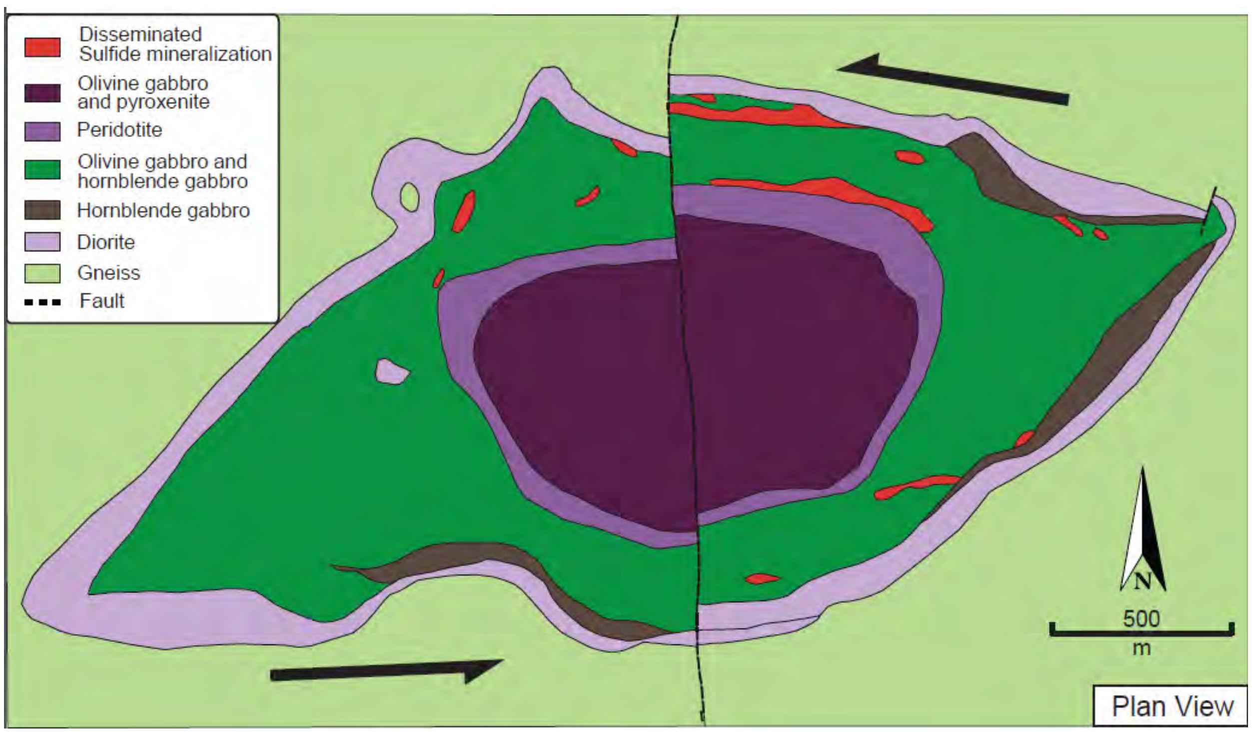
Photograph: Peter Lightfoot, 2001

Geology of the Huangshan Intrusion and the location of Cu-Ni Sulfide mineralization



Jingbulake Intrusions, Xinjiang Province

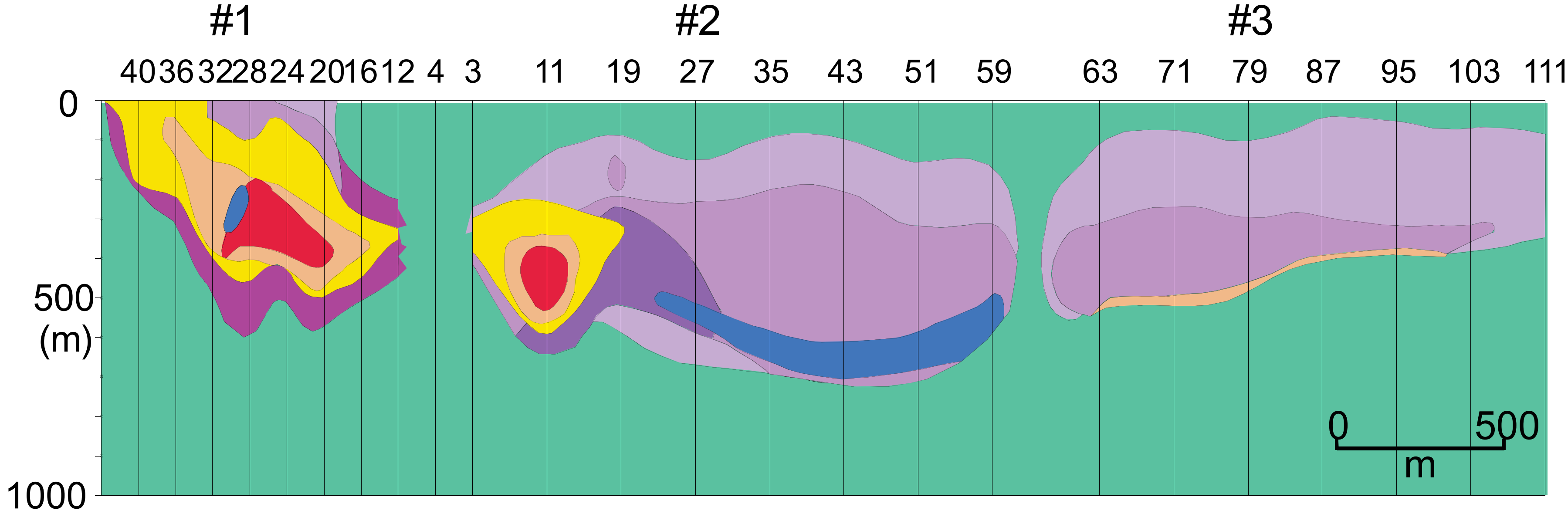




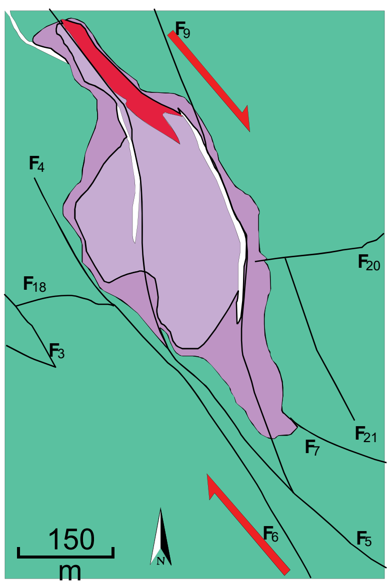
Yang et al., 2012

Western Xinjiang: the wild west of China

Karatungk Intrusion, Xinjiang Province, China: North-facing long section



Wang et al., 1991



Biotite-pyroxene diorite

Biotite-hornblende norite and Biotite-hornblende gabbronorite

Biotite-hornblende olivine gabbronorite

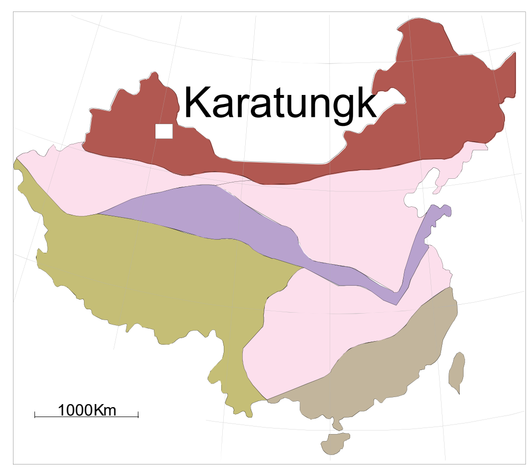
Biotite-hornblende diabase gabbro

Disseminated sulphide

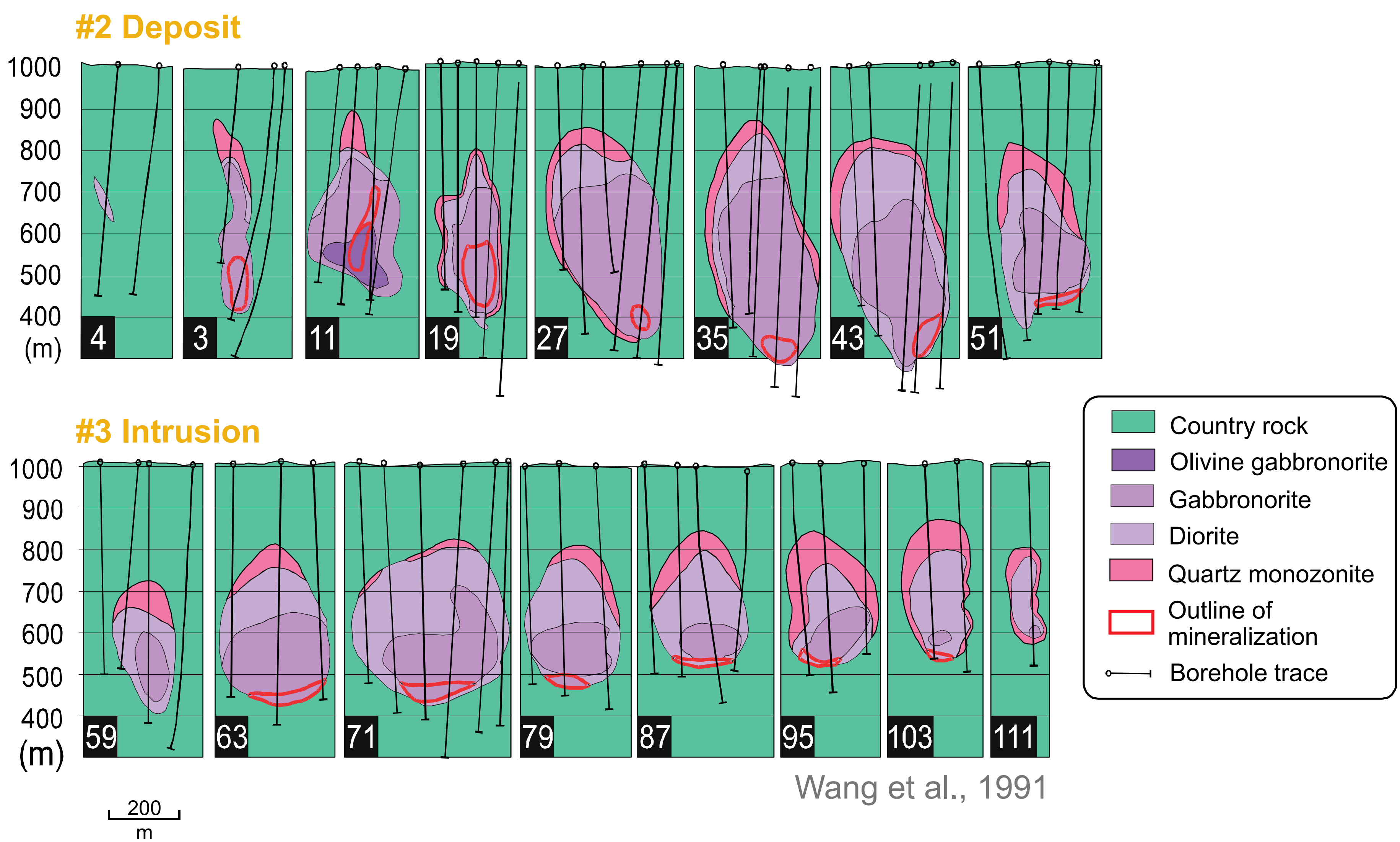
Heavy disseminated sulphide

Cu-rich massive sulphide

Ni-rich massive sulphide

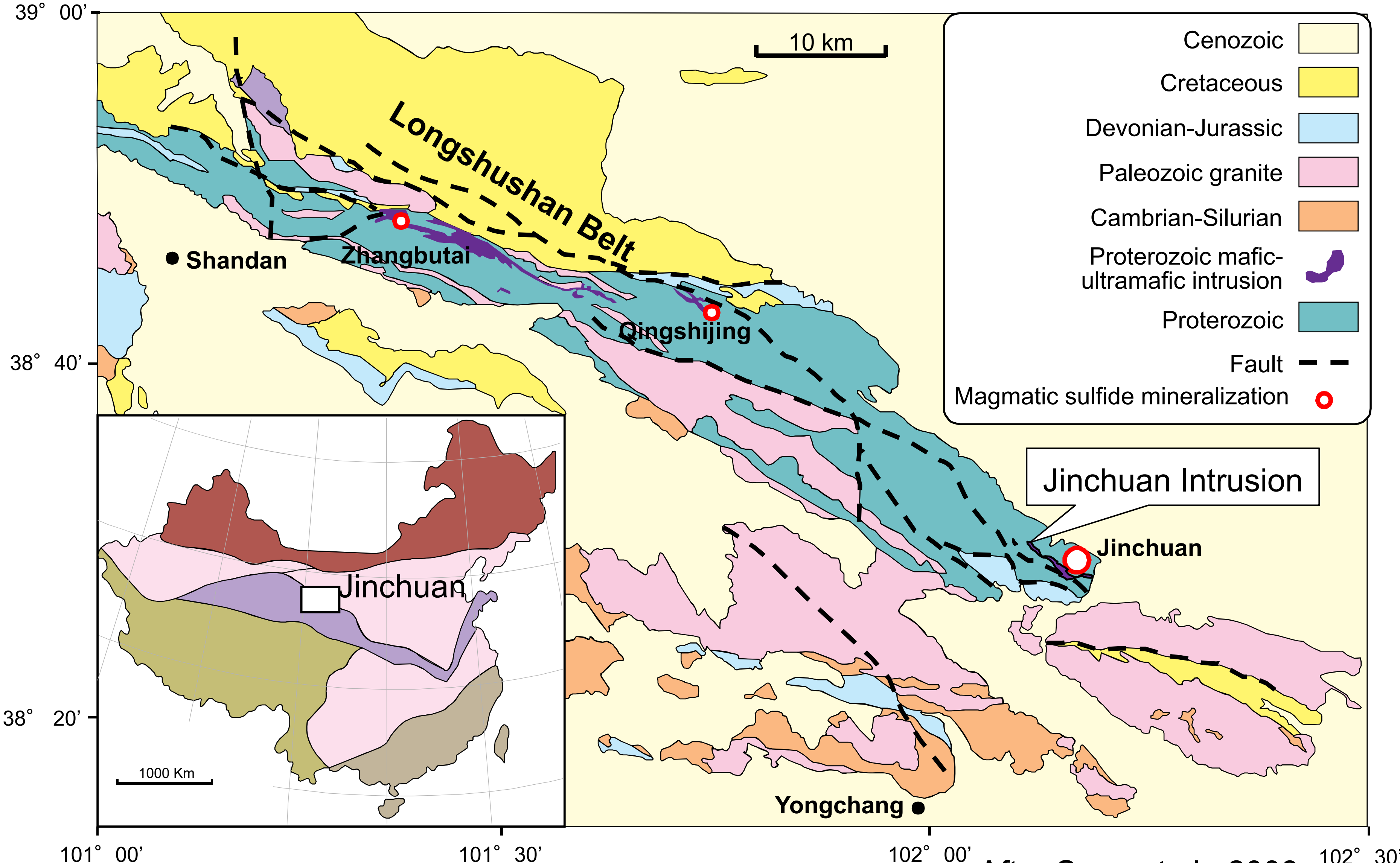


Karatungk #1,2 and 3 Intrusions, Xinjiang Province, China: West-facing long section



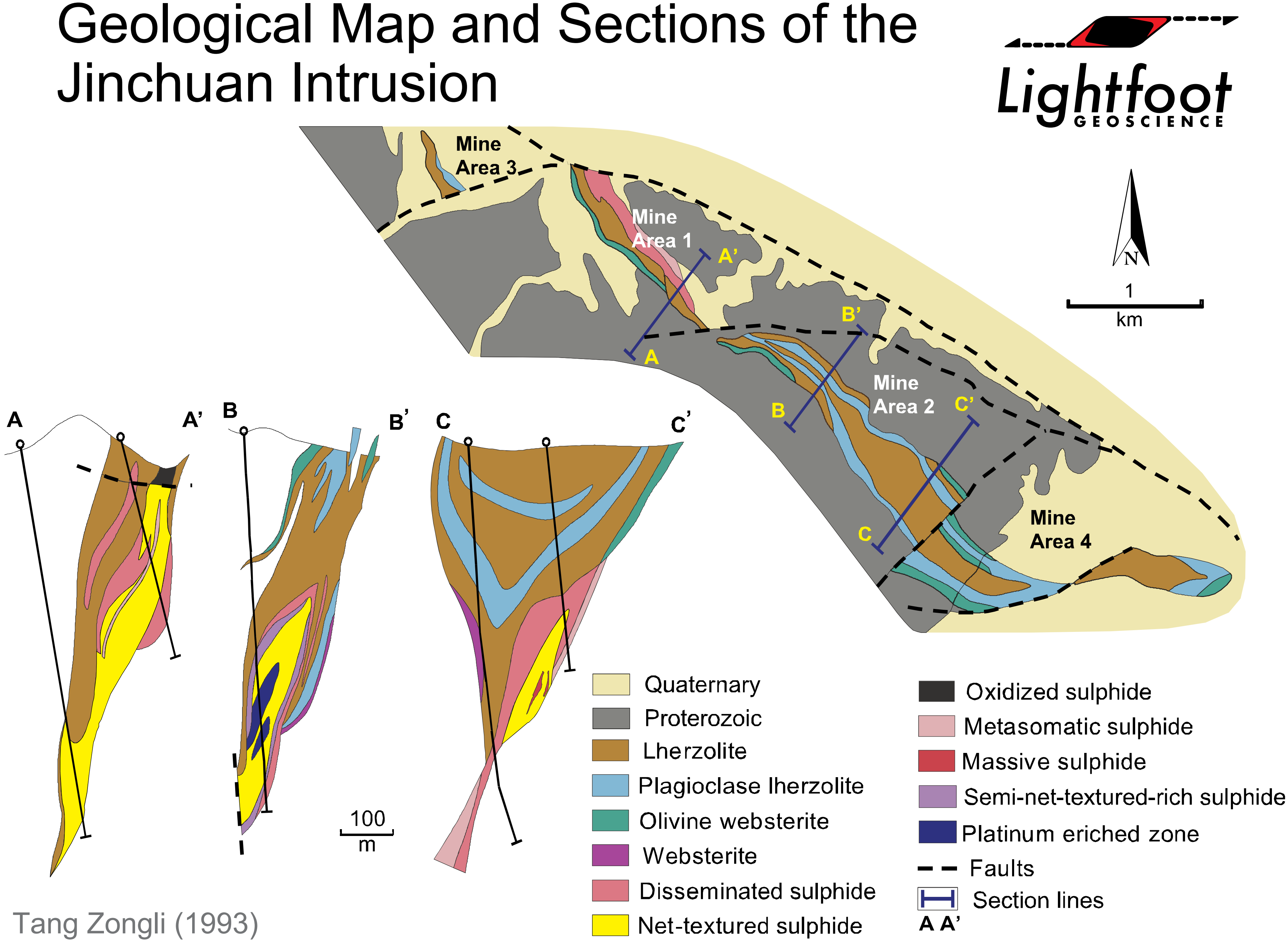
Karatungk: the outcrop footprint of the intrusion is ~400x150m

Location Map of the Jinchuan Intrusion, Proterozoic Longshushan Belt, Gansu Province, China



After Song et al., 2008

Geological Map and Sections of the Jinchuan Intrusion

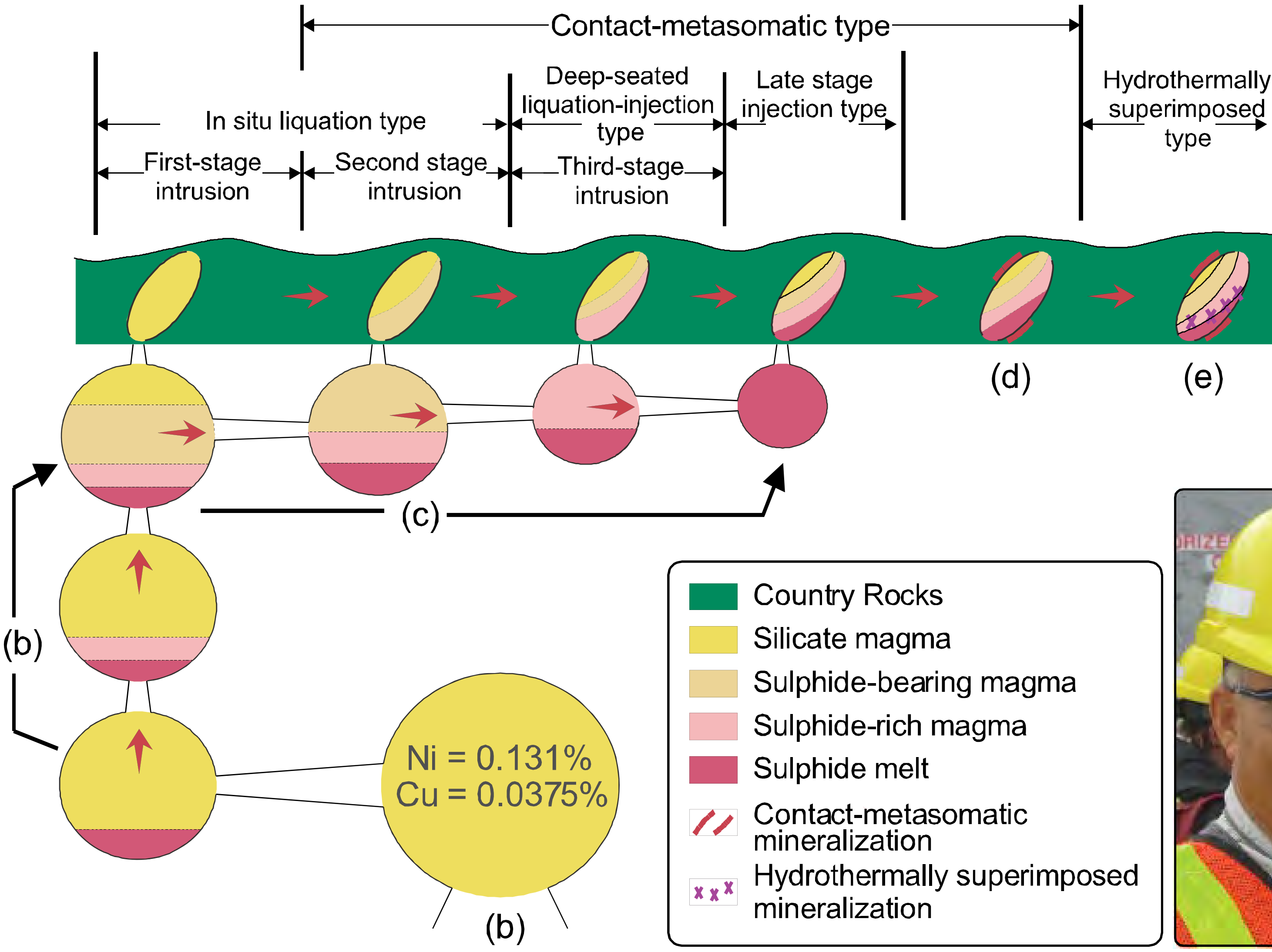


Tang Zongli (1993)

Mine area #2 – no trace of sulfide or country rock xenoliths inside the intrusion at surface

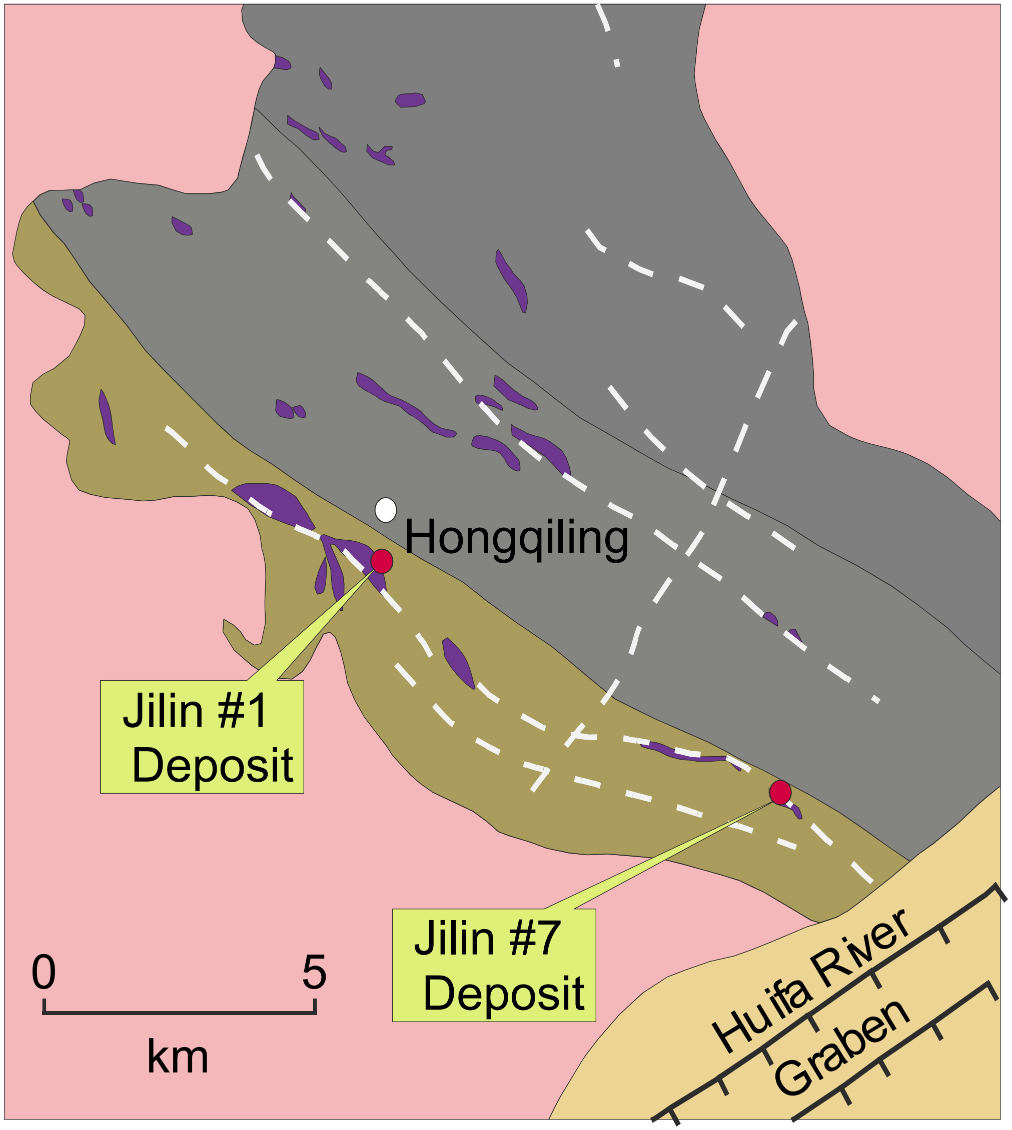
Photograph: Peter Lightfoot, 2000

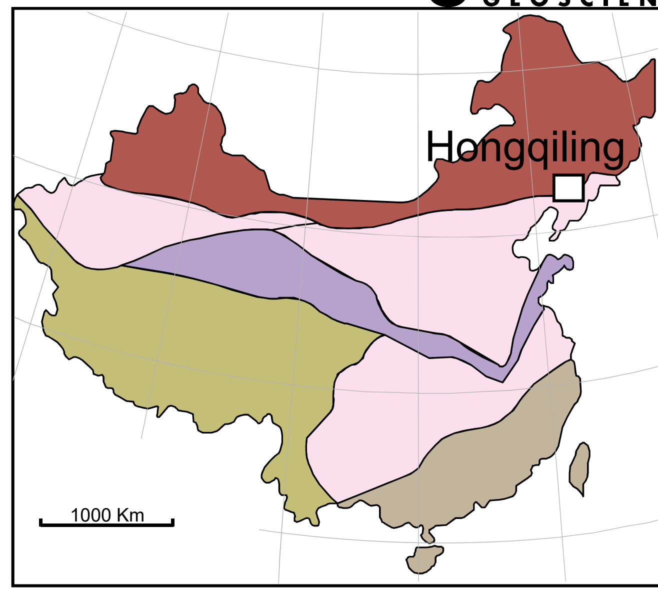
Jinchuan Model



Tang Zongli (1993)

Hongqiling – Geology, Structure and Mineral Occurrences

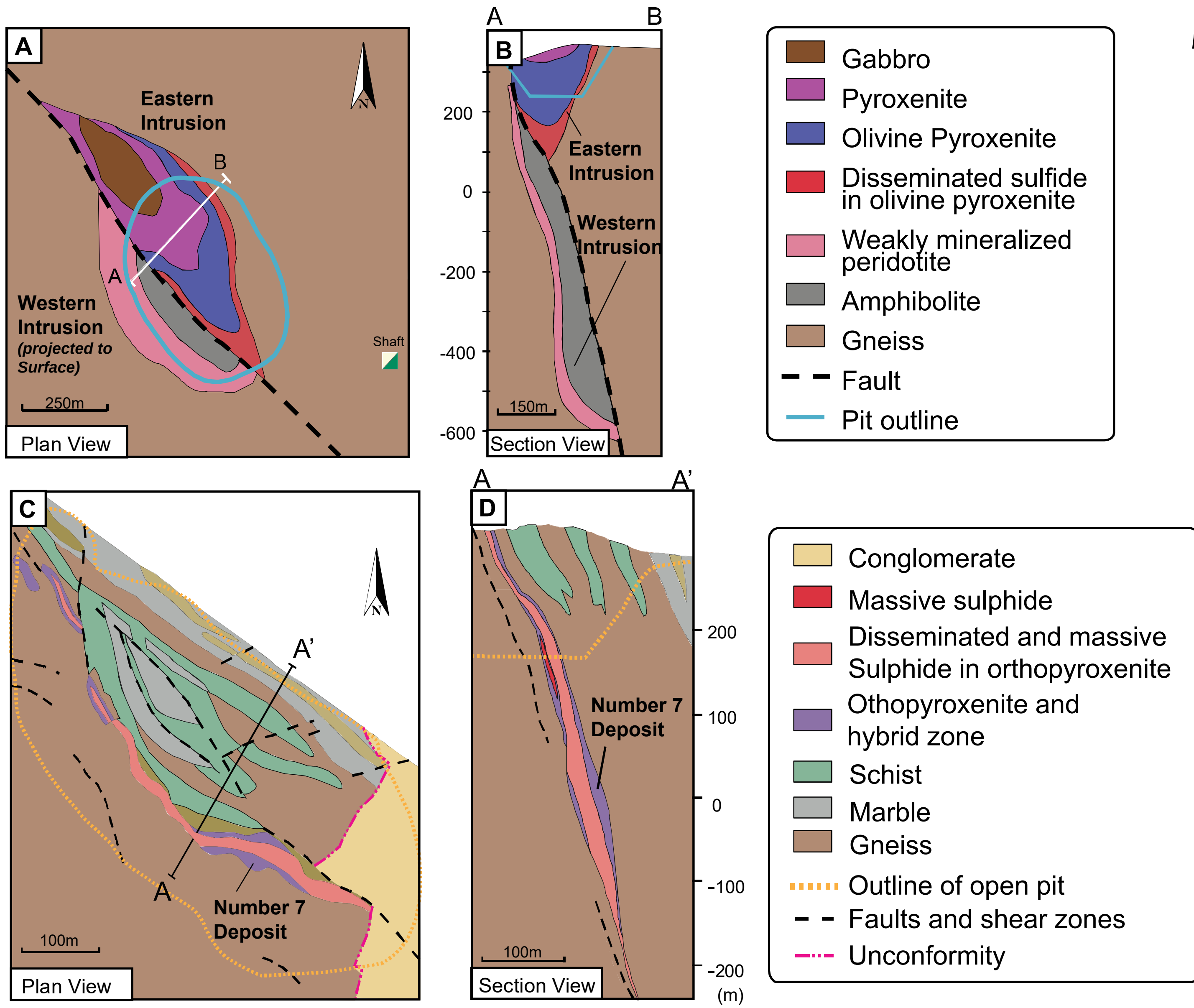




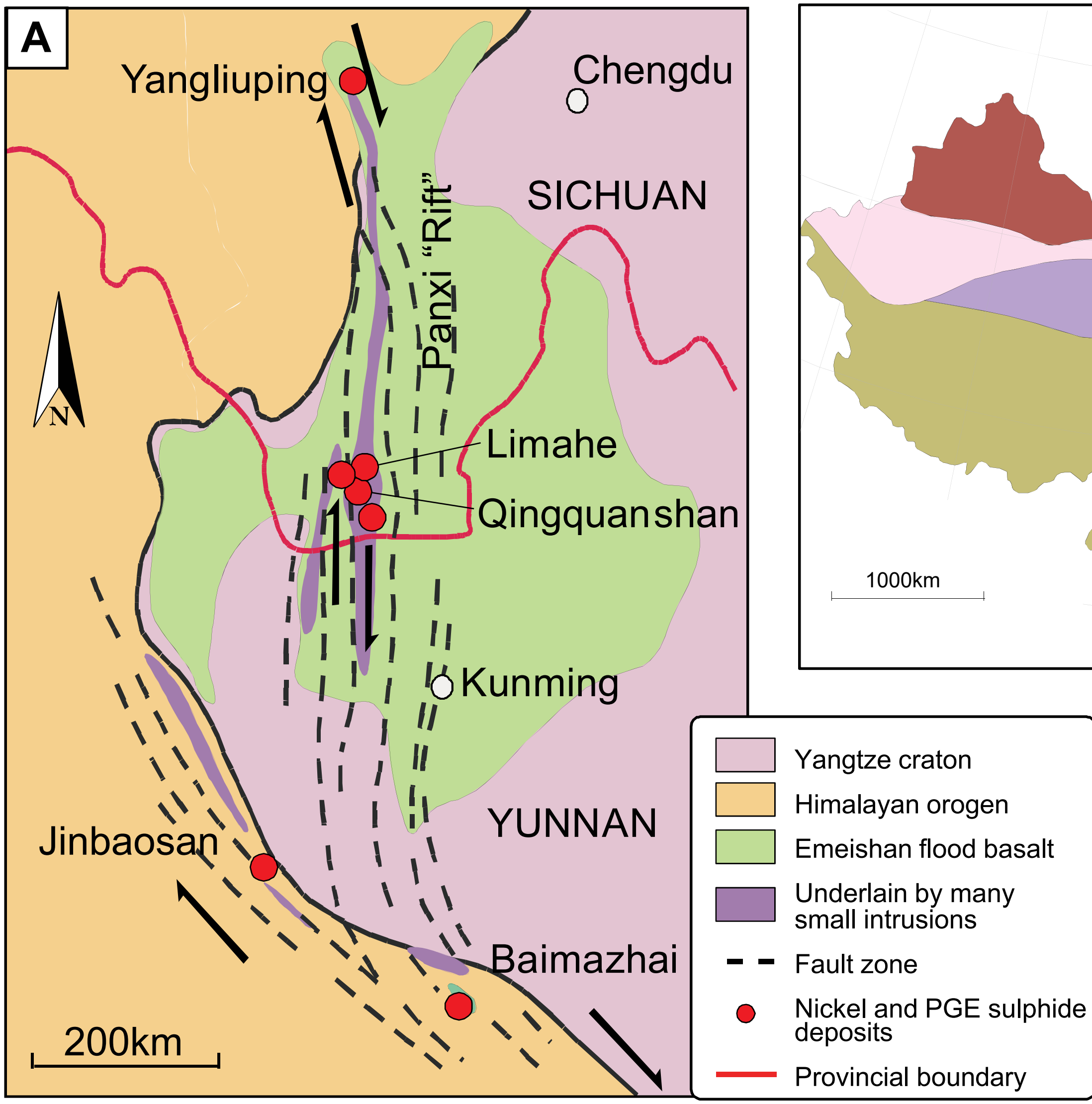
Mesozoic sedimentary rocks
Granitoid rocks
Mafic-ultramafic Intrusions
Hulan Group Gneiss (younger)
Hulan Group Gneiss (older)
Fault

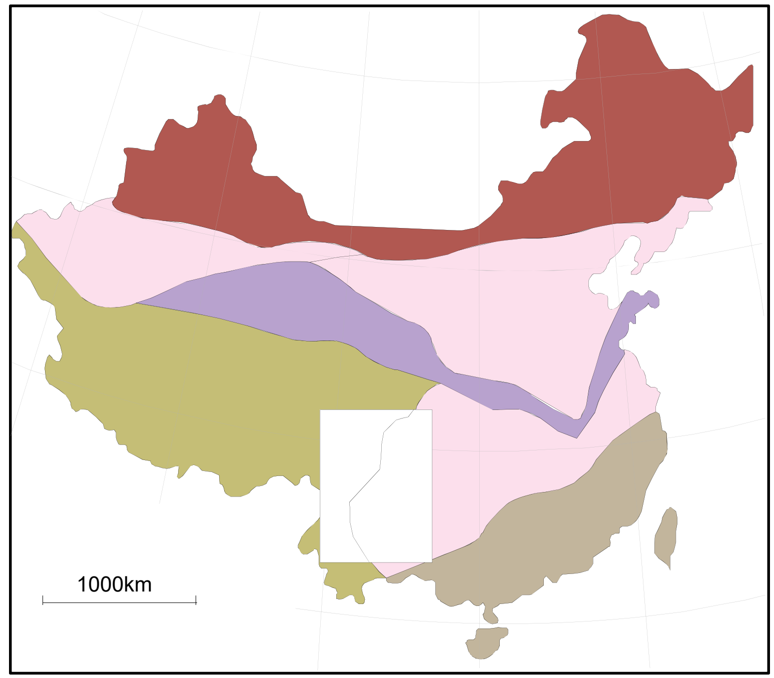
After Zhou et al., 2000

Hongqiling: Jilin Province

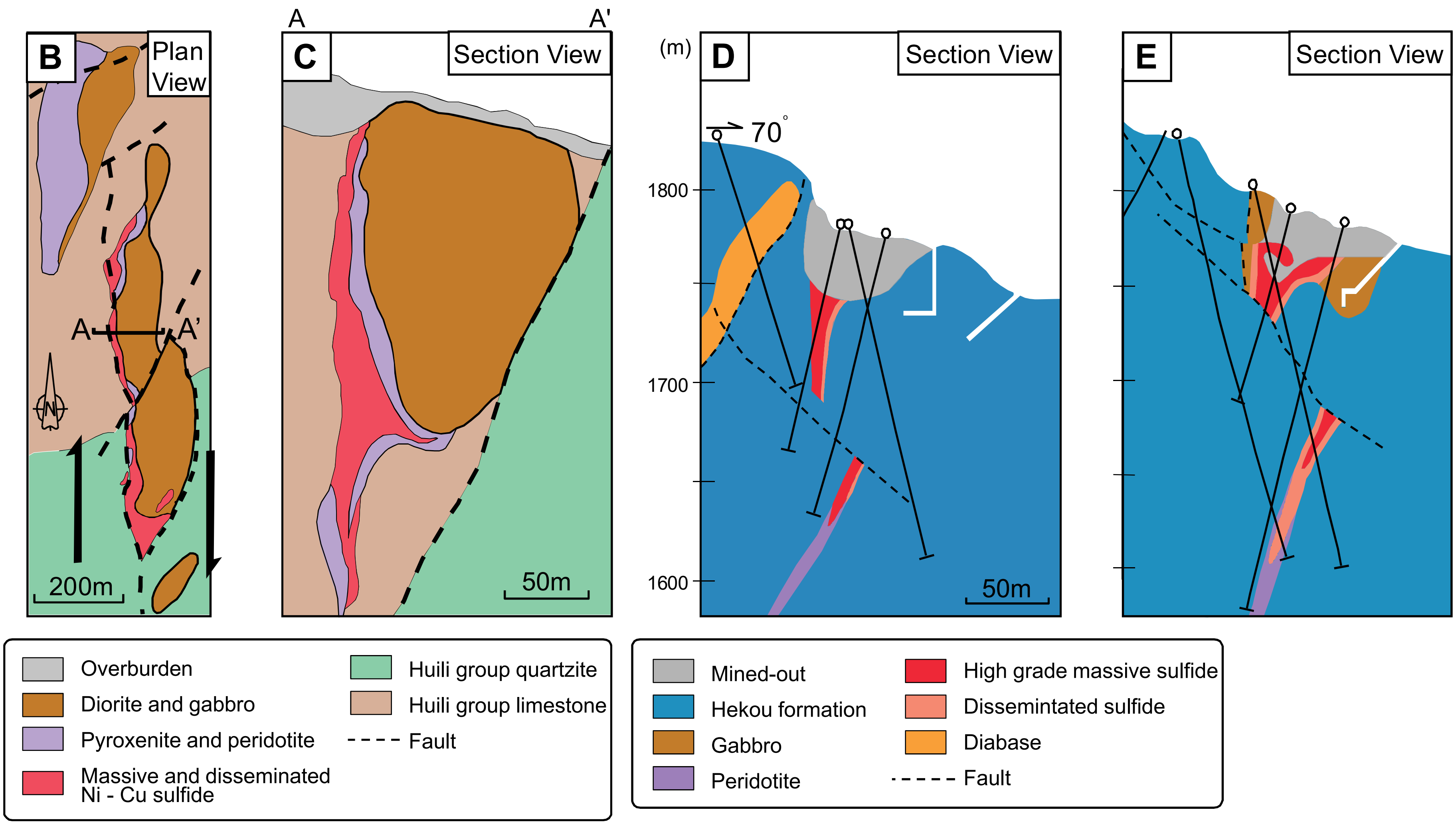


Intrusions controlled by structures beneath the ~260 Ma Emeishan Flood Basalt, SW China



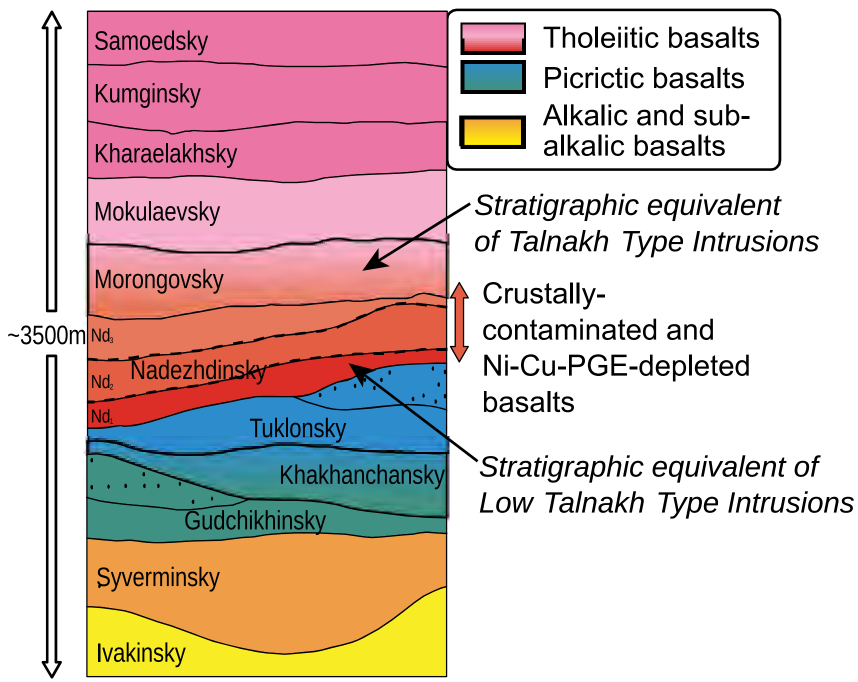


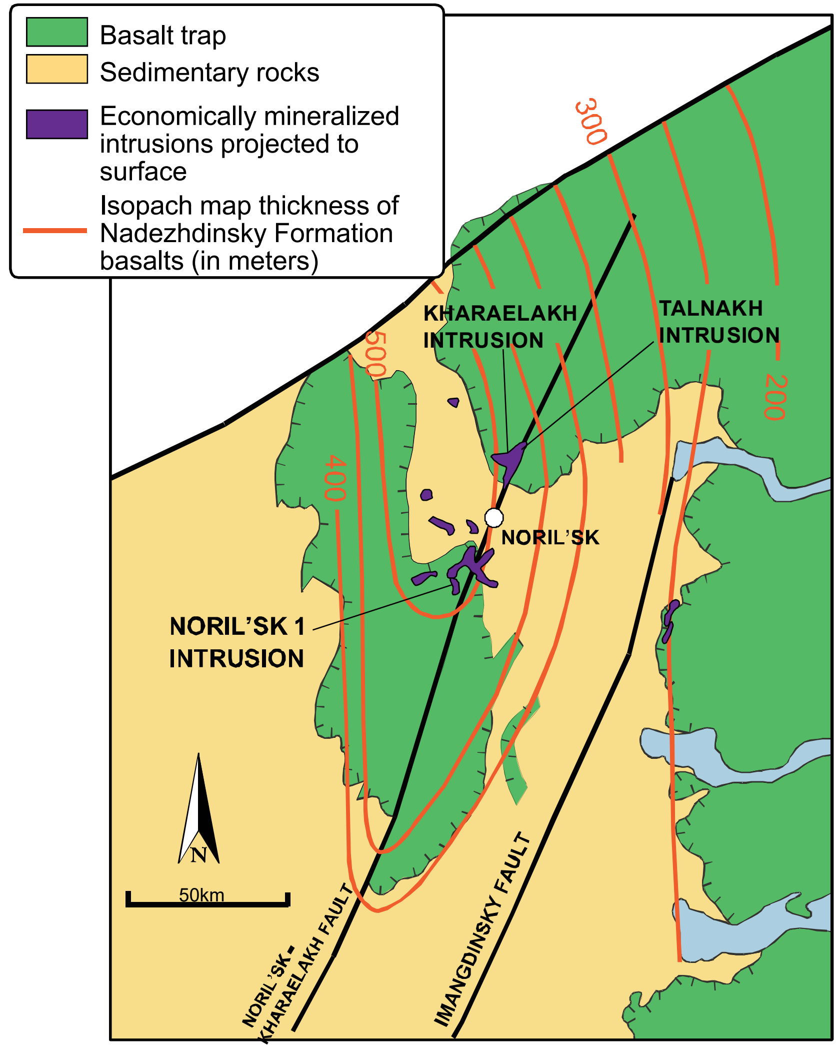
Geology of the Limahe and Qingquanshan Cu-Ni Sulfide Deposits (Sichuan Province)



Distribution of Siberian Trap Basalts

www.largeigneousprovinces.org/LOM.html





Naldrett et al (1995)

Noril’sk

Lightfoot
GEOSCIENCE

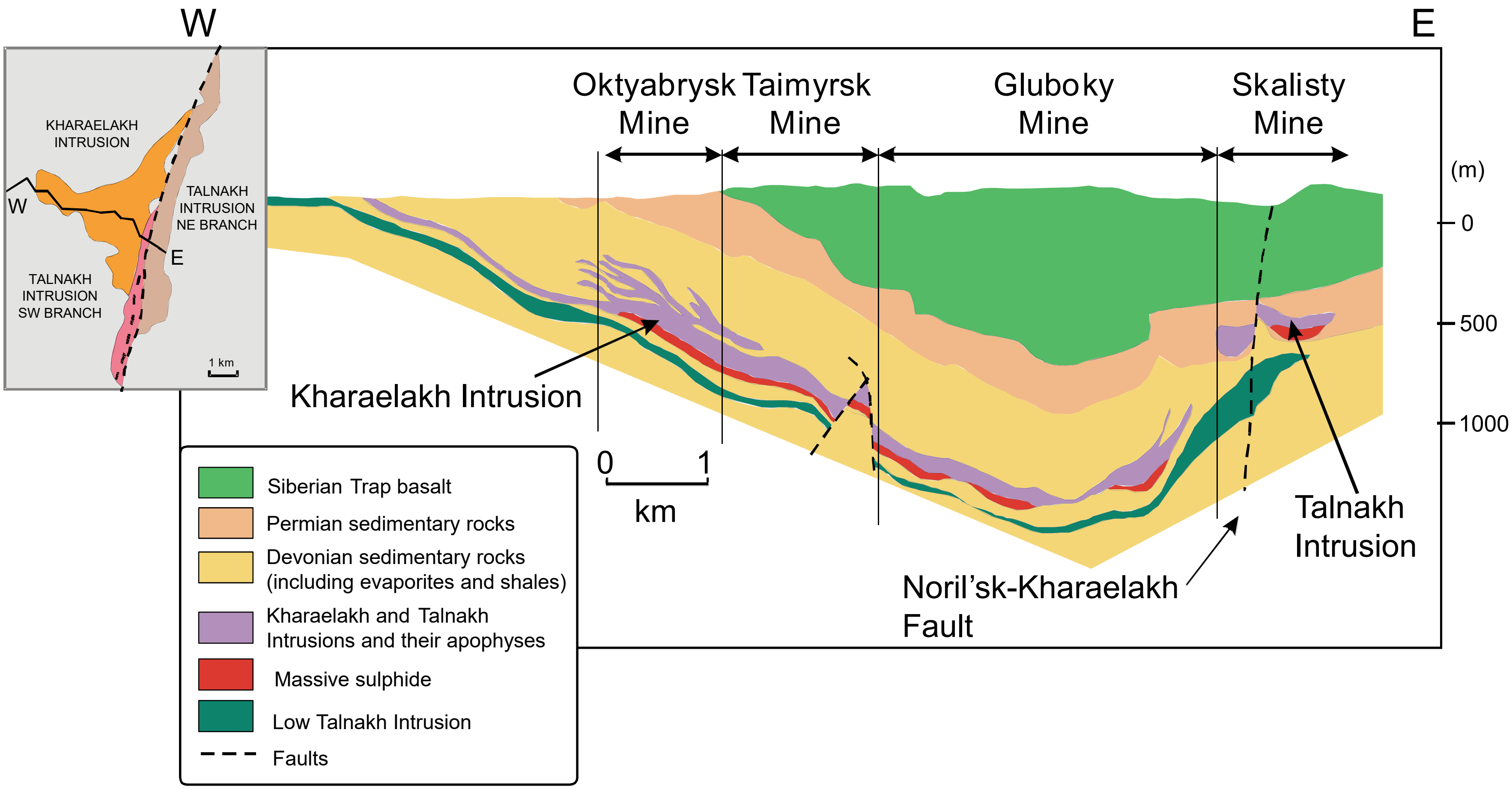
Panoramic view from Bear’s Brook towards north

Photograph: Peter Lightfoot, 2002

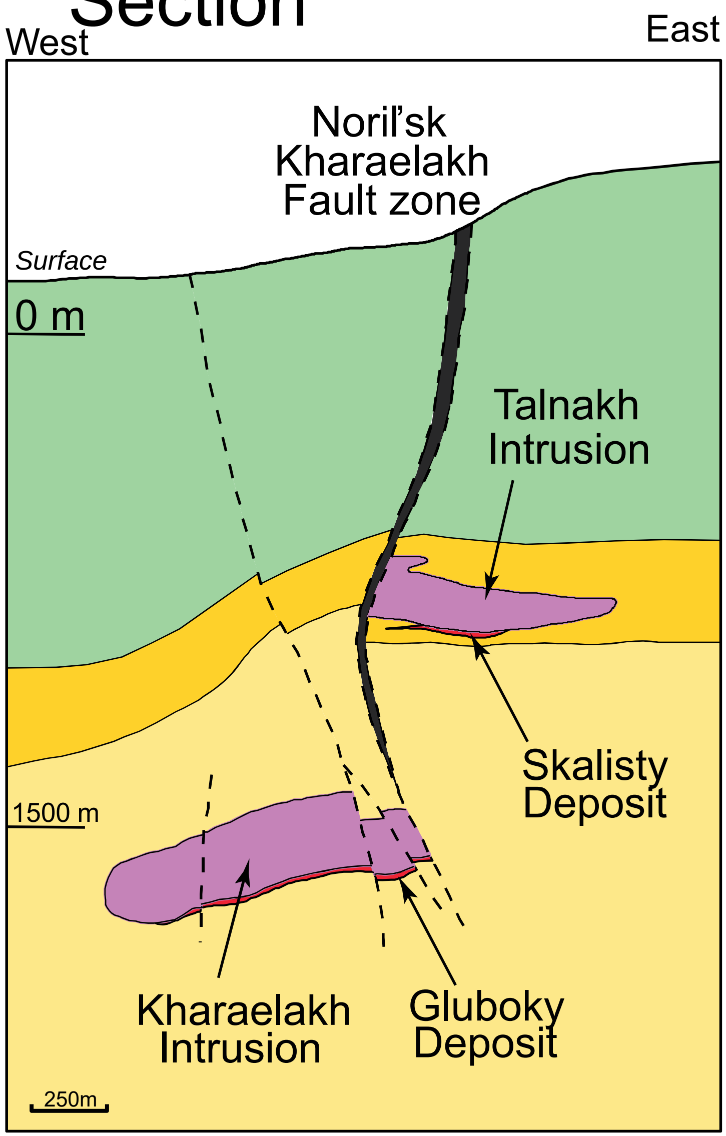
Footprint of ~20 million tonnes of nickel at Talnakh

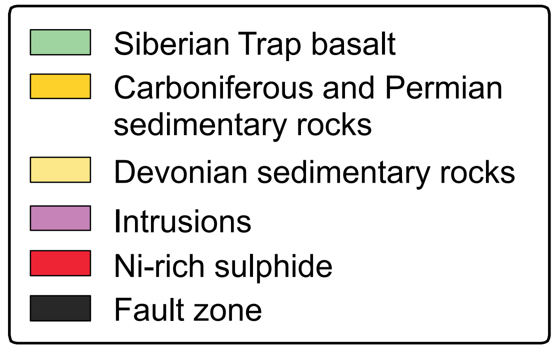
Photograph: Peter Lightfoot, 2002

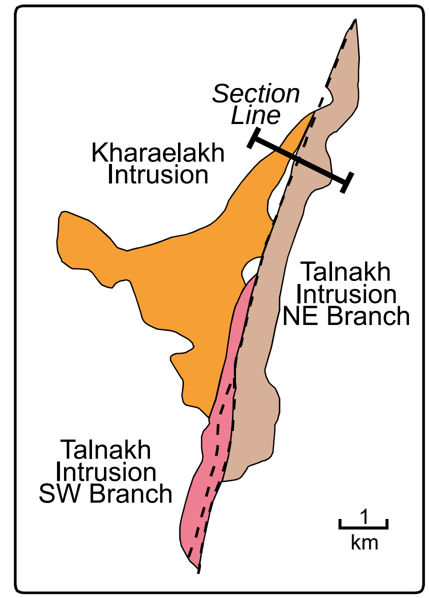
Morphology of the Talnakh and Kharaelakh chonoliths

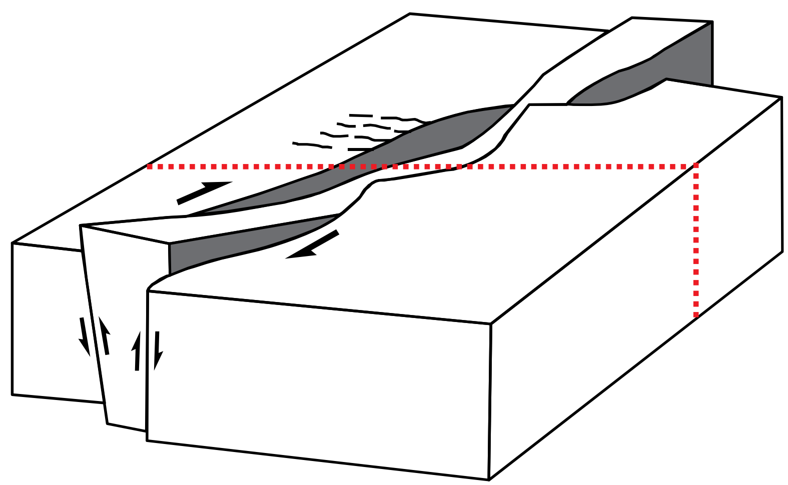


Skalisty and Gluboky Mines, Talnakh and Kharaelakh Intrusion: North-facing Section



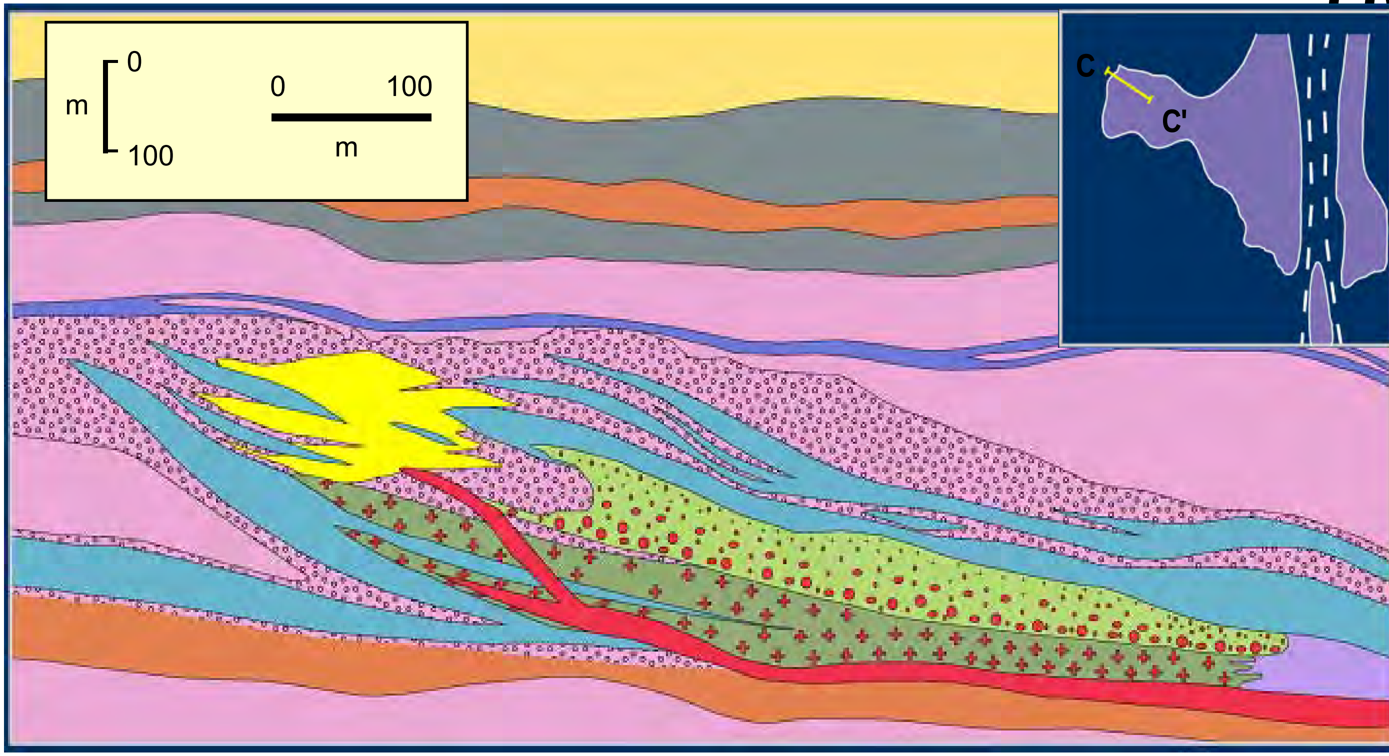






Lightfoot and Evans-Lamswood (2014)

“Horns and Ears” of the Kharaelakh Intrusion



Sandstone
Dolomite and limestone
Dolomite, anhydrite and marl
Shale and marl
Ti-augite dolerite
Massive sulphide
Cuprous breccia ores
Olivine-free and olivine-bearing gabbrodolerite
Troctolite
Disseminated sulphide in taxitic gabbrodolerite
Disseminated sulphide in picritic gabbrodolerite
Ti-augite dolerite

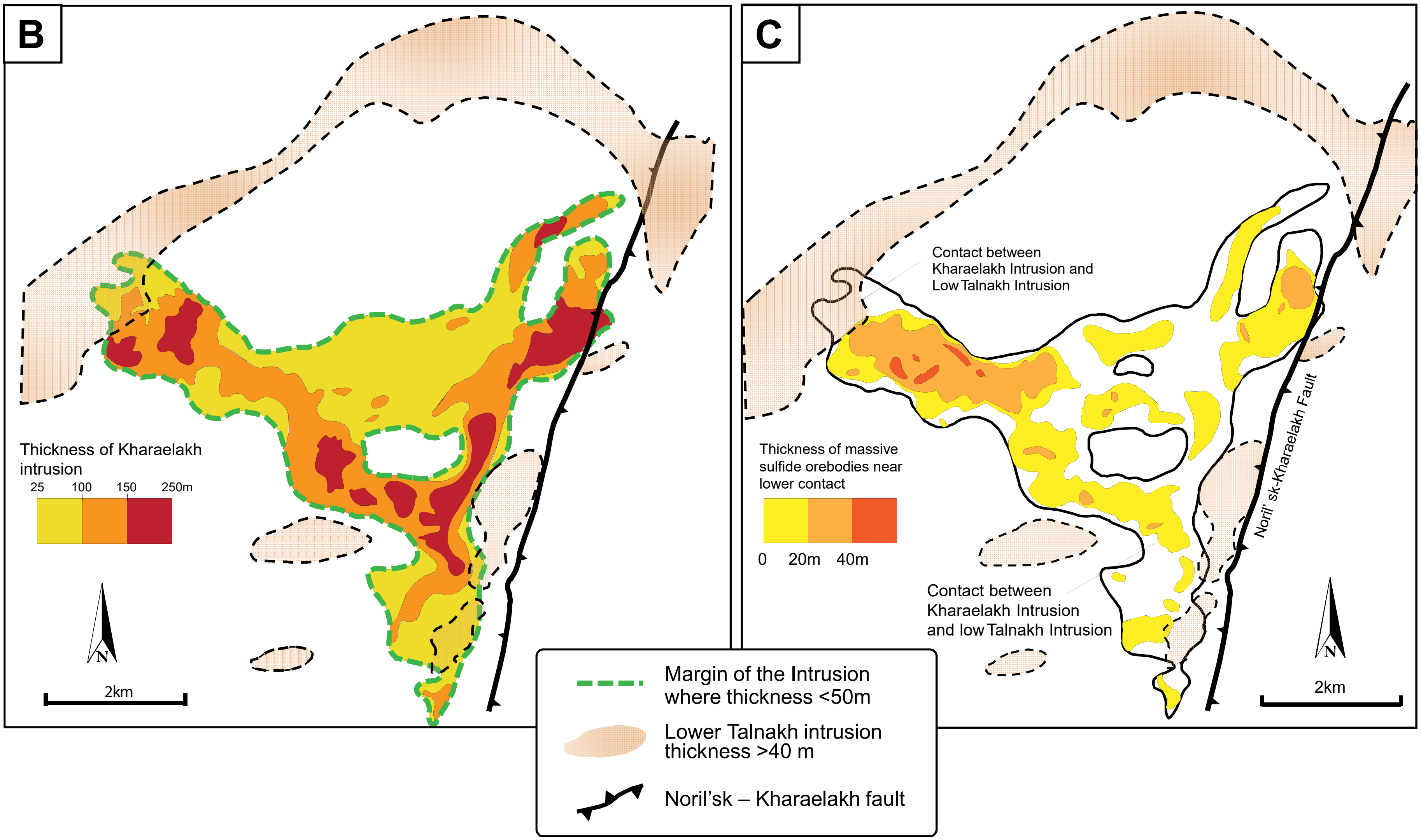
Lightfoot and Zotov (2006)

Contact metamorphism and apophyses of the Kharaelakh Intrusion

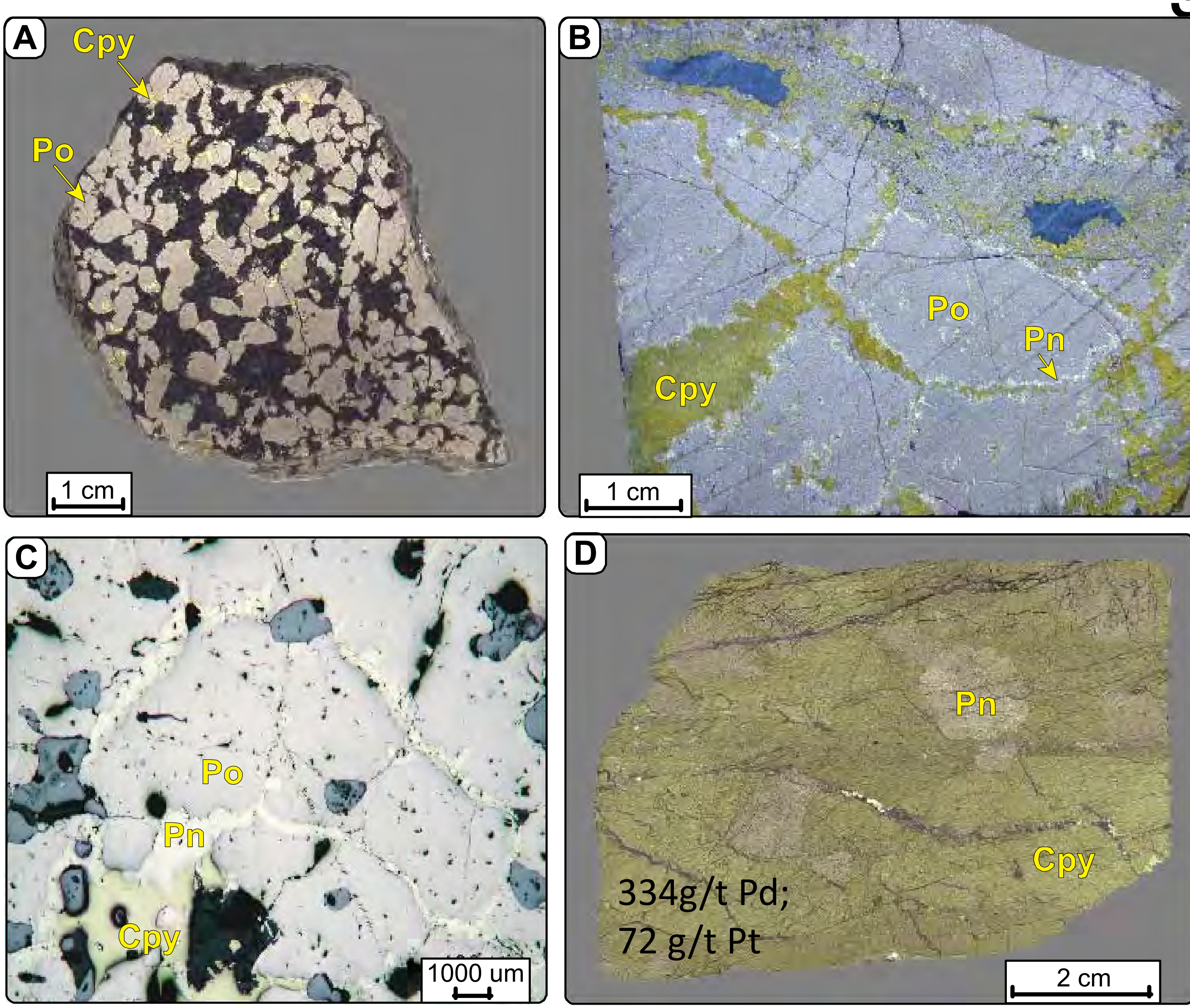
Kharaelakh Intrusion: Apophyses of Chilled Gabbrodolerite (Lightfoot and Zotov, 2013)

Kharaelakh Intrusion: Spotted Hornfels 952m; Drill Core TG21 (Lightfoot and Zotov, 2006)

Morphology of the Kharaelakh chonolith



Noril'sk-Talnakh: Massive Ni-rich contact ores



Lightfoot, 2016

Disseminated sulfide ores in taxites; Noril'sk and Talnakh

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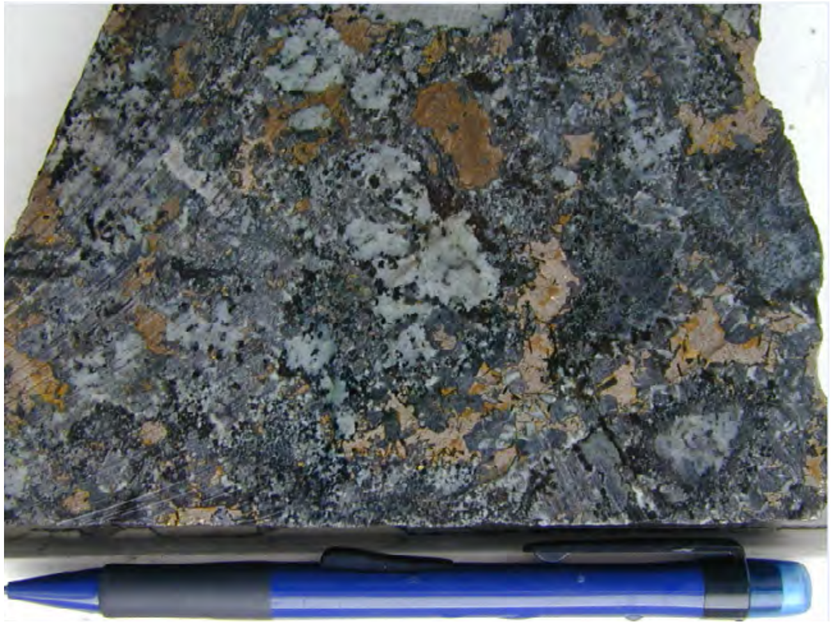
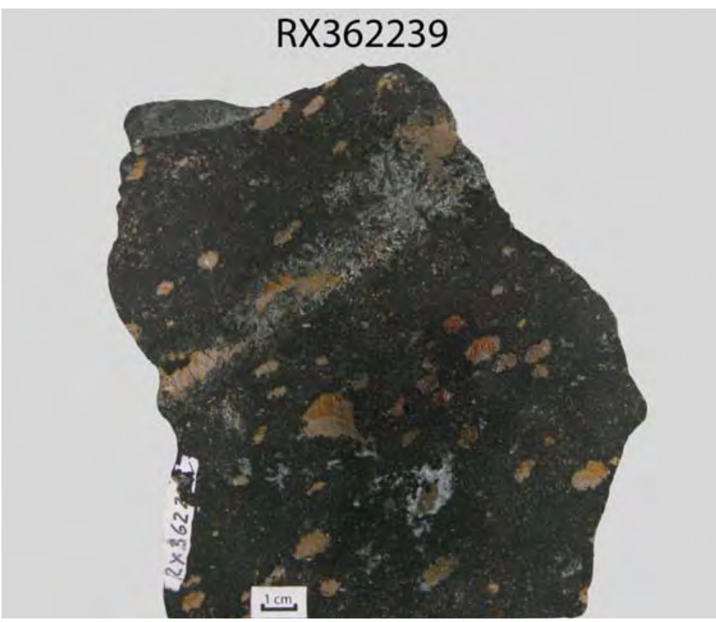
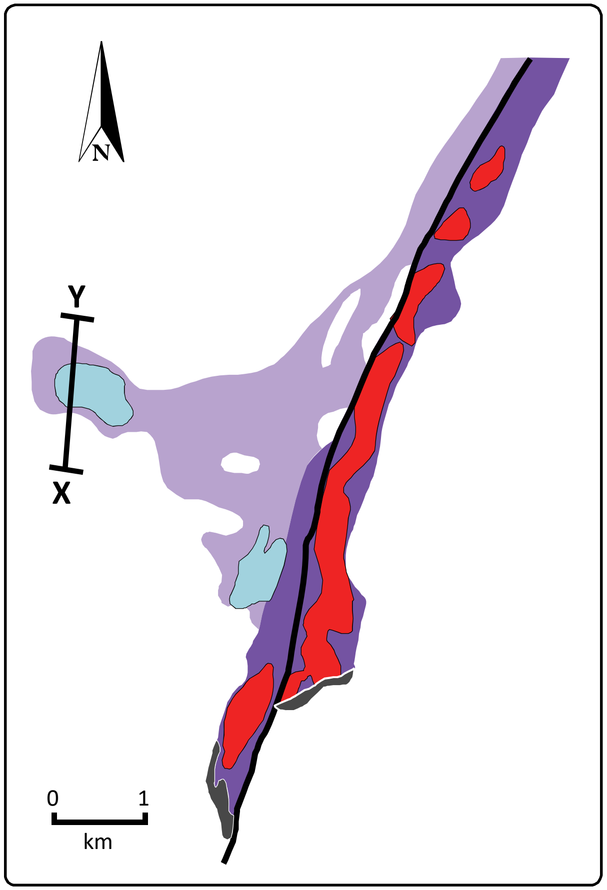
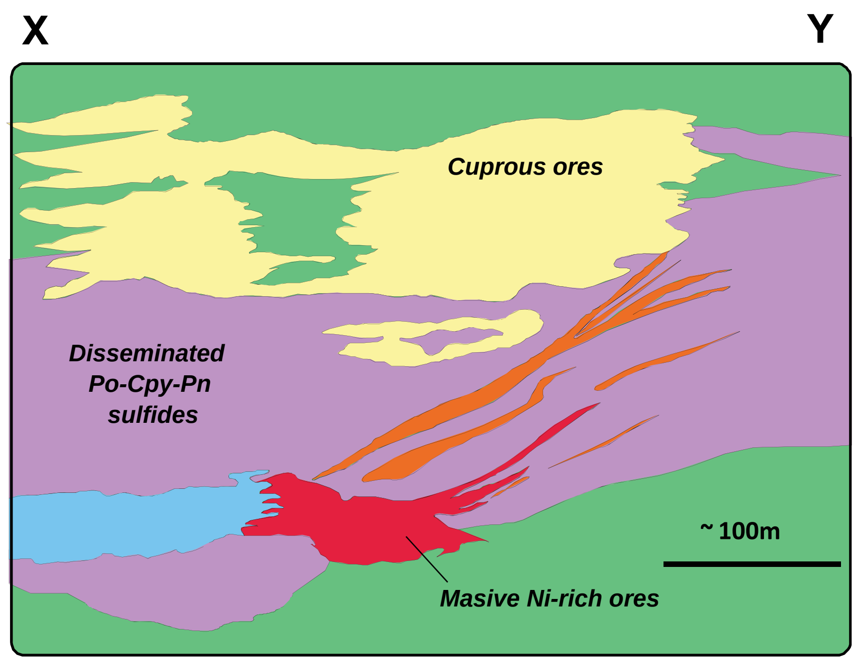




Cuprous Ores at Kharaelakh and Talnakh



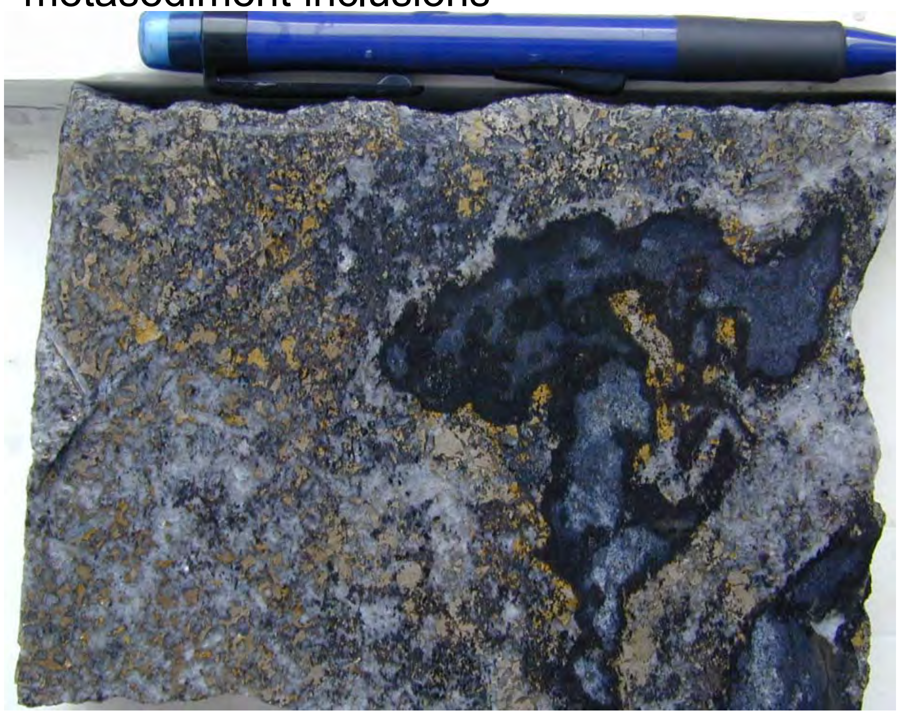
- Cuprous mineralization of the hanging wall and breccia zones
- Cuprous mineralization of the footwall
- Talnakh Intrusion
- Kharaelakh Intrusion
- Outcrop
- Noril'sk Kharaelakh Fault

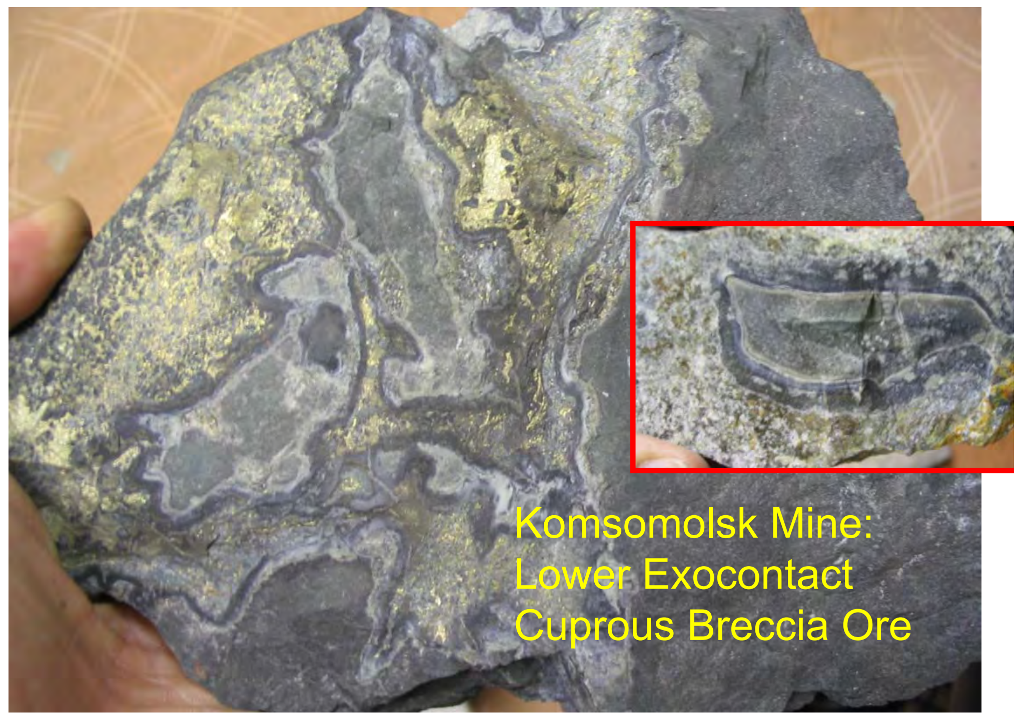


- Mk and Mk-Cub massive sulfide
- Cpy-Cub massive sulfide
- Cpy-Po vein sulfide
- Country rocks
- Kharaelakh Intrusion
- Cuprous breccia sulfide

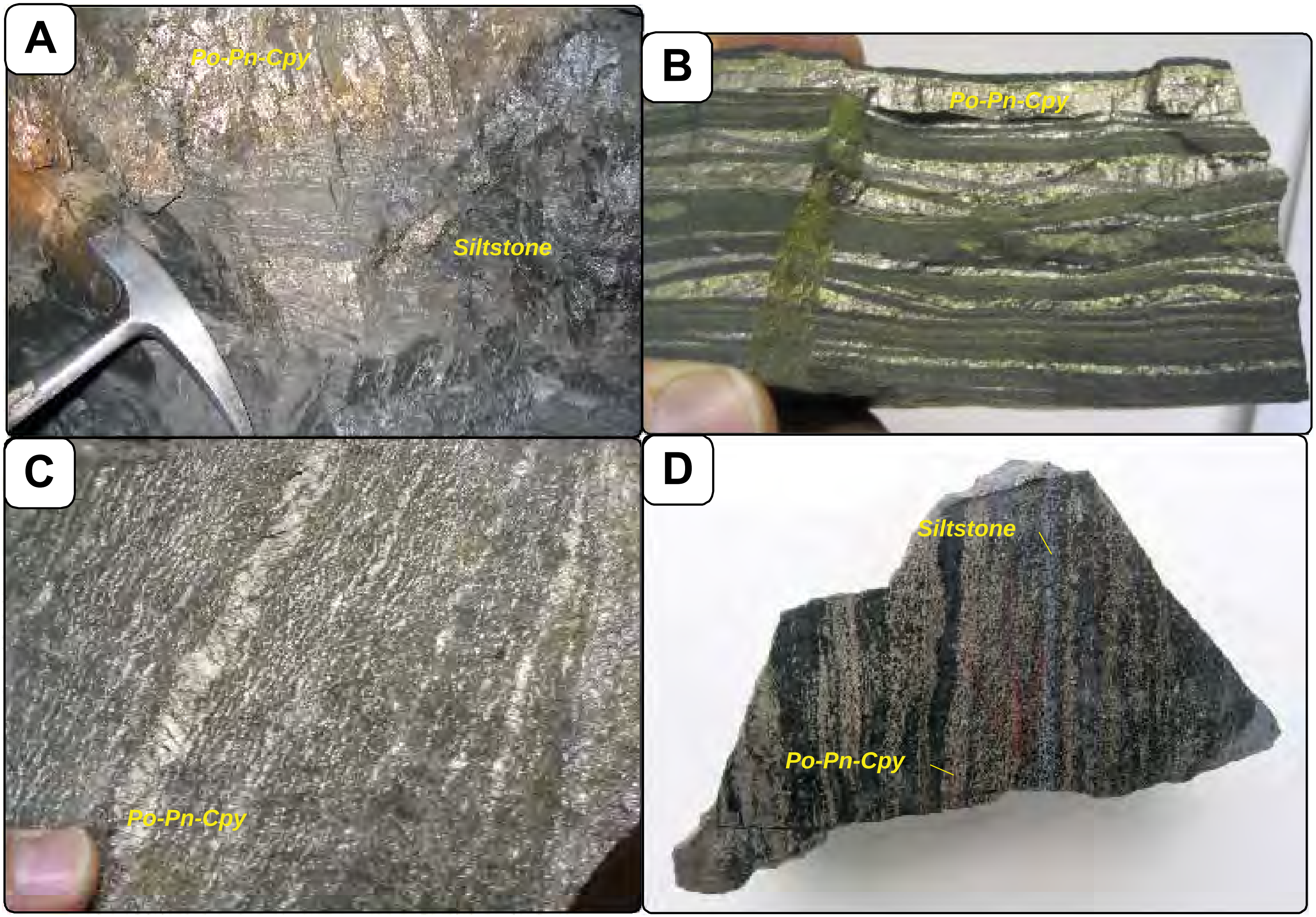
Kharaleakh and Talnakh Cuprous ores (Lightfoot and Zotov, 2013) – hosted in adjacent country rocks (skarns, metasomatism, and replacement textures in associated with magmatic sulfides)

Oktyabrsky MineUpper contact – mineralisation in ahhydrite; metasediment inclusions

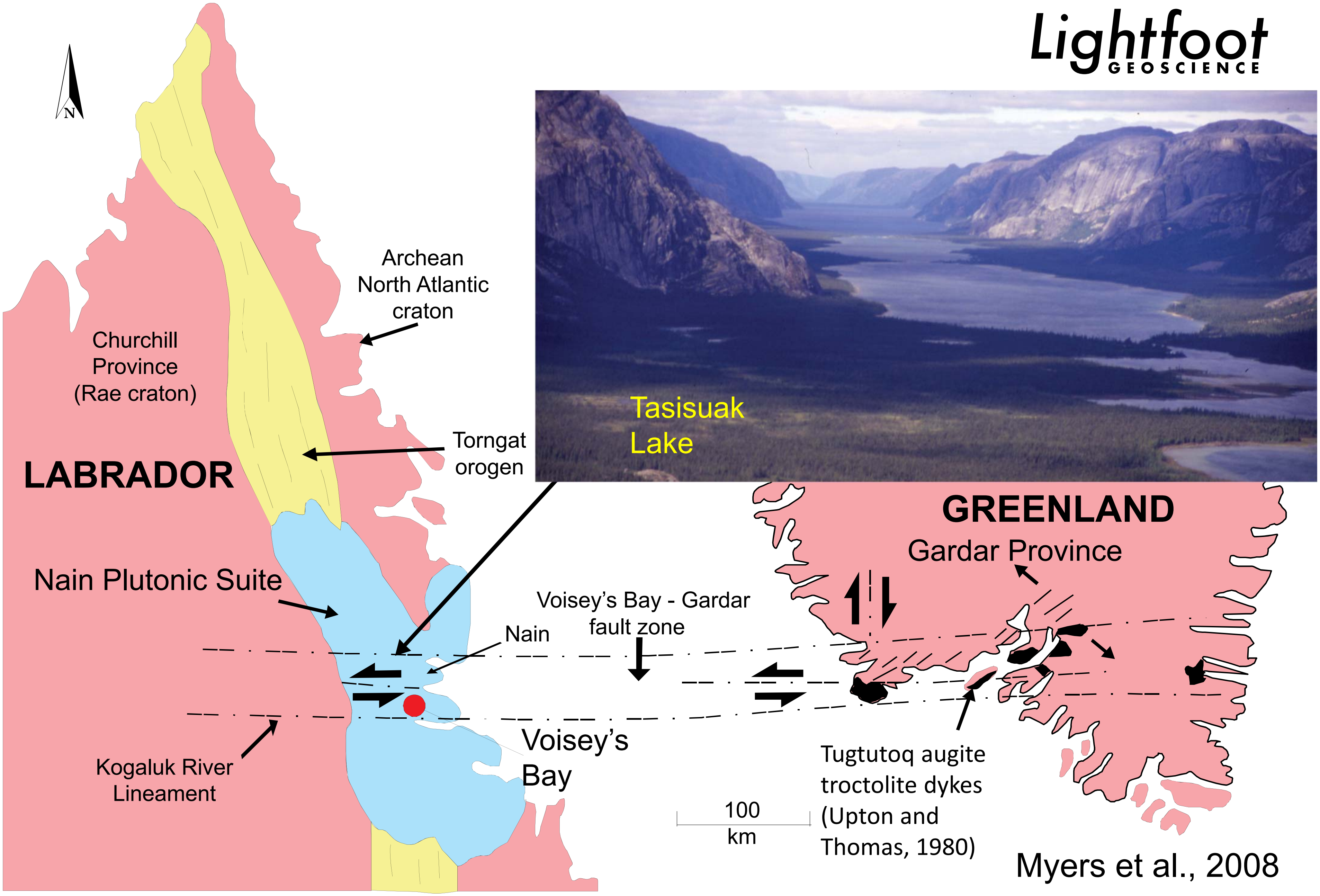




Talnakh Intrusion: Skalisty Mine. Cuprous Ore along bedding in footwall hornfels



Location of the Voisey's Bay - Gardar fault zone



Gardar Province, Greenland

Photograph: Peter Lightfoot, 1996

Gardar Province, Greenland

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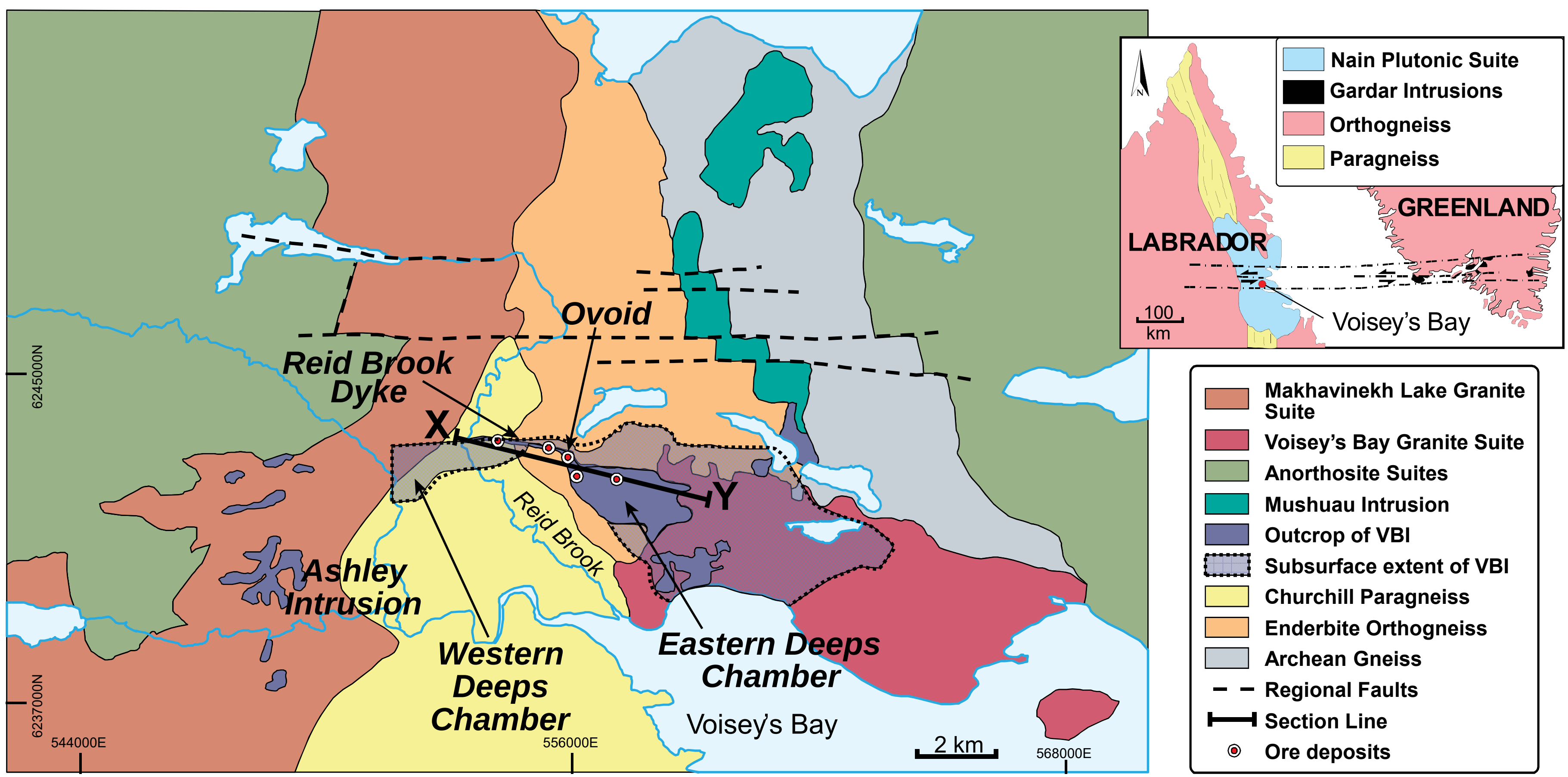
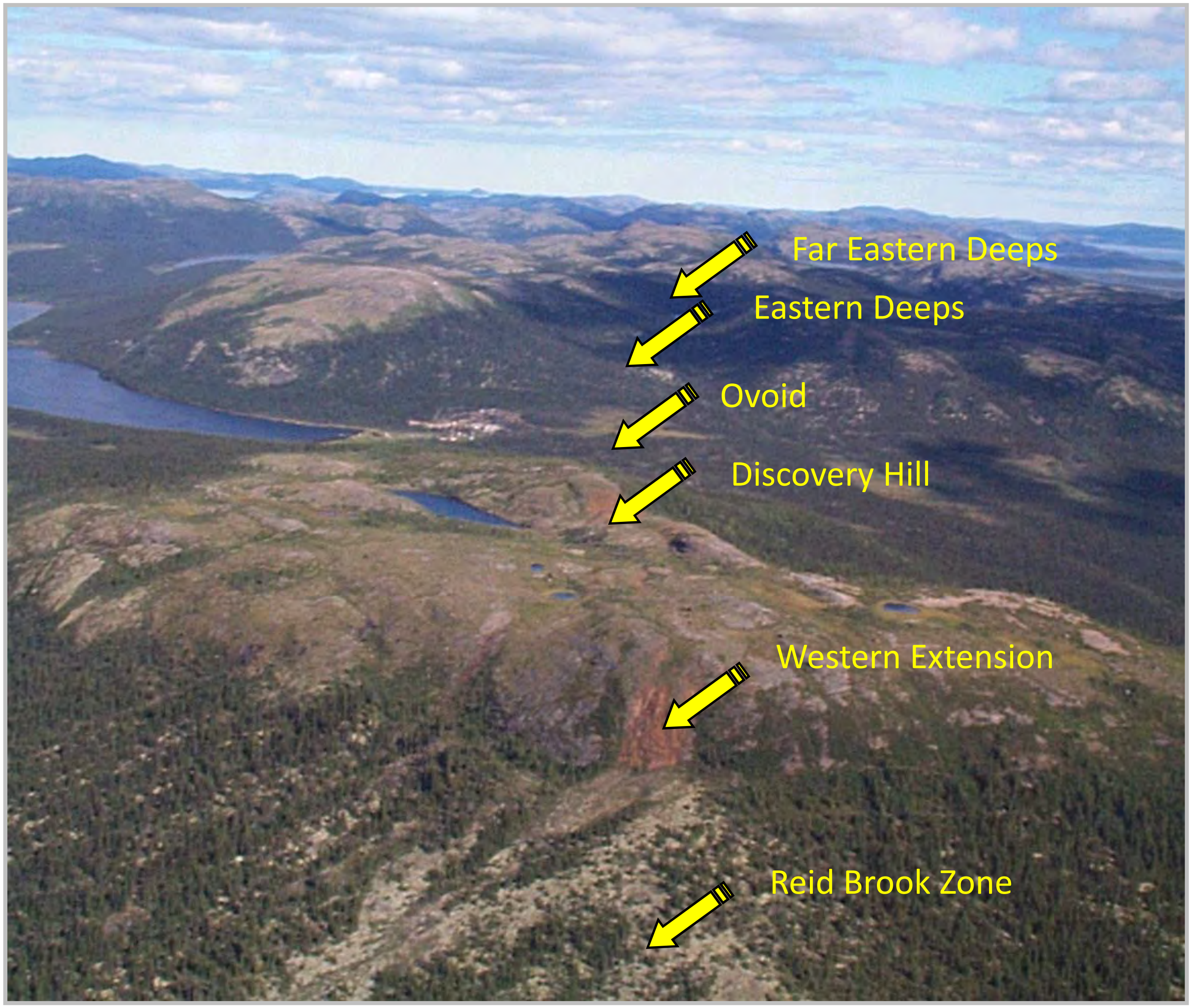
Photograph: Peter Lightfoot, 1996

Geology of the Voisey's Bay Deposit



Voisey's Bay: location of mineral zones



Voisey’s Bay: Arrival at Camp Pond, 1996

Photograph: Peter Lightfoot, 1997

1996 Camp, Voisey's Bay (Ovoid)

Lightfoot GEOSCIENCE

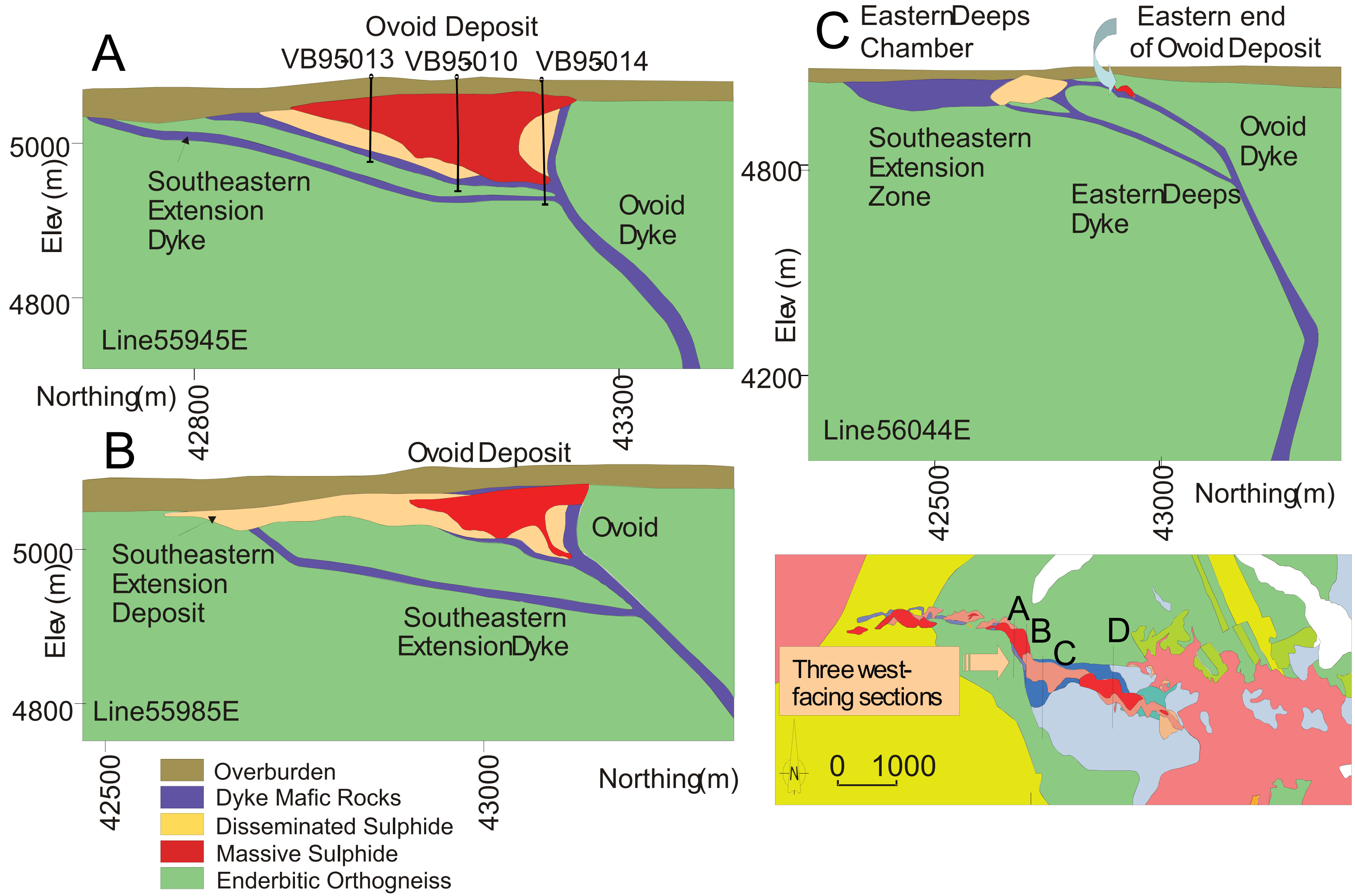
Exploration defined 31.7 m tonnes 2.83%Ni, 1.68%Cu, and 0.12% Co

Photograph: Peter Lightfoot, 1996

Voisey's Bay: Camp pond

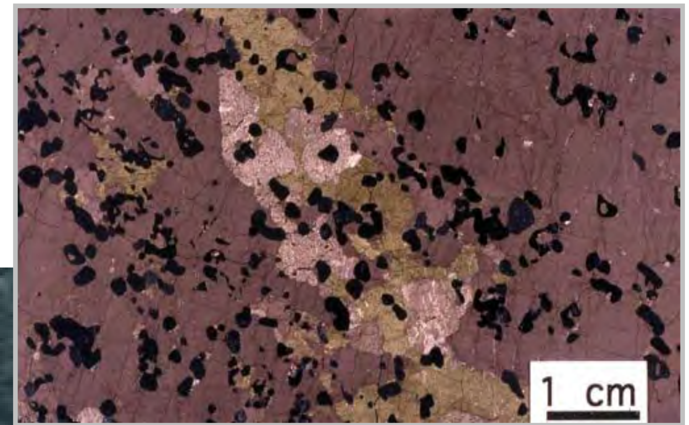
Photograph: Peter Lightfoot, 1997

Geological relationships in the Ovoid



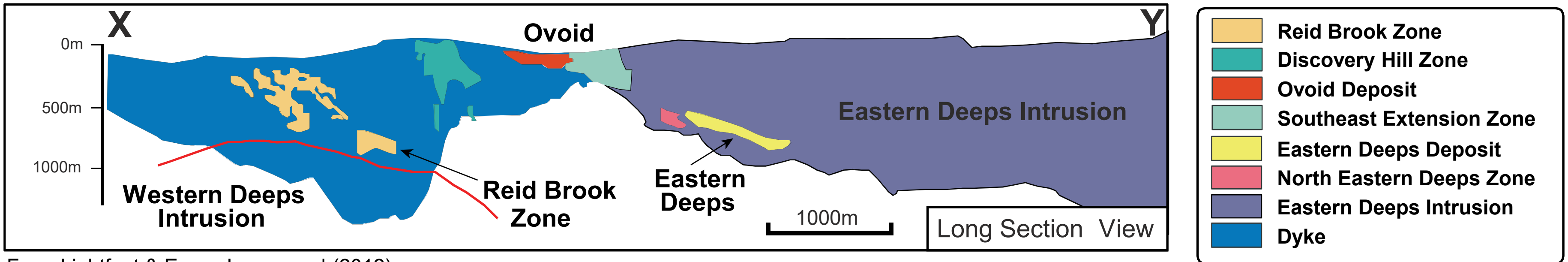
Lightfoot et al (2011)

Ovoid Deposit

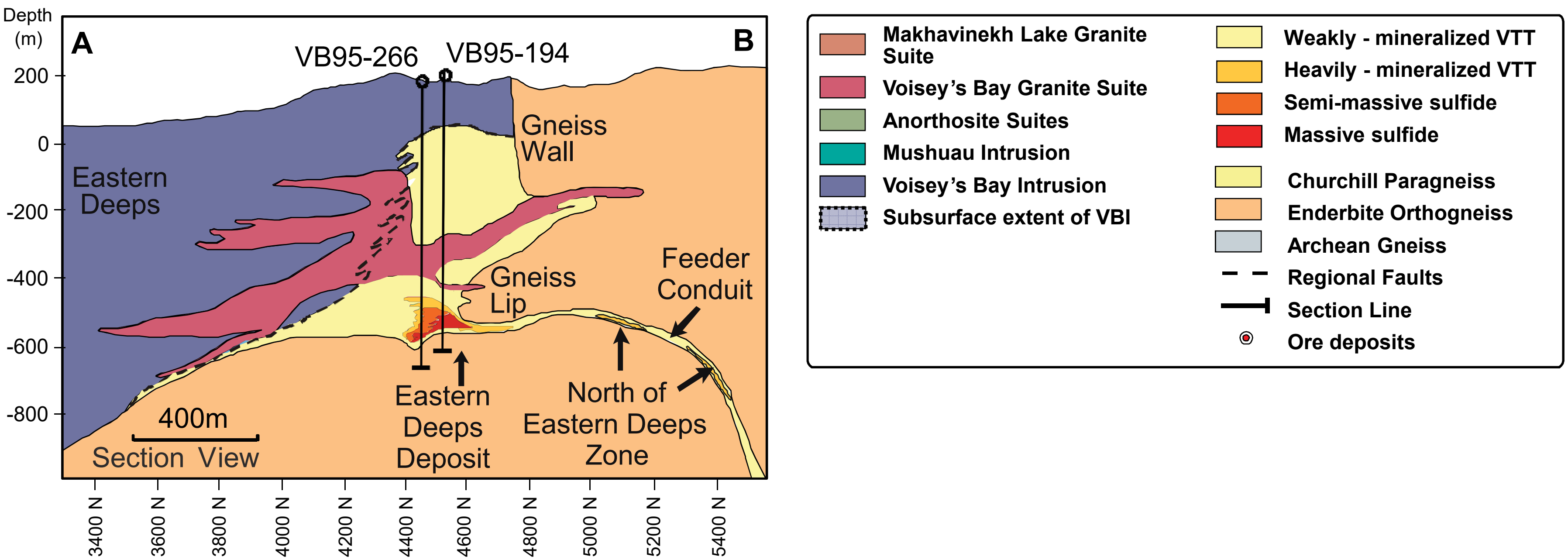


Photograph: Peter Lightfoot, 2007

Geology of the Voisey's Bay Deposit



From Lightfoot & Evans Lamswood (2012)



Voisey's Bay: Drill rig on Eastern Deeps, 1997

Exploration defined indicated resource of 50 m tonnes 1.63%Ni, 0.67%Cu, and 0.09% Co

Photograph: Peter Lightfoot, 1997

Voisey's Bay: Eastern Deeps, 1997

Photograph: Peter Lightfoot, 1997

1999: Anakhtalak Bay Camp

Lightfoot GEOSCIENCE

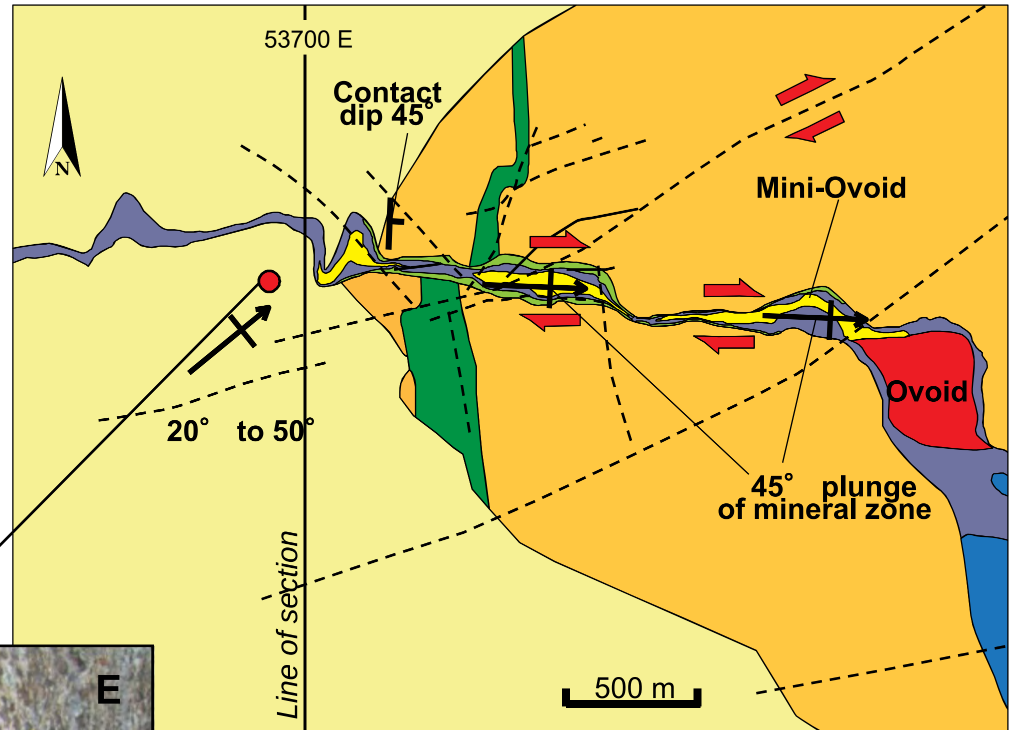
Photograph: Peter Lightfoot, 1999

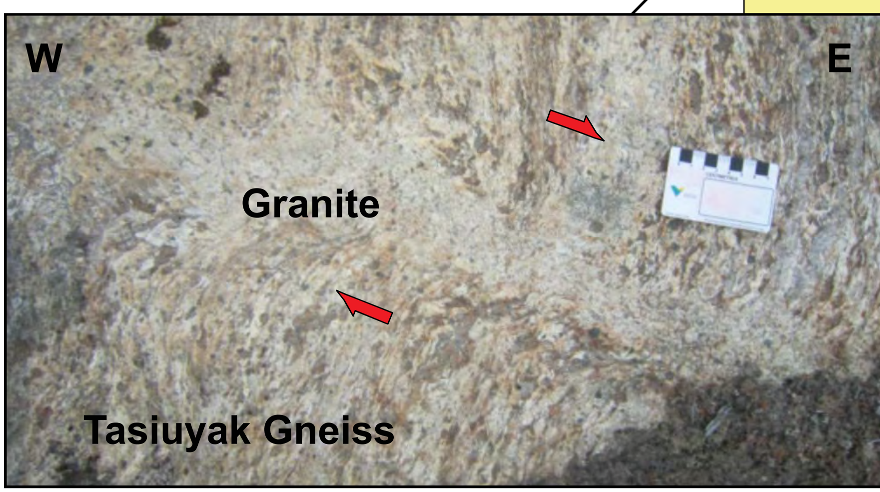
2007: Voisey's Bay Mine

Photograph: Peter Lightfoot, 2007

Geology of the Reid Brook Zone

- Massive sulfide
- Leopard troctolite
- Variable troctolite with heavy disseminated sulfide
- Troctolite
- Ferrogabbro
- Churchill paragneiss
- Felsic Enderbite
- Mafic Enderbite
- Faults
- Plunge of mineral zone



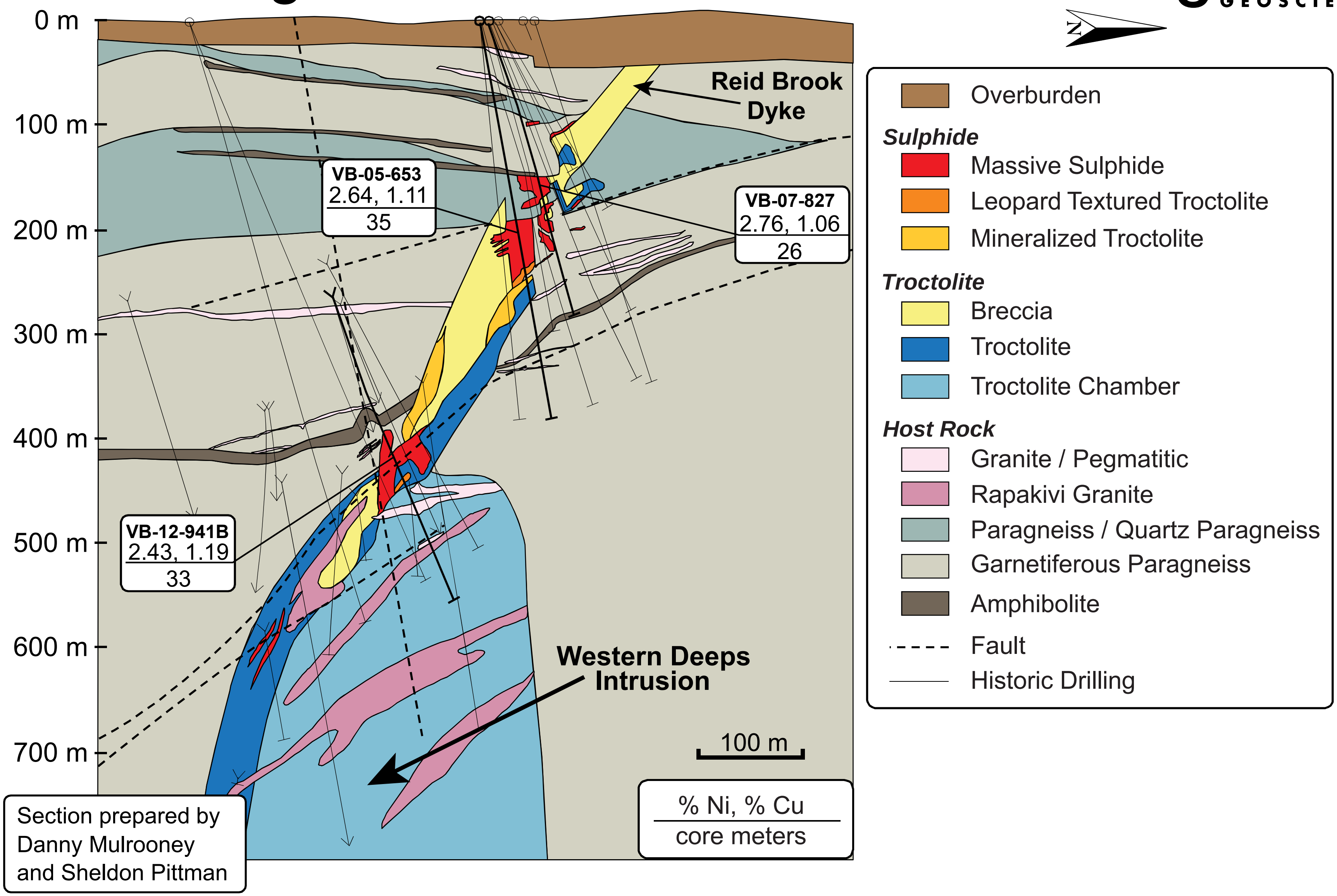


Evidence for syn-magmatic dextral transtension

1. Displaced contacts
2. Magnetic fabric
3. Morphology of intrusion
4. Shear zones with granite
5. Fabric of gneiss rotated into north wall of Eastern Deeps

From Lightfoot & Evans Lamswood (2012)

Reid Brook Zone: 53700E Section – Looking West



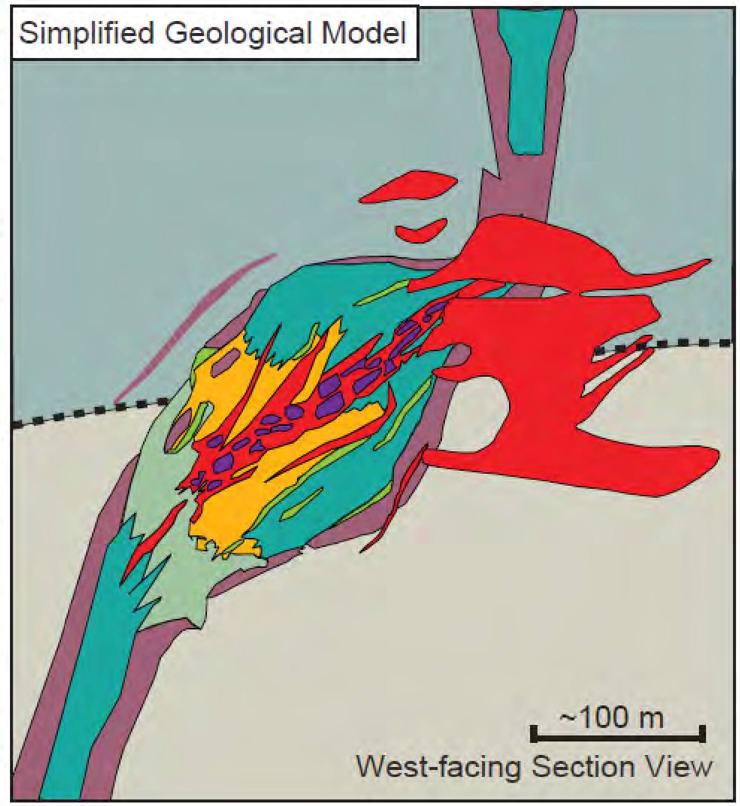
Geological Mode: Reid Brook Zone

Faulted contact of quartzofeldspathic paragneiss with garnet paragneiss: epidote-chlorite-carbonate alteration.

Massive sulphide: pyrrhotite surrounded by loops of chalcopyrite with pentlandite eyes.

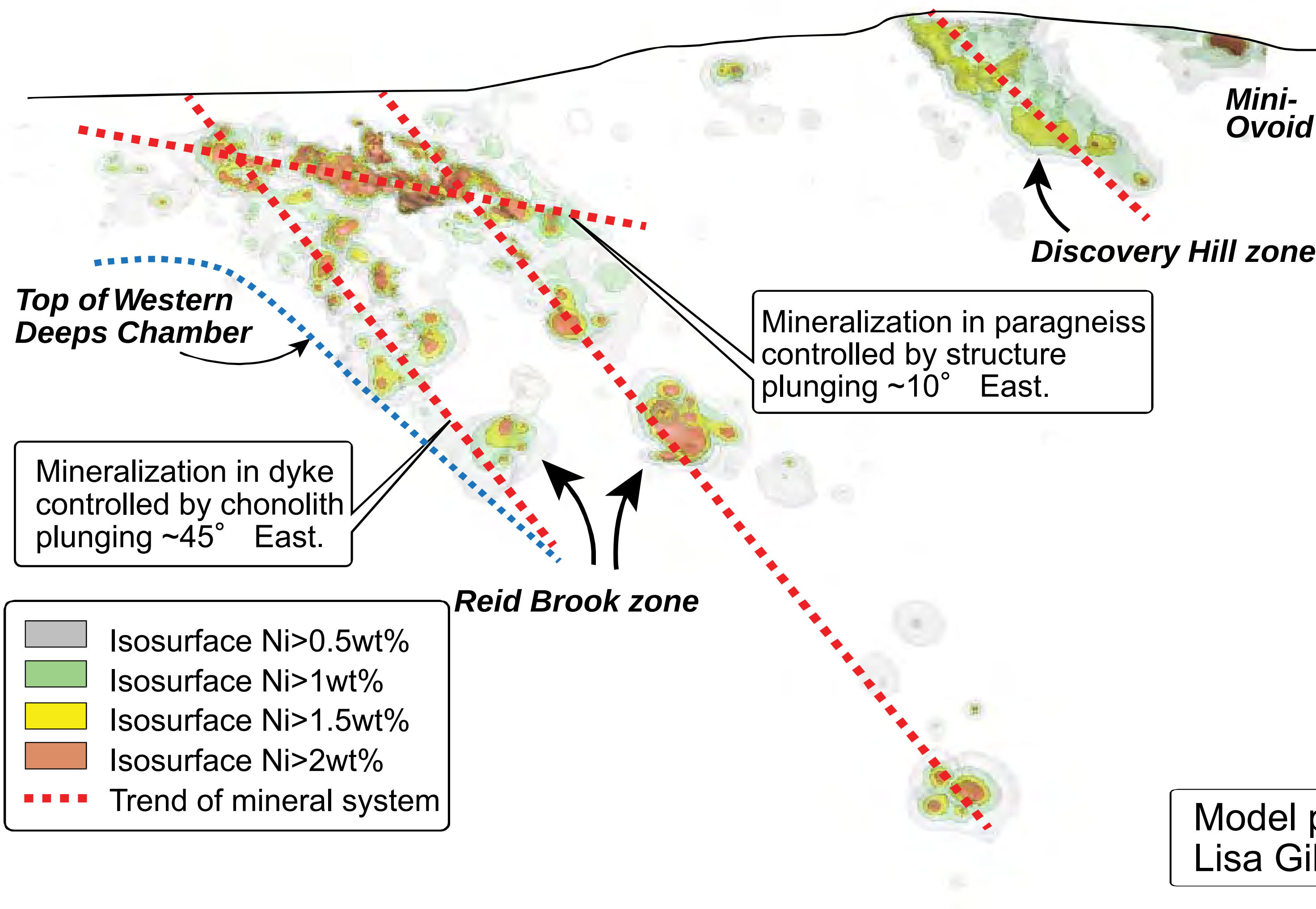
Tasiuyak quartzofeldspathic paragneiss with gneissic fabric.

- Variable troctolite with <10% fragments and <10% sulfide
- Massive sulphide
- Mafic to ultramafic fragments
- Zone of aligned gneiss fragments
- Leopard-textured troctolite
- Variable troctolite
- Ferrodiorite and biotite Ferrogabbronorite
- Paragneiss / Quartz Paragneiss
- Garnetiferous Paragneiss



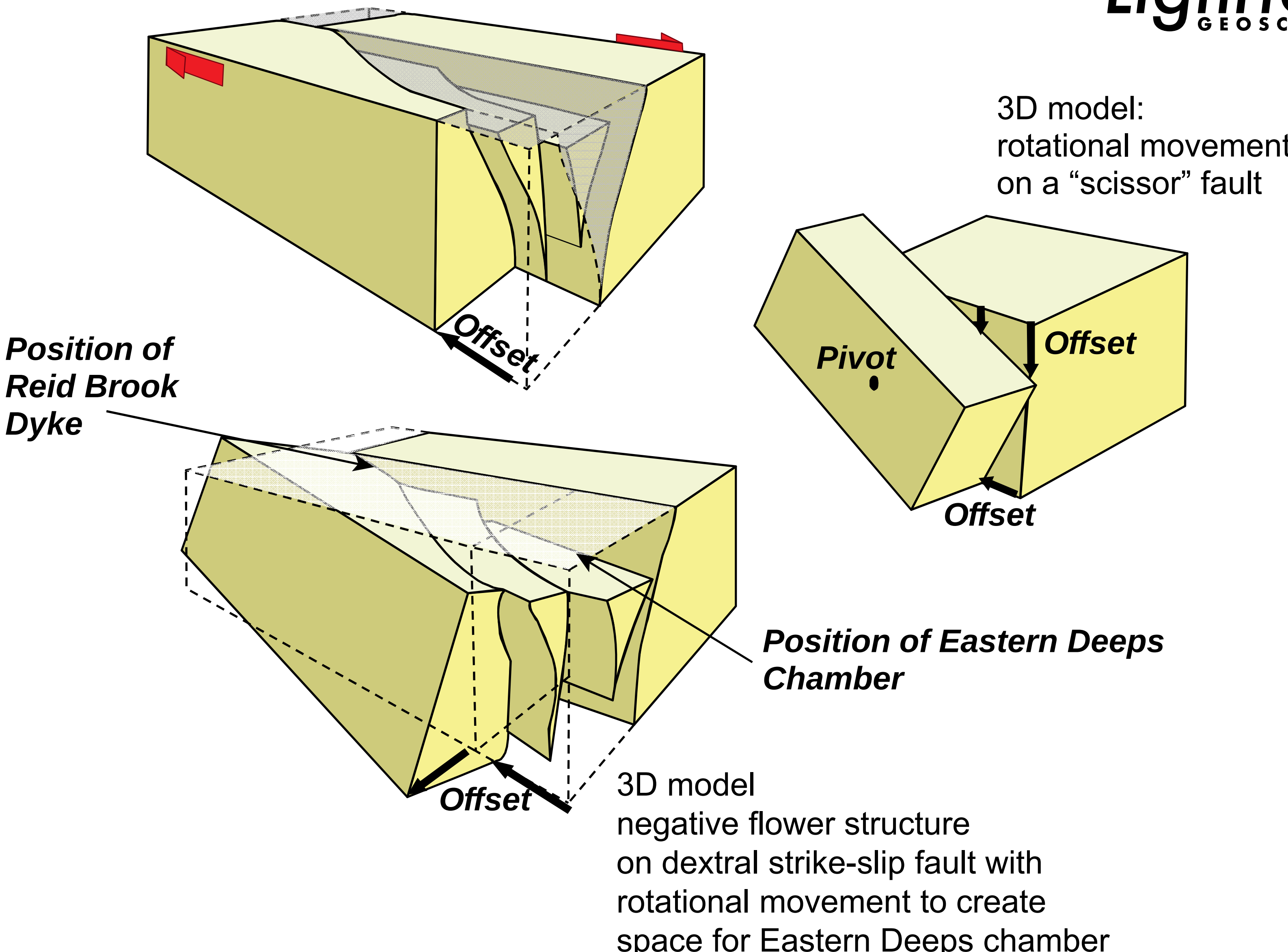
After Lightfoot & Evans Lamswood (2012)

Leapfrog model showing Ni grade distribution in the Reid Brook Zone projected onto W-E long section



Model prepared by Lisa Gibson

Kinematics: Summary for Voisey's Bay



From Lightfoot & Evans Lamswood (2012)

Summary

- Magmatic Ni-Cu-(PGE) sulphide ore bodies: often not the product of simple *in-situ* gravity settling within a magma chamber.
- Sulphide-laden magma ascended through a sub-vertical conduit system in a structural zone from a parental source/chamber at depth.
- Common theme now recognised in a spectrum of Ni sulphide ore deposits that underpin process models for their formation
  - Funnel-shaped intrusions
  - Chonoliths
  - Dykes
- Conduit morphology is controlled through the intersection of regional structures that create space, and are localized by dilations and traps created by transtension in strike-slip fault zones:

Global Examples of magma conduits (red – this talk):

- FUNNEL MORPHOLOGY: Jinchuan, Hong Qi Ling #1, Jingbulake, Huangshan, Huangshandong, Limahe, Qingquanshan, Lengshuiqing, Zhubu, Ban Phuc, Ovoid, Discovery Hill, Eastern Deeps, Eagle, Double Eagle, Aguablanca, Maksut, Santa Rita, Suwar, Savanah, South Raglan
- PIPE (CHONOLITH) MORPHOLOGY: Baimazhai, Tongdongzi, Talnakh, Kharaelakh, Noril'sk I, Karatungk, Noril'sk II, Chernagorsk, Maslovskoe, Tamarack, Current Lake, Babel-Nebo, Nkomati, Limoeiro, Chibasong, Wellgreen, Voronezh, Zhouan, Xiarihamu
- DYKE MORPHOLOGY: Reid Brook, NED, Worthington (Sudbury), Copper Cliff (Sudbury), Hong Qi Ling #7, Tong Dong Zi

Controls on emplacement and morphology of komatiites (Yilgarn, Thompson, Pechenga, and Raglan) may also share primary structural controls.

Thank You: Vale

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