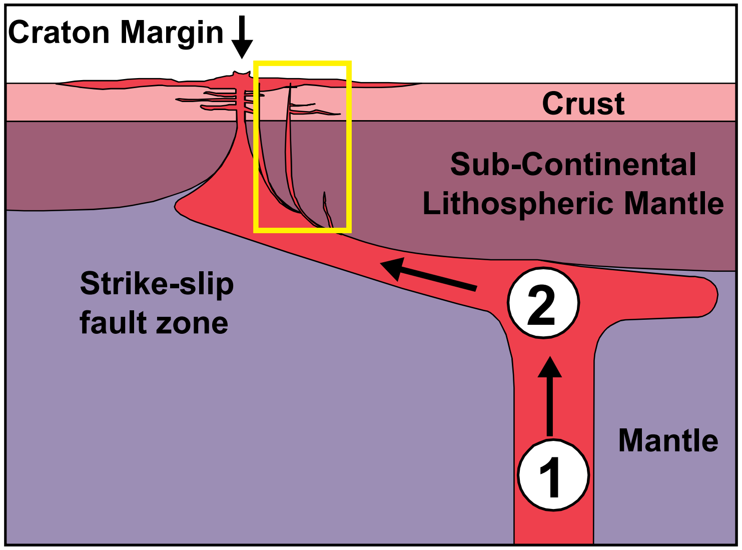
Structural controls on the primary distribution of mafic-ultramafic intrusions containing Ni-Cu-Co-(PGE) sulfide mineralization

Peter C Lightfoot and Dawn Evans-Lamswood, Vale Base Metals

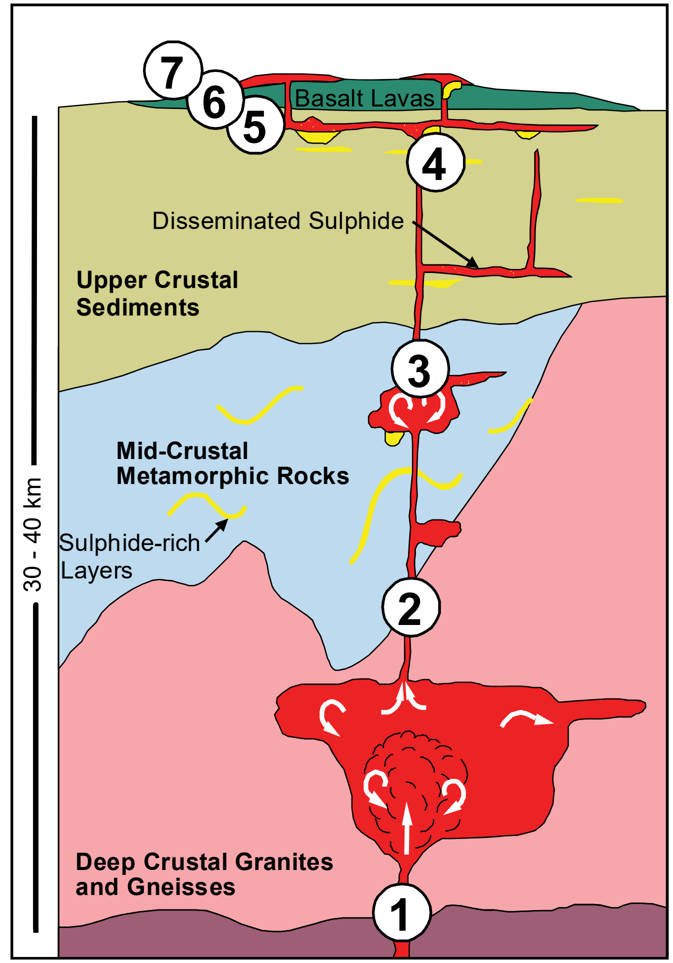
Process Controls on Formation of Nickel Sulfides

Tetonic Setting



Begg et al (2011)

Crustal Architecture



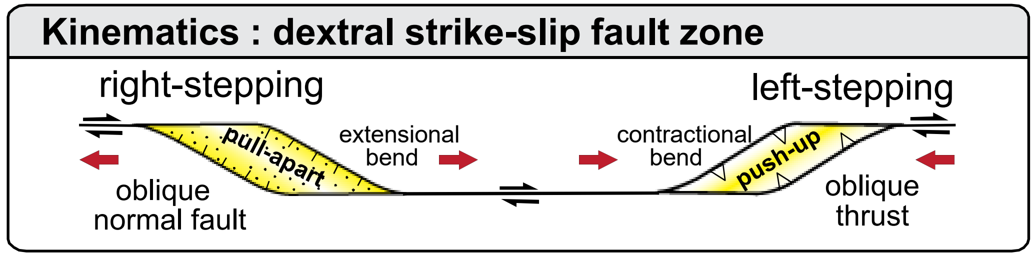
After: Lightfoot (2007) and Naldrett (2010)

Key Process Controls

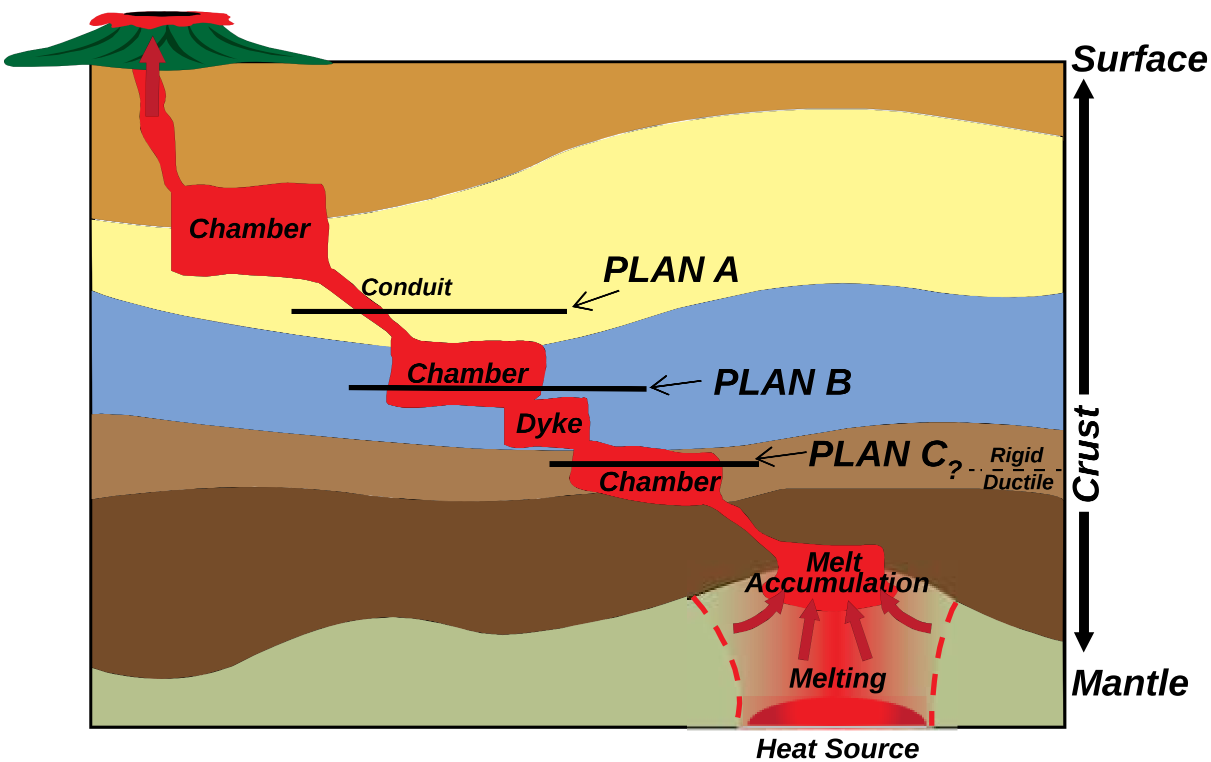
- (7) Syn-tectonic and post-tectonic modification
- (6) Sulphide segregation
- (5) Sulphide saturation and metal endowment
- (4) Emplacement
- (3) Fractionation and contamination
- (2) Ascent of magma
- (1) Generate ultramafic magma from metal endowed source

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

Magma Conduits

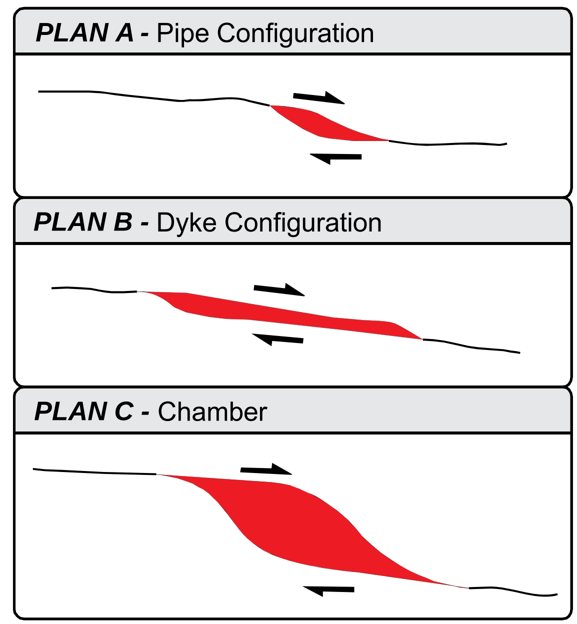


View Along Plane of Stike-Slip Shear Zone



Plan View

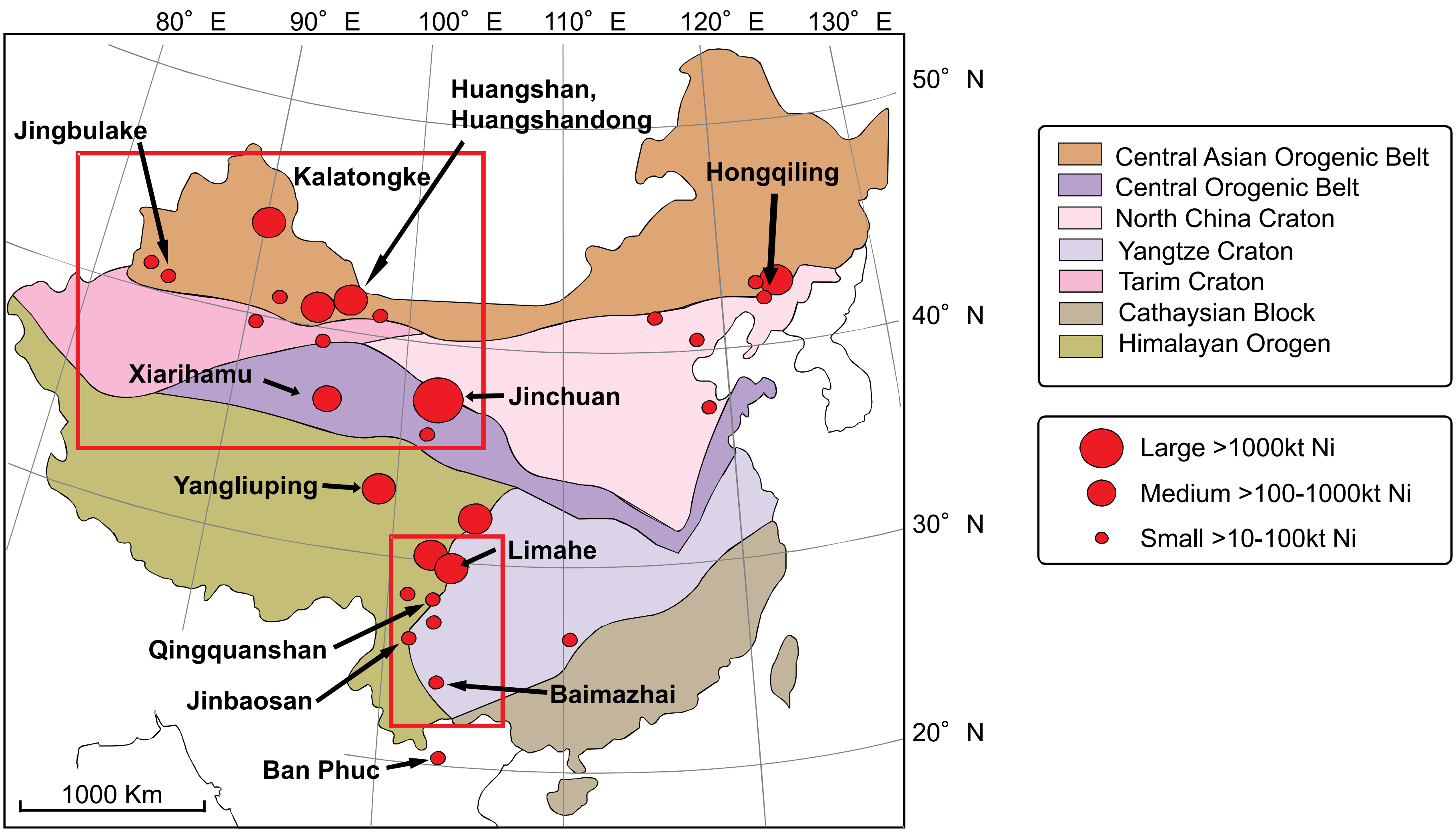
Magma Conduits (pipes, dykes, chambers) at different crustal levels



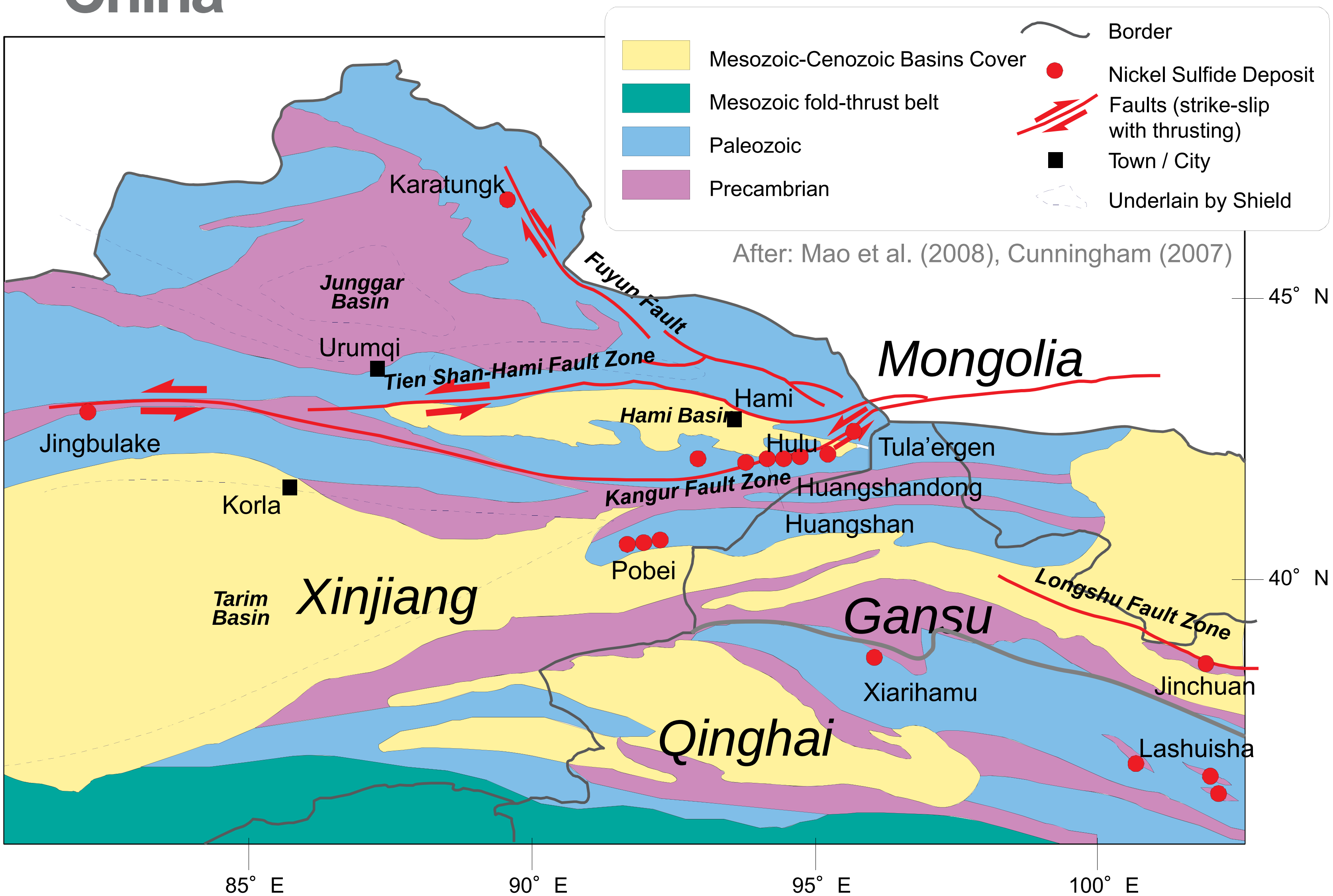
Key Points To Take Away

- 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, Norli'sk and Voisey's Bay
- Chamber geometry, ore distribution, and transport of magmatic sulfide controlled by dilational space created in a right-lateral fault zone

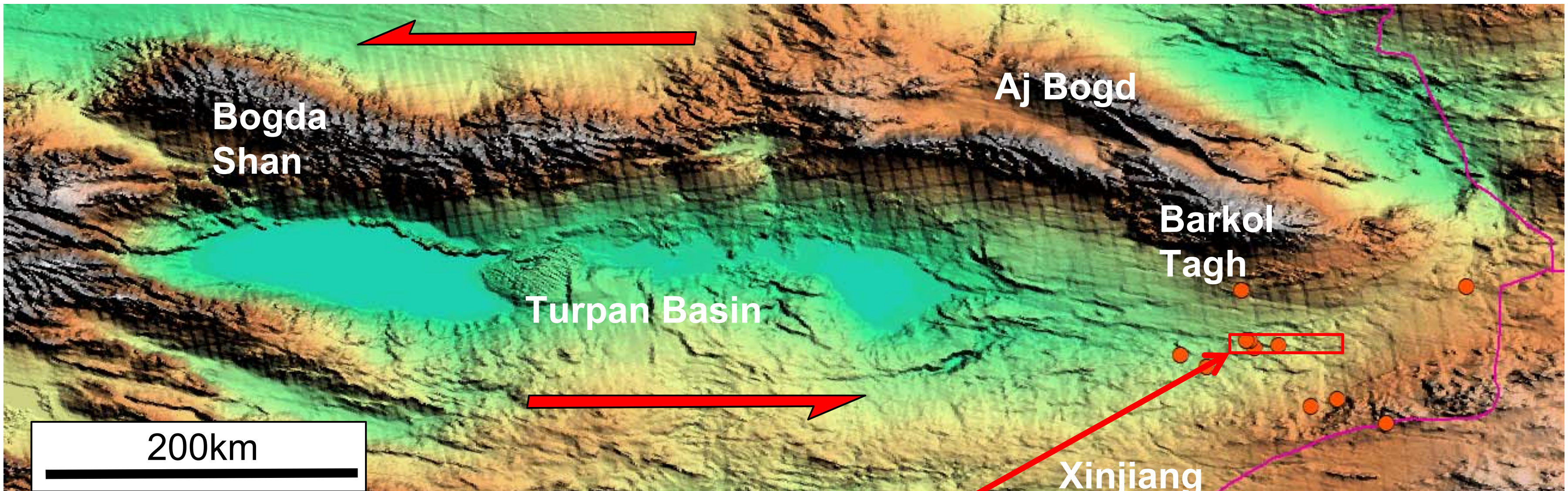
Distribution and scale of Ni sulfide deposits in China



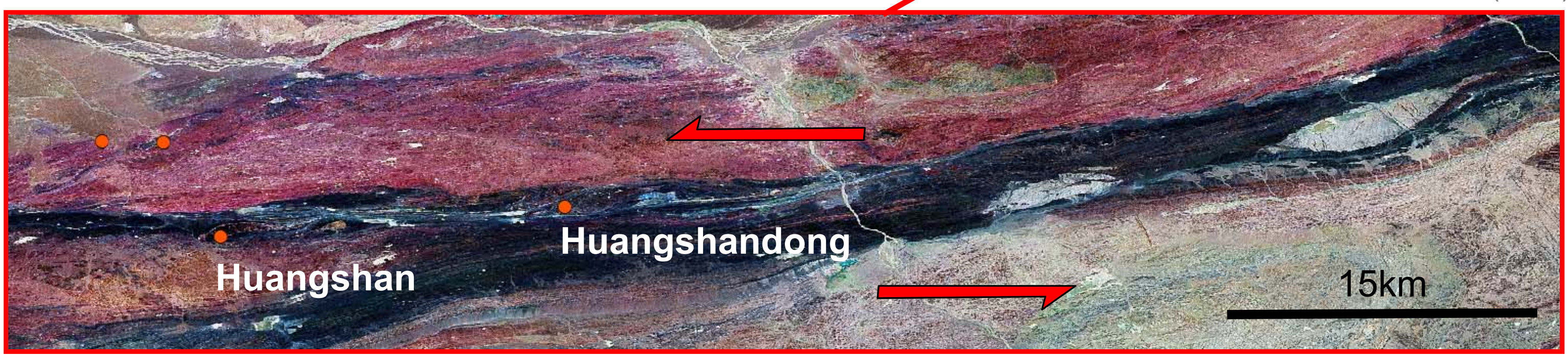
Distribution of nickel deposits in Western China



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

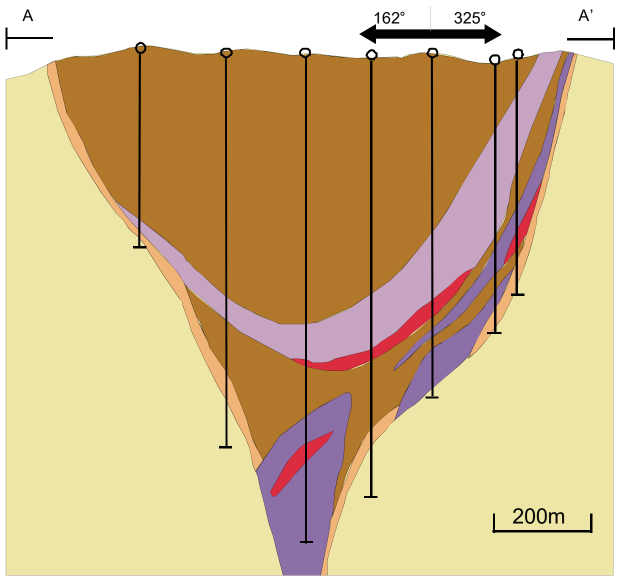


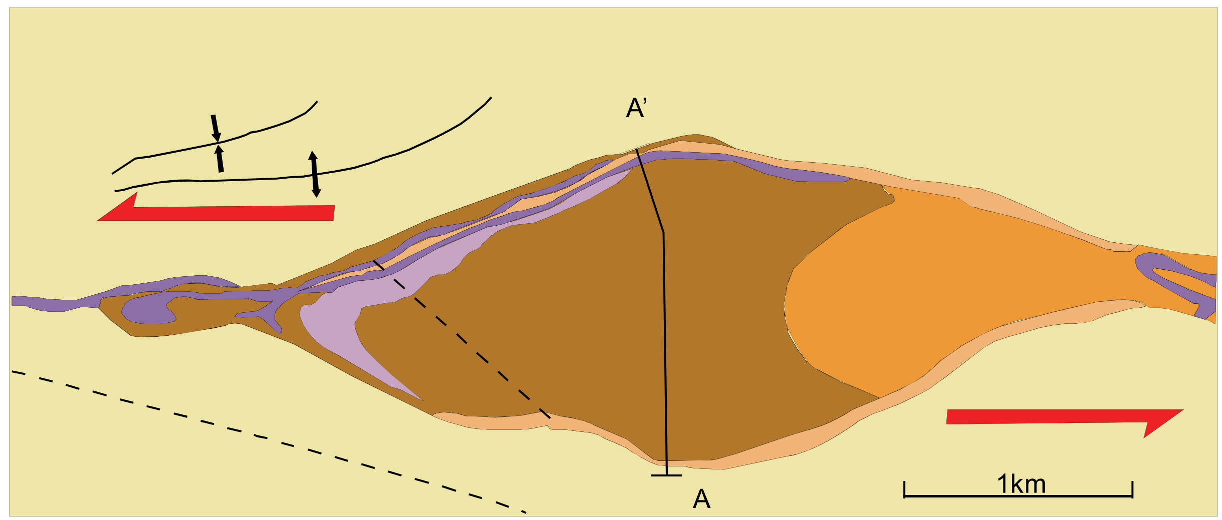
After: Mann, (2007)

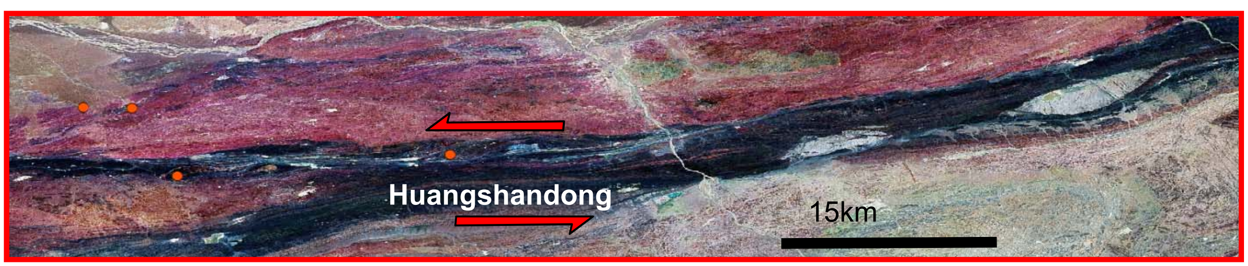


Lightfoot, Evans-Lambswood, (2007)

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

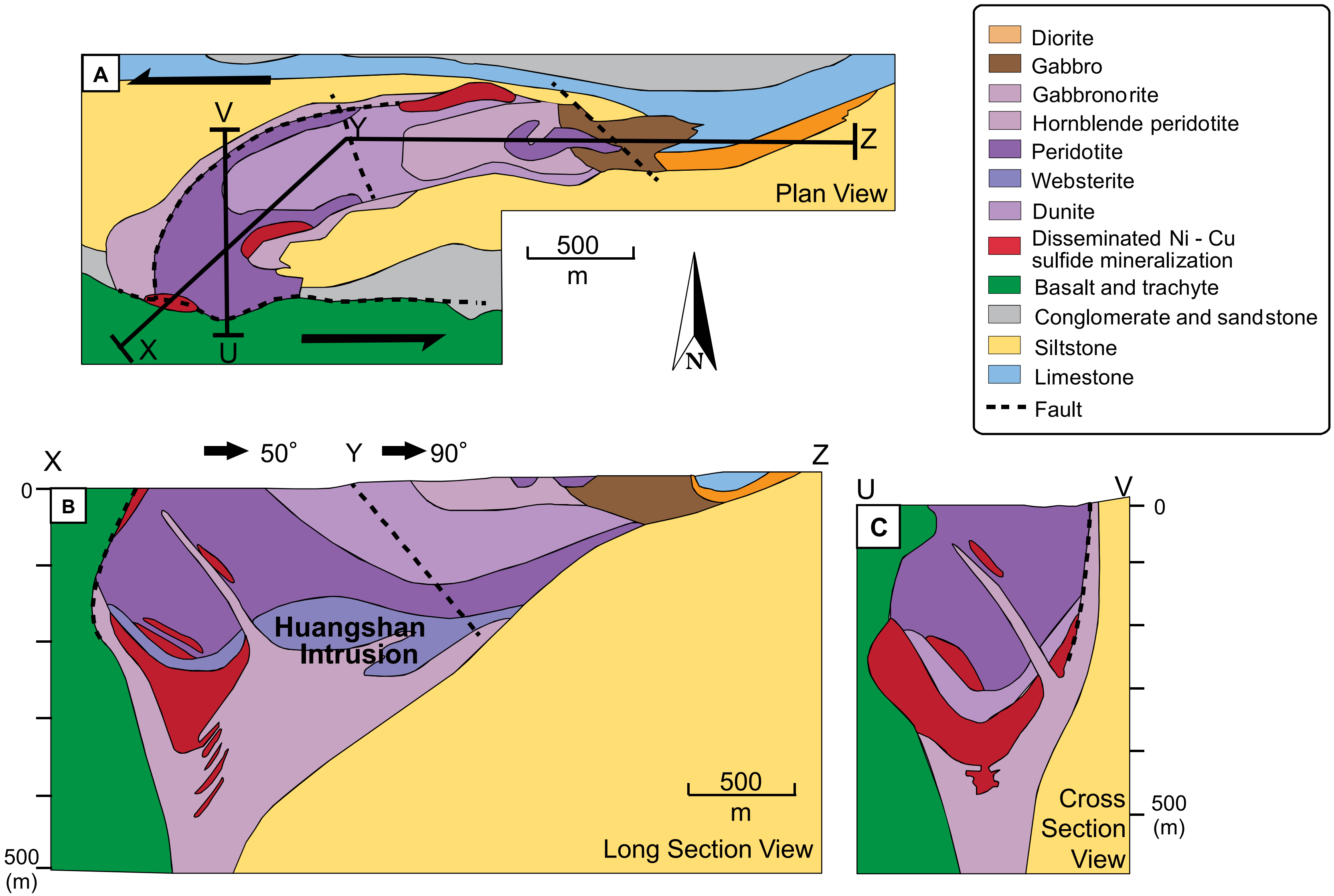
Xinjiang: Hami Belt – shaft on Huangshandong

Photograph: Peter Lightfoot, 2001

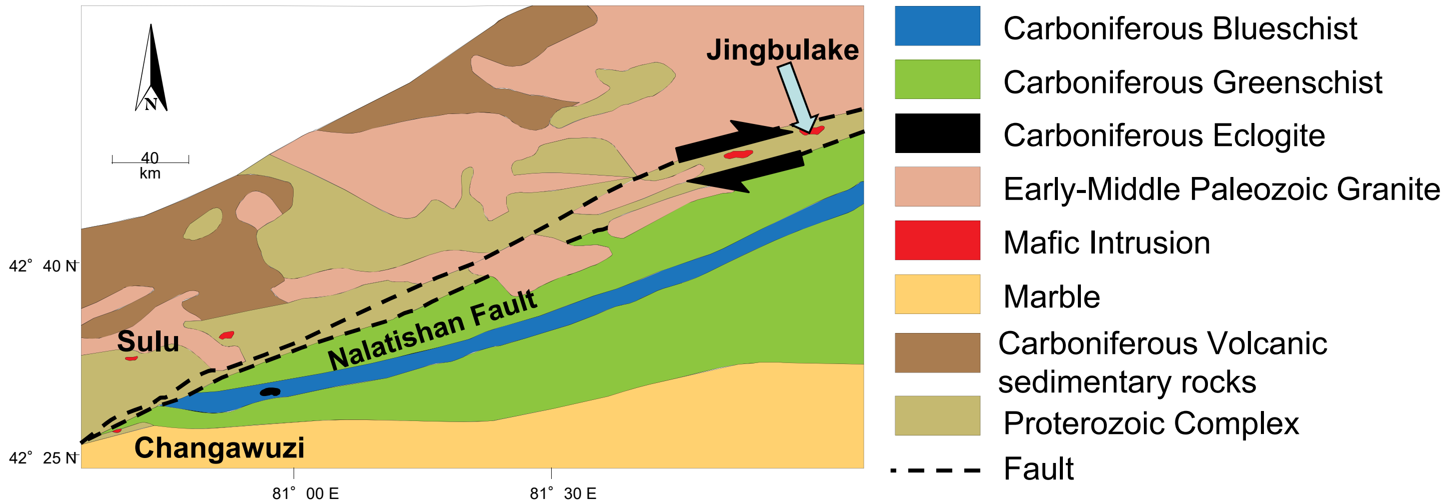
Xinjiang: Hami Belt – exploration under Chairman Mao's 5 Year Plans

Photograph: Peter Lightfoot, 2001

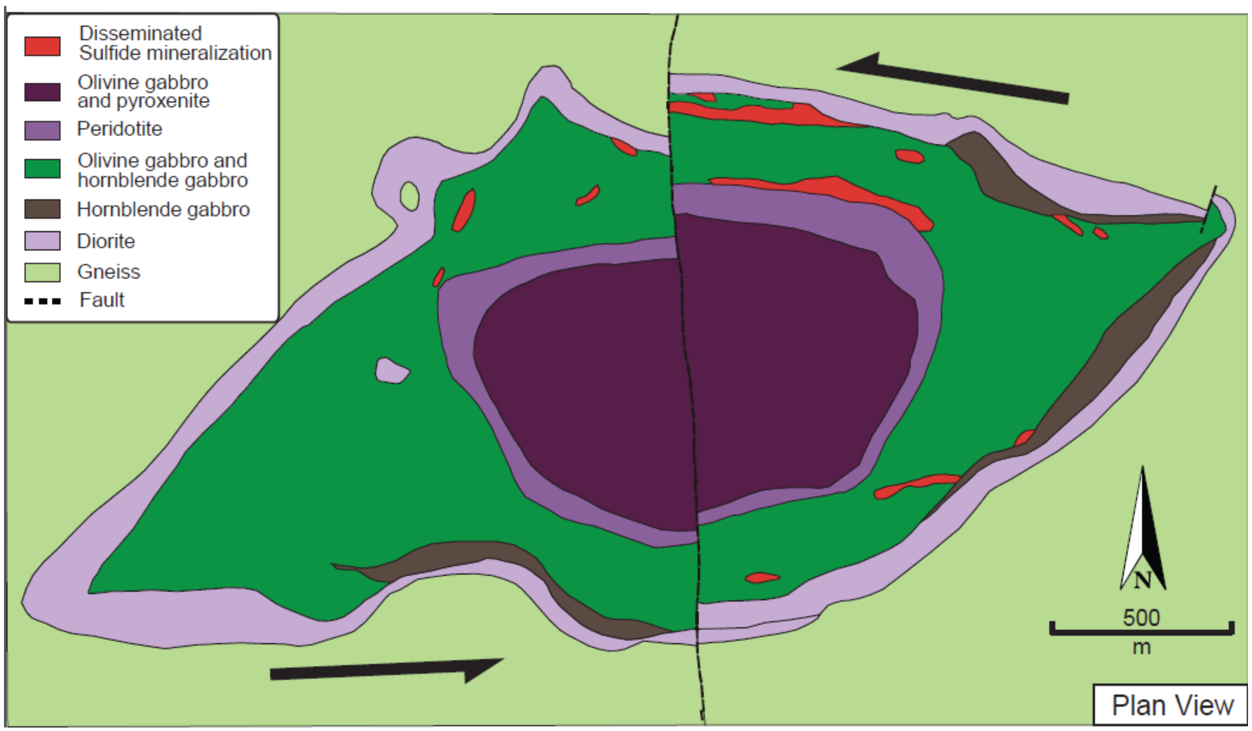
Geology of the Huangshan Intrusion and the location of Cu-Ni Sulfide mineralization



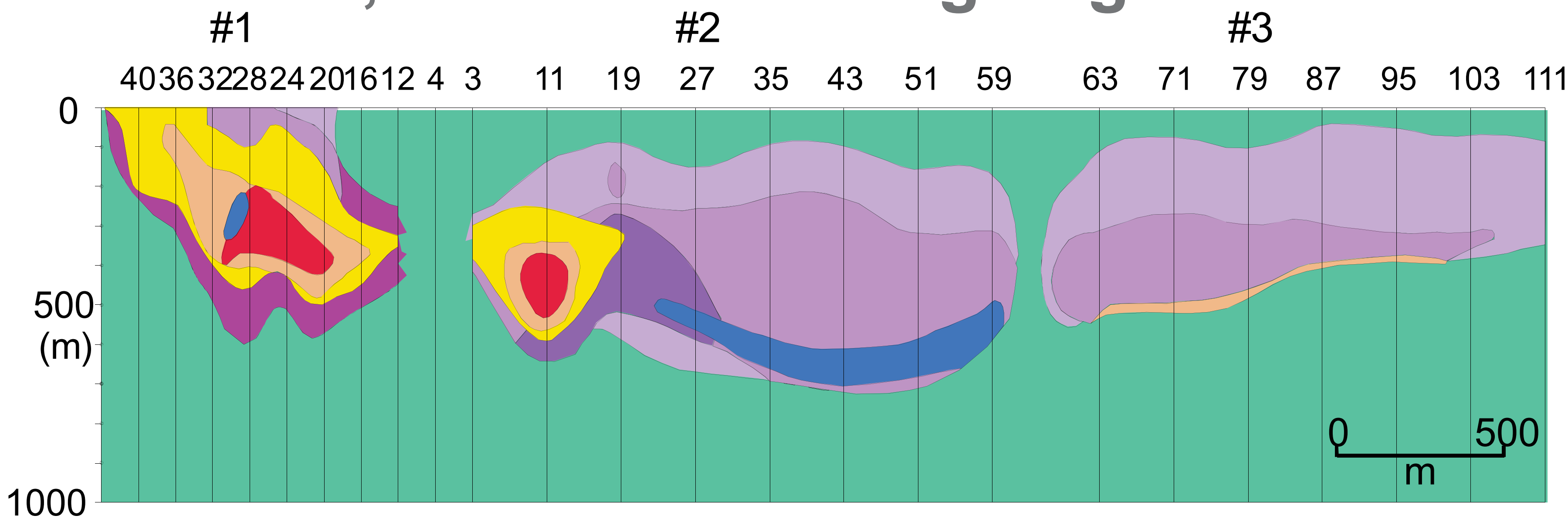
Jingbulake Intrusions, Xinjiang Province



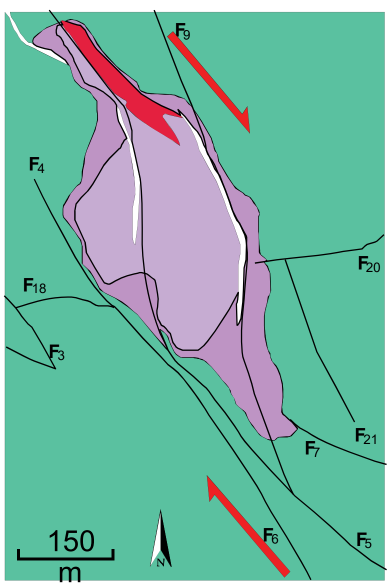
Yang et al., 2012



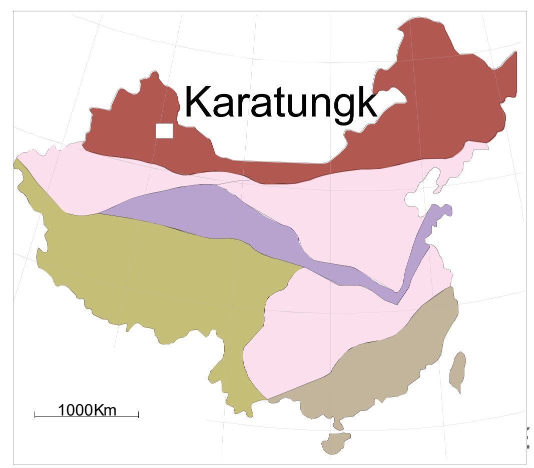
Karatungk #1,2 and 3 Intrusions, Xinjiang Province, China: North-facing long section



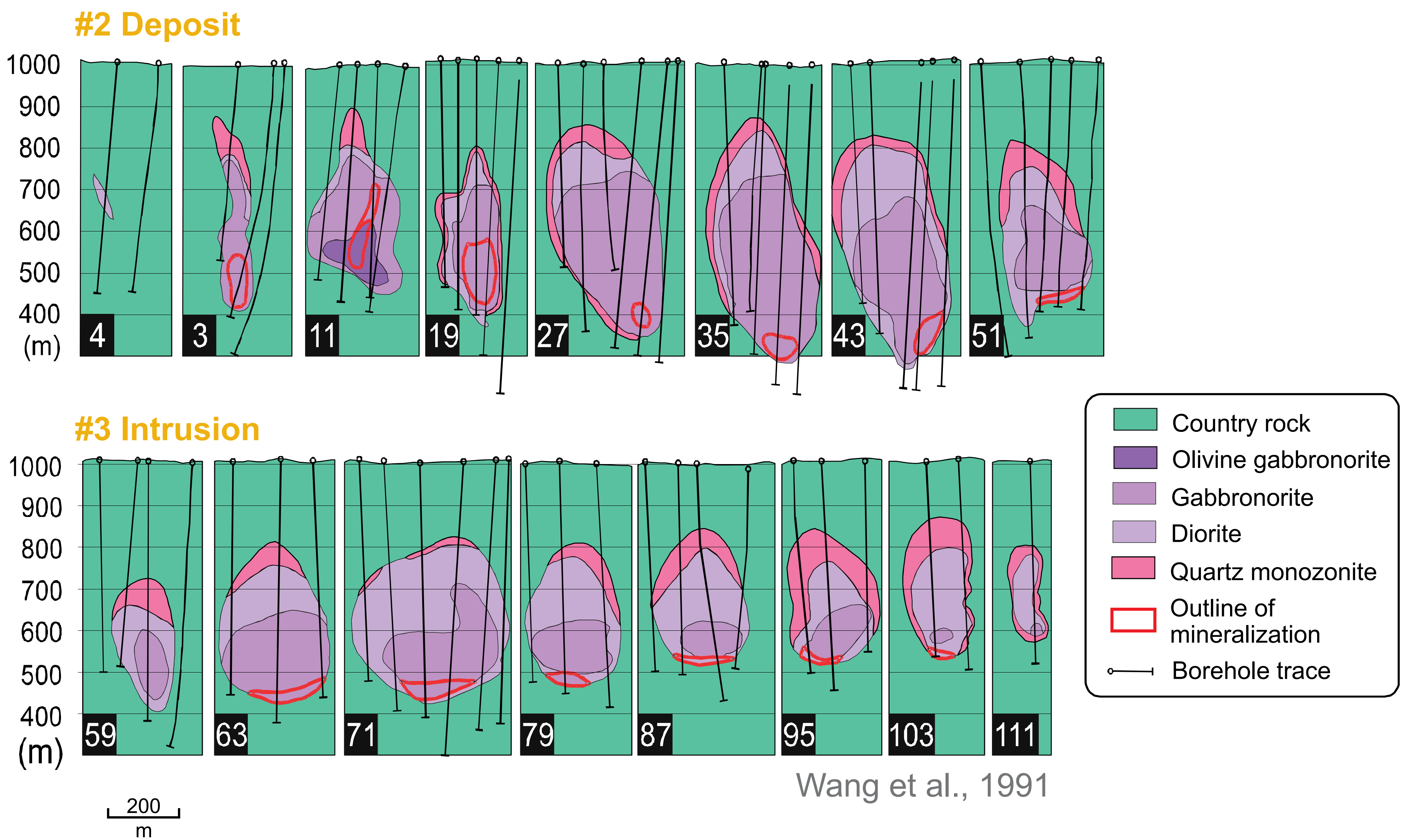
Wang et al., 1991



- 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



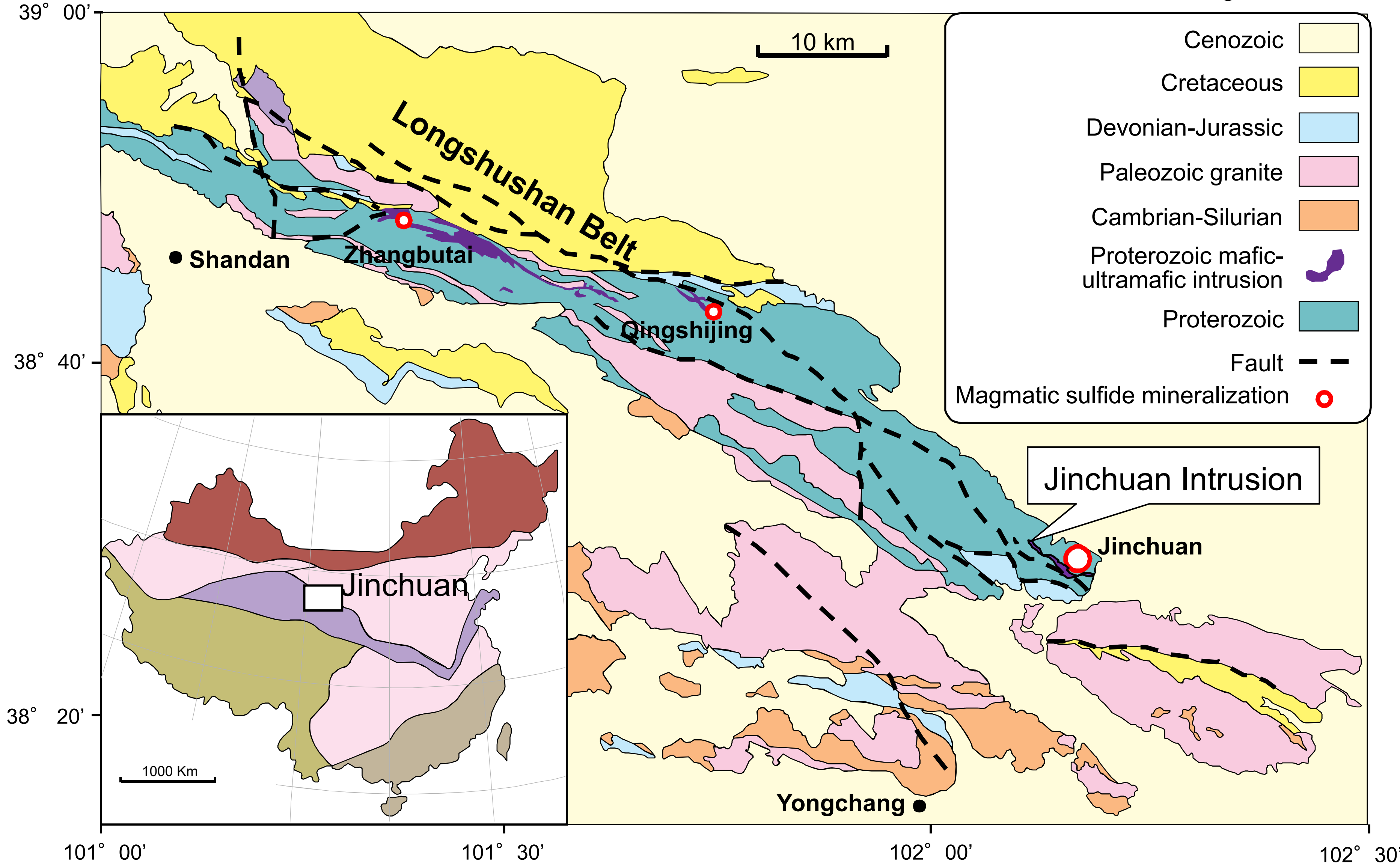
Karatungk #1,2 and 3 Intrusions, Xinjiang Province, China: West-facing long section



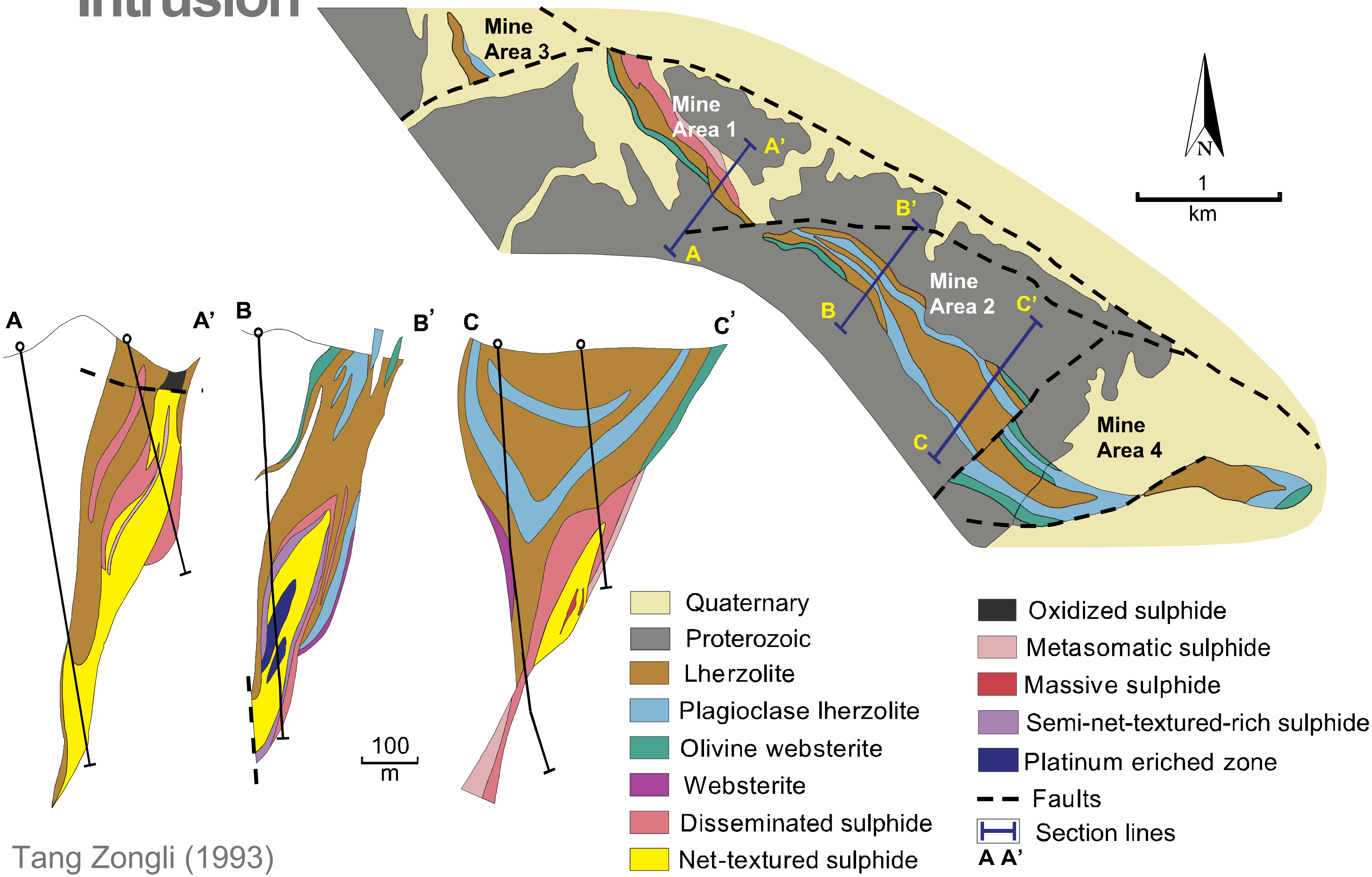
Wang et al., 1991

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

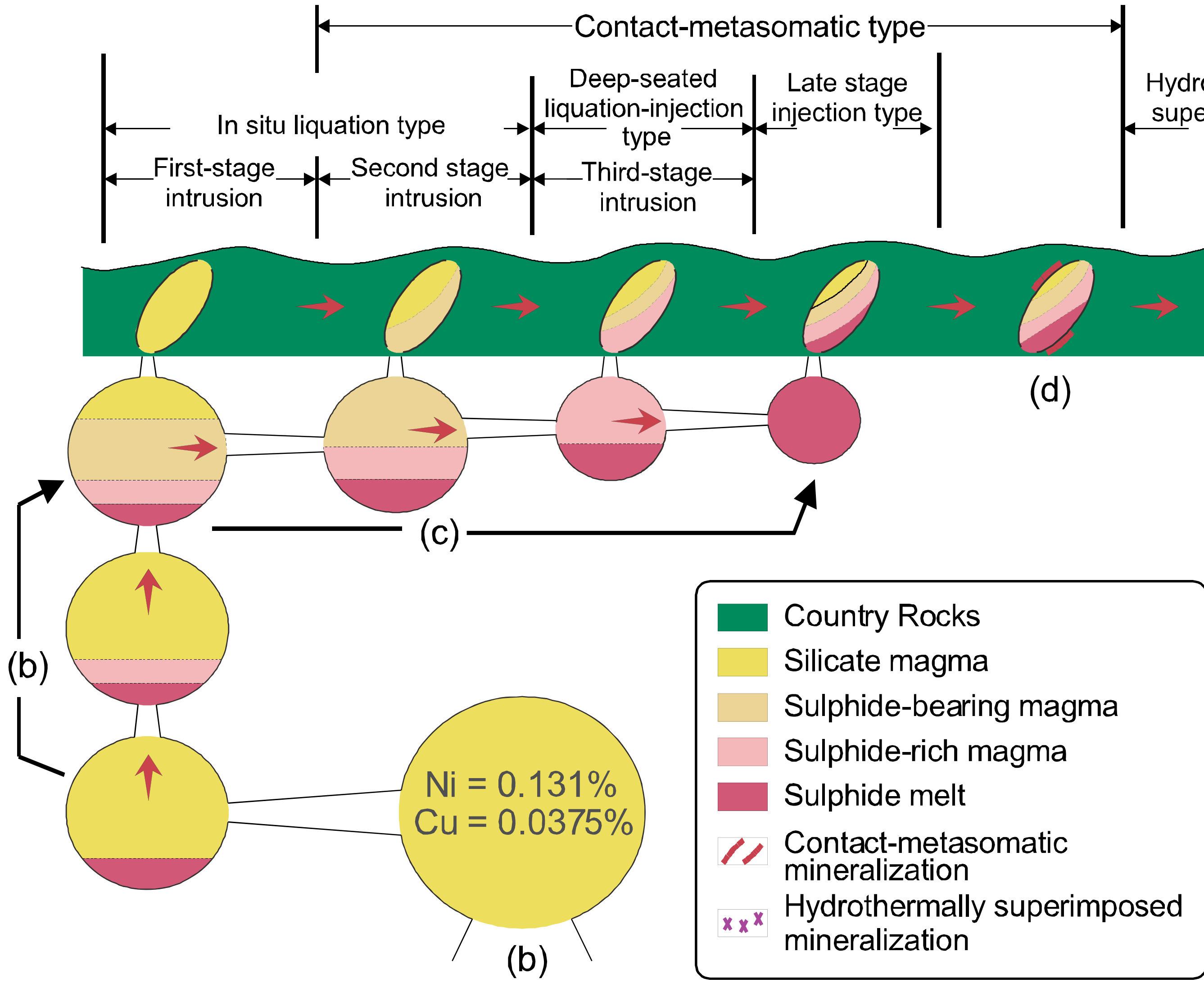


Tang Zongli (1993)

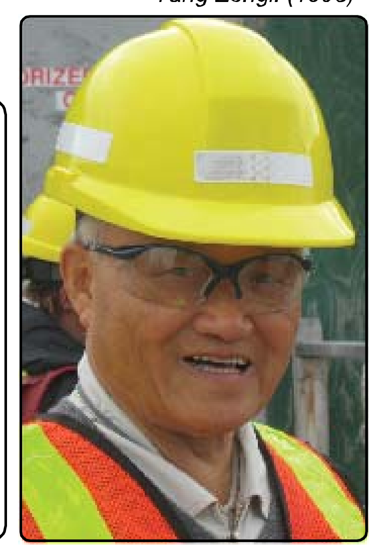
Mine area #2 – no trace of sulfide or country rock xenoliths inside the intrusion at surface

Photograph: Peter Lightfoot, 2000

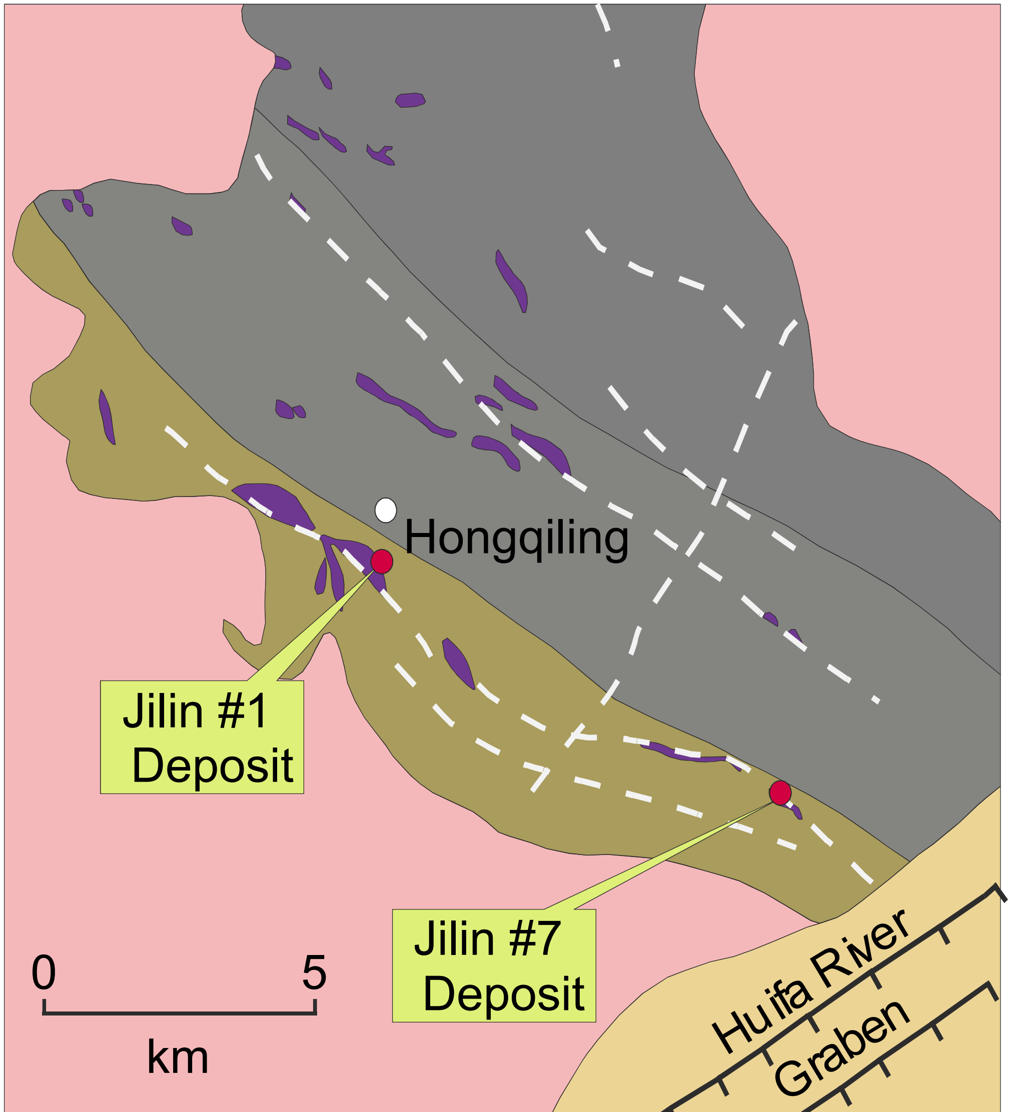
Jinchuan Model

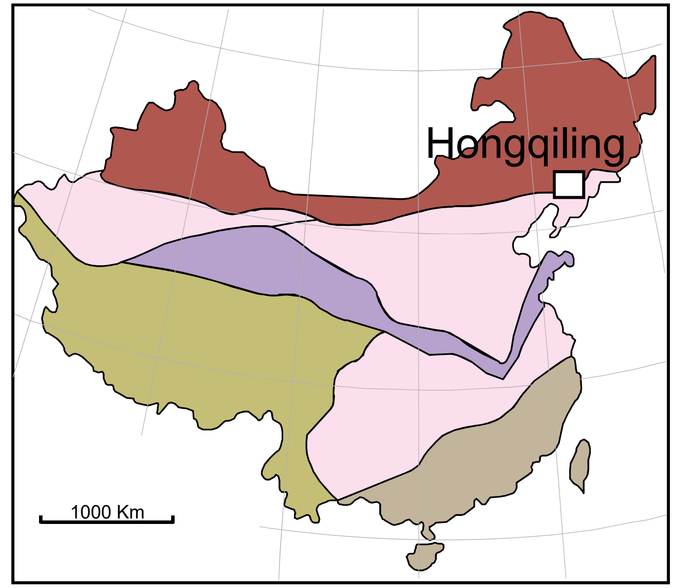


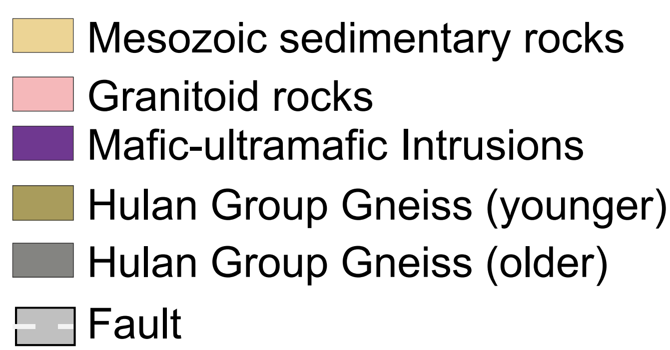
Tang Zongli (1993)



Hongqiling – Geology, Structure and Mineral Occurrences

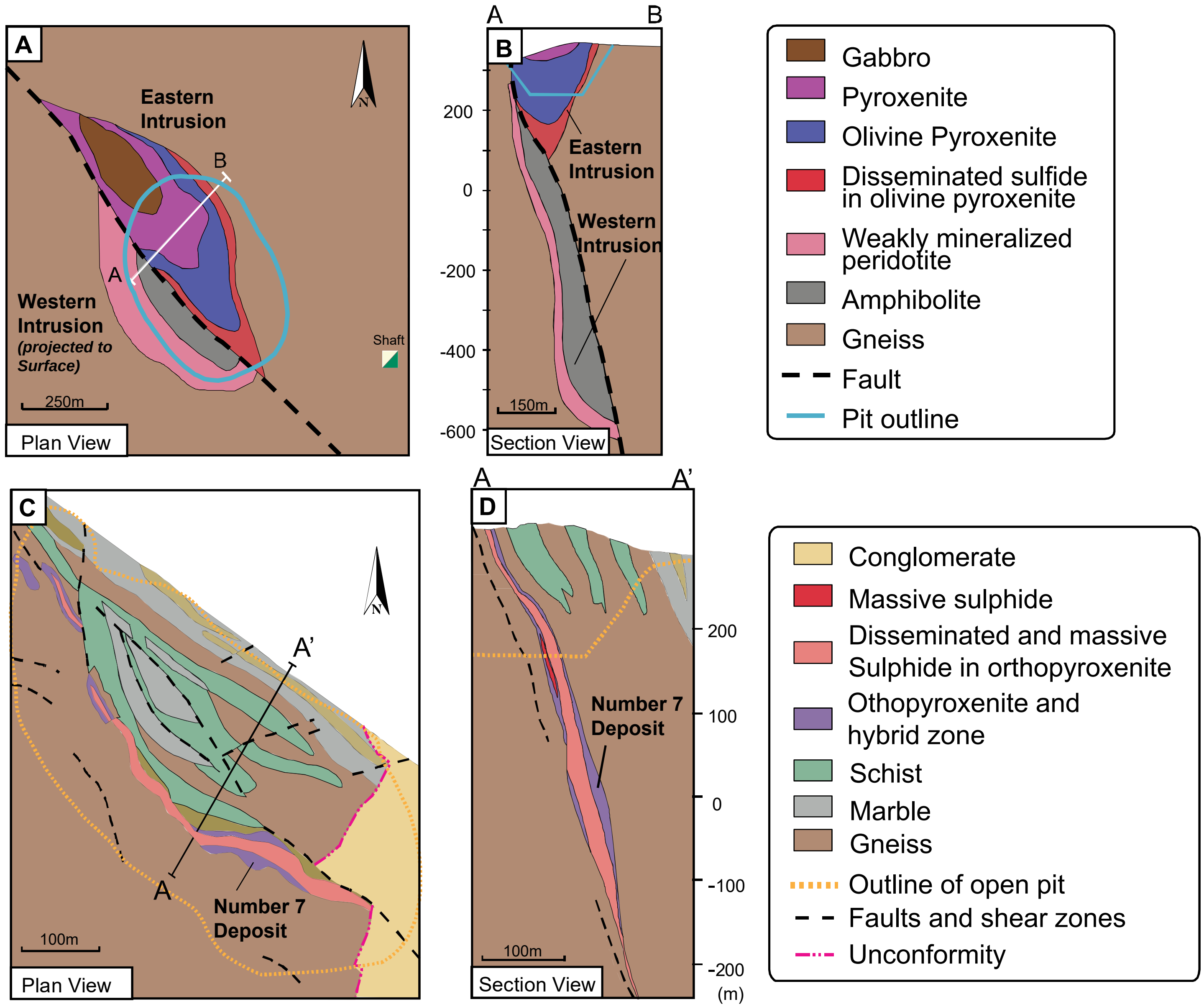




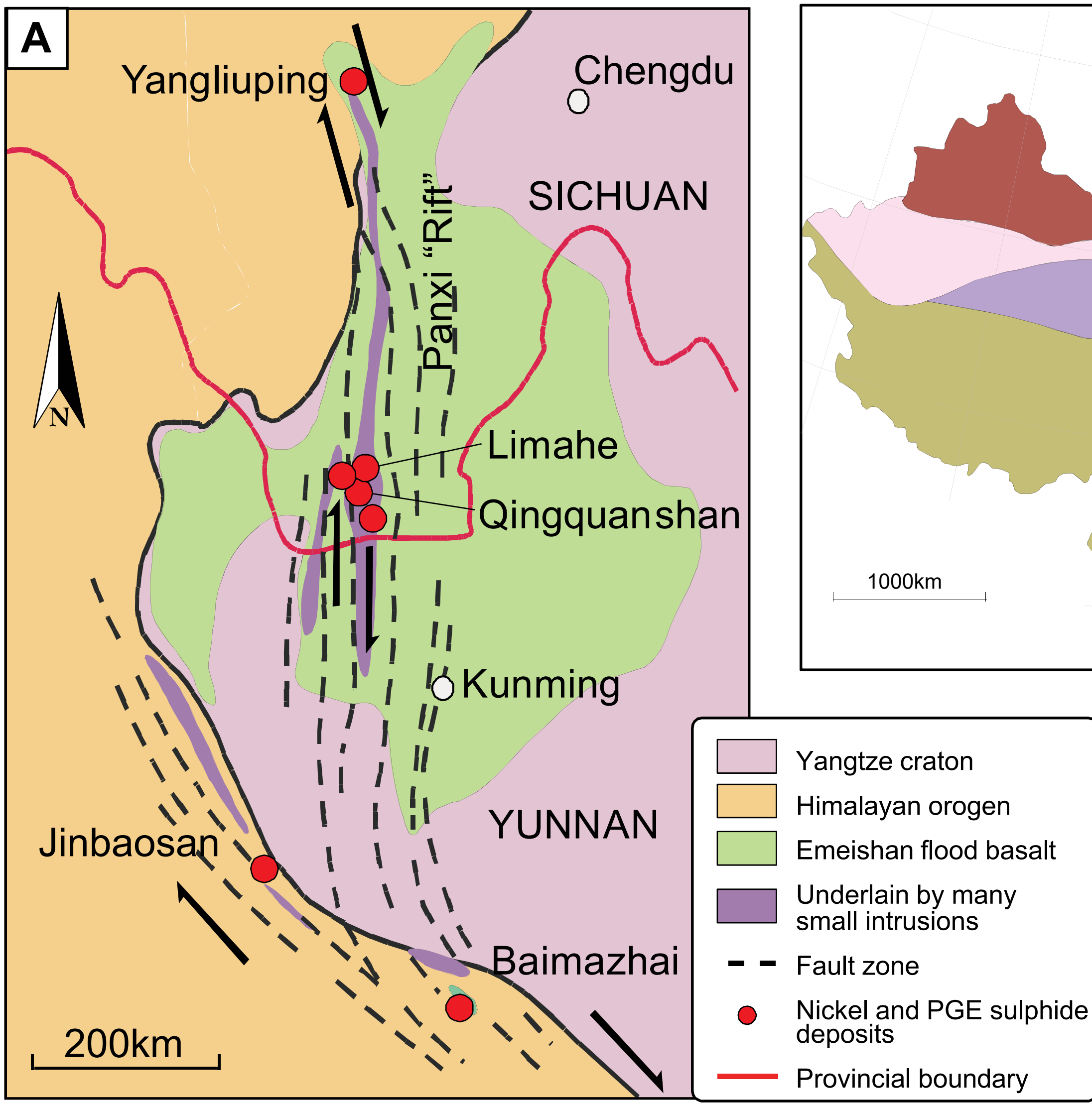


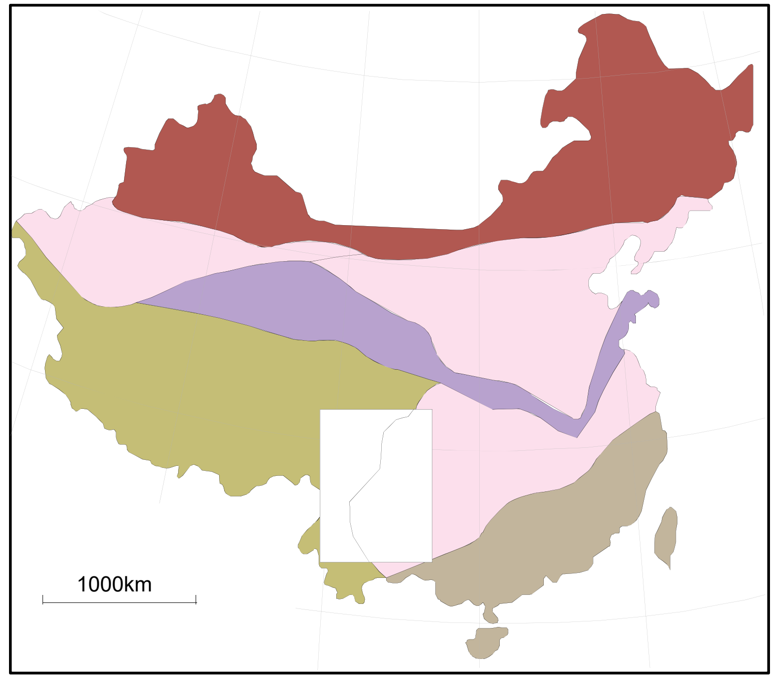
After Zhou et al., 2000

Hongqiling: Jilin Province

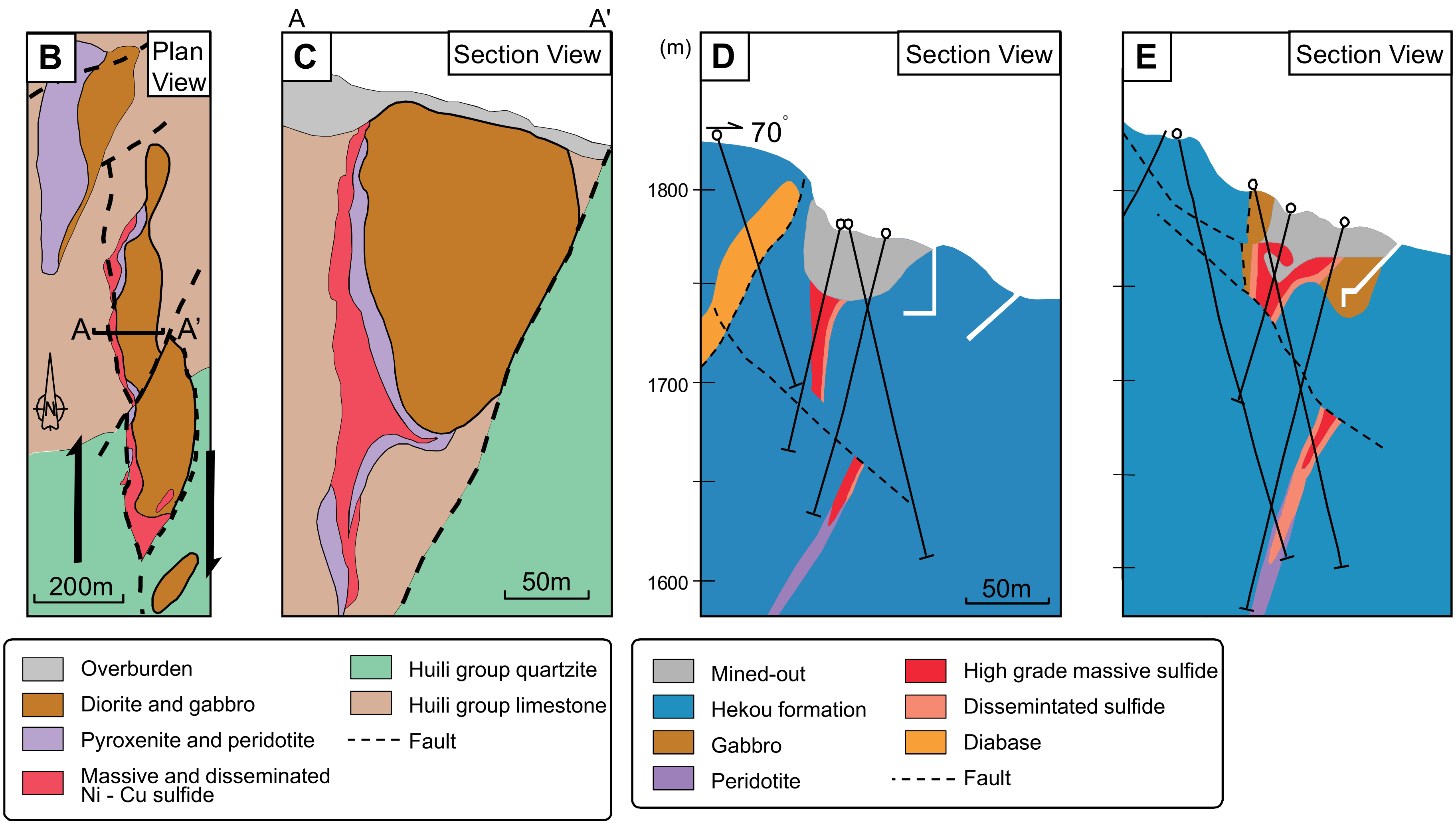


Intrusions controlled by structures beneath the ~260 Ma Emeishan Flood Basalt, SW China





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



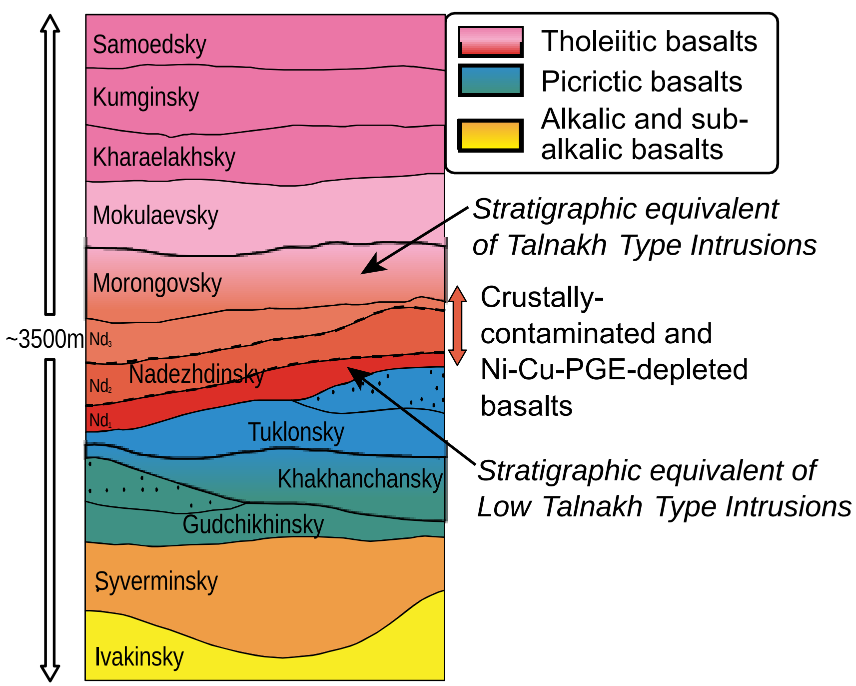
Noril’sk

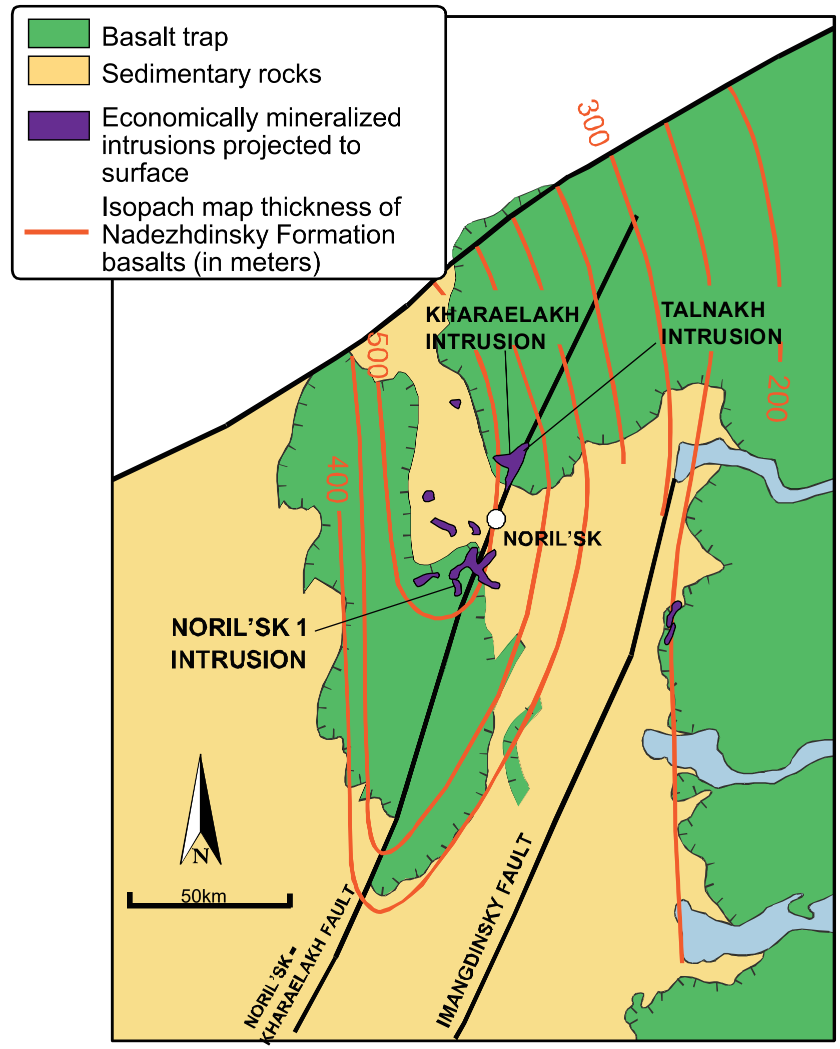
Panoramic view from Bear’s Brook towards north

Photograph: Peter Lightfoot, 2002

Distribution of Siberian Trap Basalts

www.largeigneousprovinces.org/LOM.html

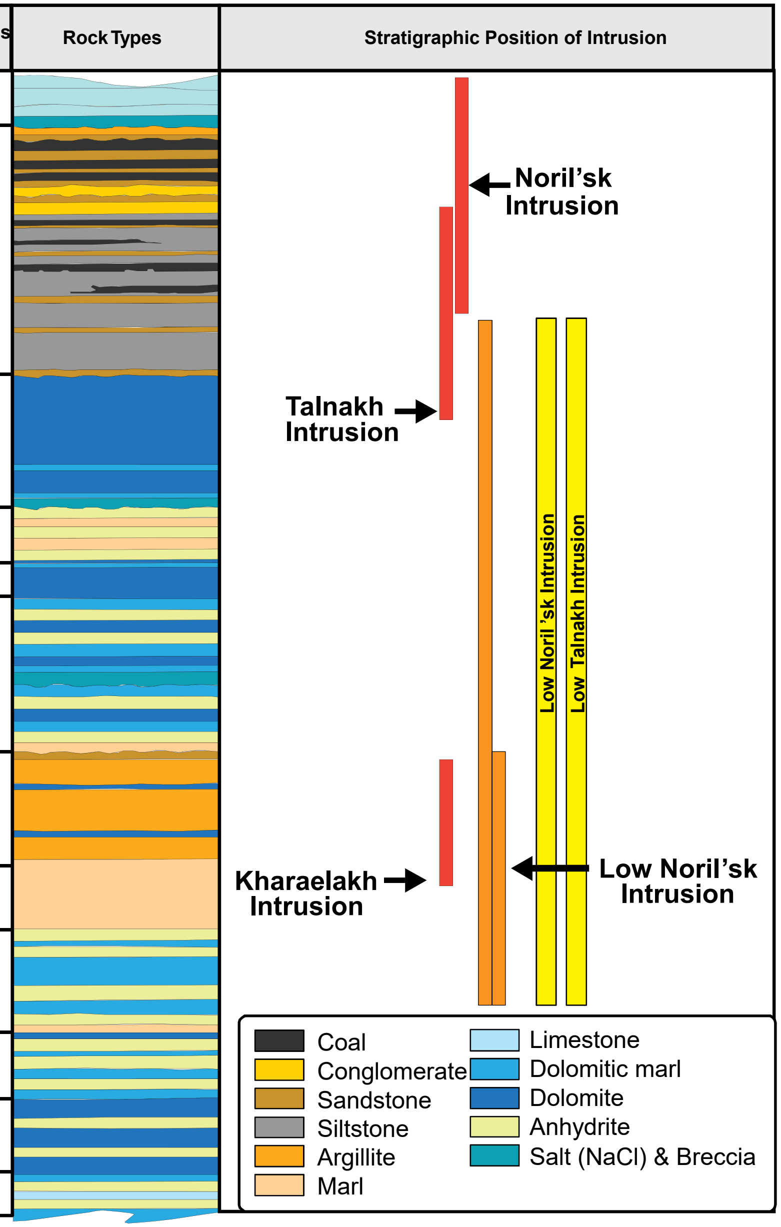




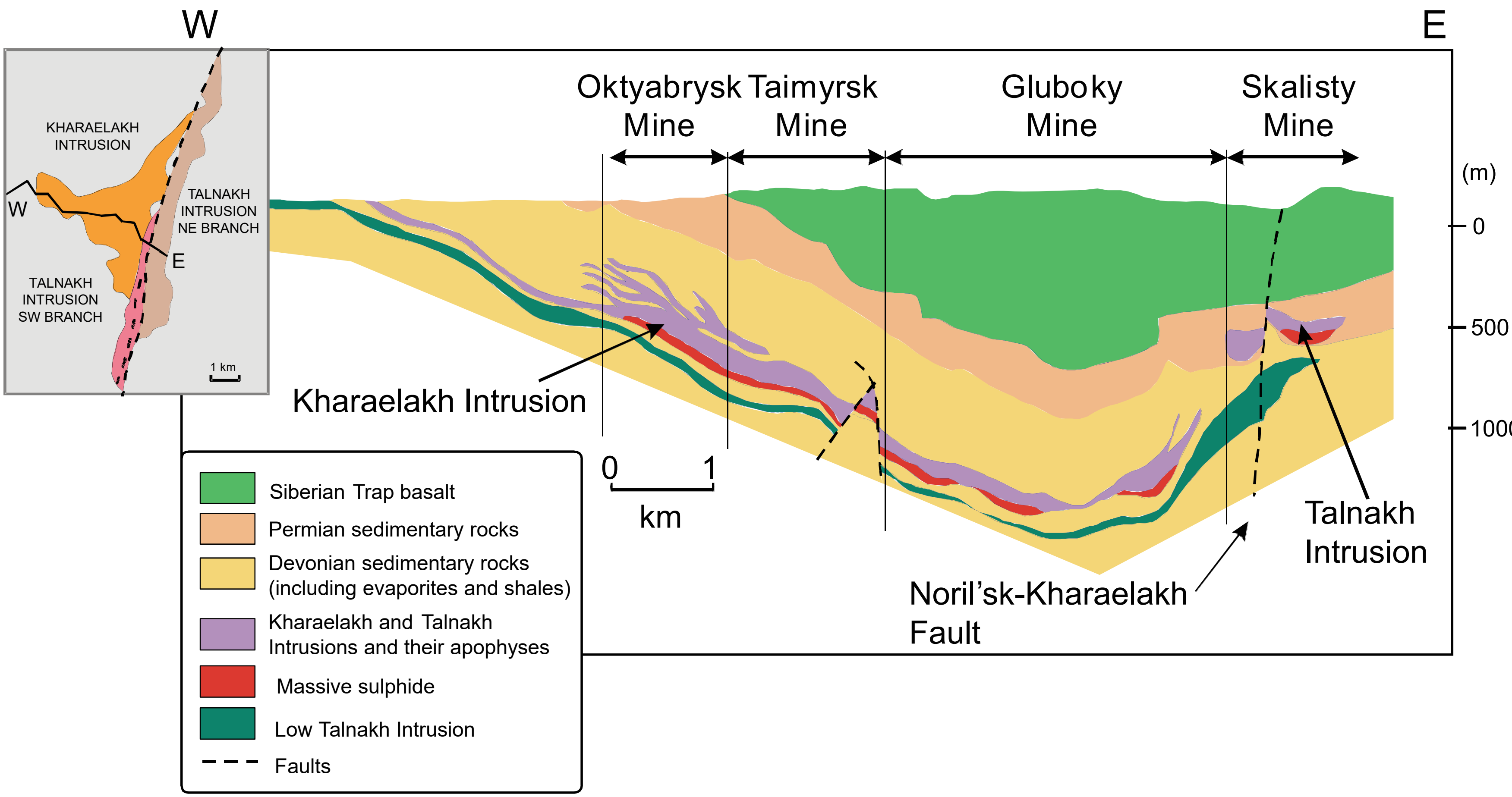
Naldrett et al (1995)

Stratigraphy of the Noril'sk Region

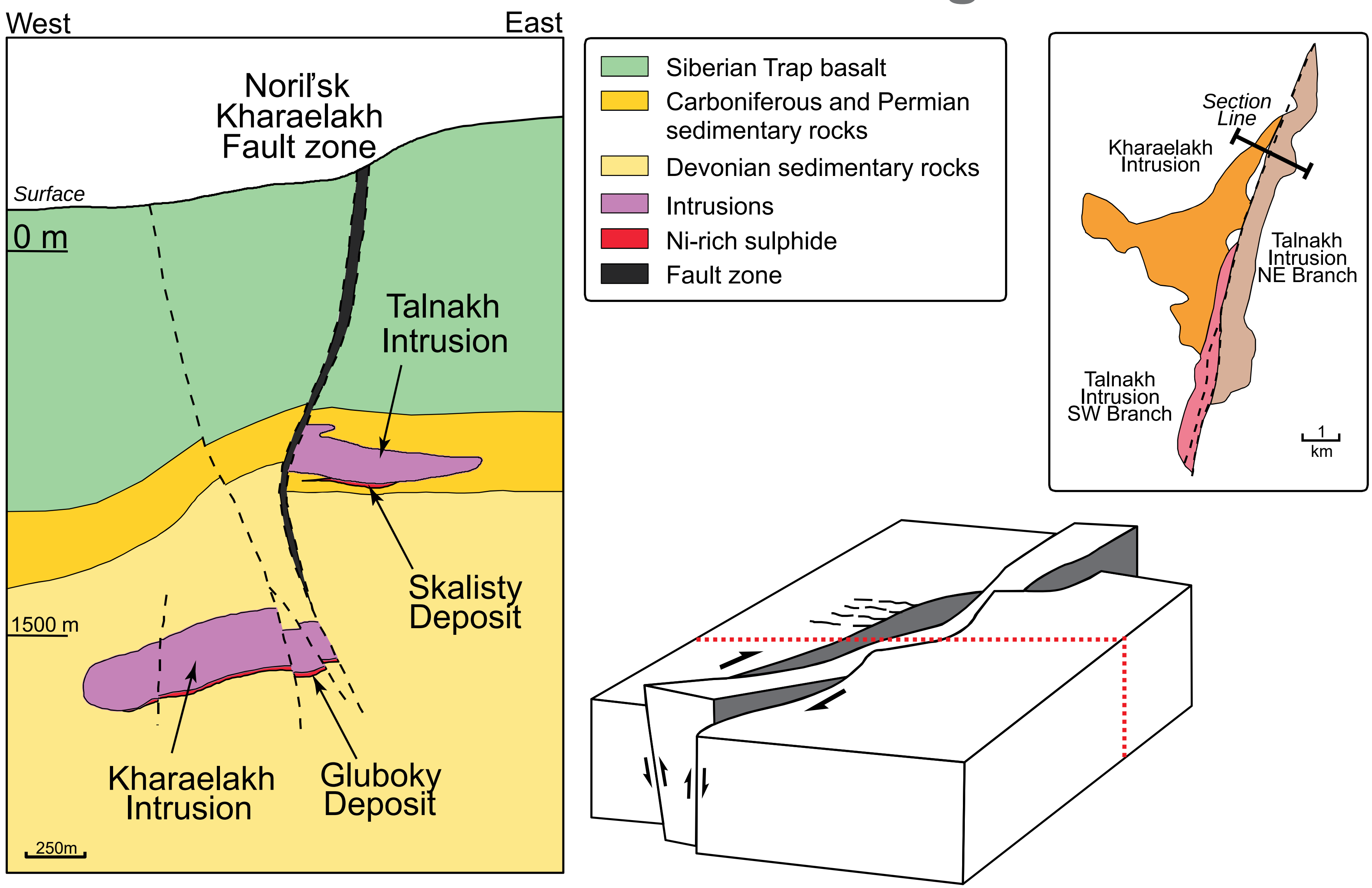
Period and Unit		Basalt Formation or Series	Thickness (m)
Upper Permian	P_2iv	Ivakinsky suite	80 - 140m
Middle Carboniferous Lower Permian	C_2-P_2	**Tungusskaya series**	280 - 330
Upper Devonian	D_3kl	Kalargonsky formation	140 - 180
	D_3nk	Nakokhozsky formation	2 - 80
Middle Devonian	D_2jk	Yuktinsky formation	12 - 40
	$D_{1\text{-}2}mt$	Manturovsky formation	110 - 210
Lower Devonian	D_1rz	**Razvedochninsky formation**	110 - 150
	D_1kr	Kureysky formation	62 - 85
	D_1zb	Zubovsky formation	110 - 140
	D_1hr	Khrebtovsky formation	30 - 90
	D_1jm	Yampakhtinsky formation	50 - 100
Upper Silurian	S_2ps	Postichny formation	96 - 105



Morphology of the Talnakh and Kharaelakh chonoliths

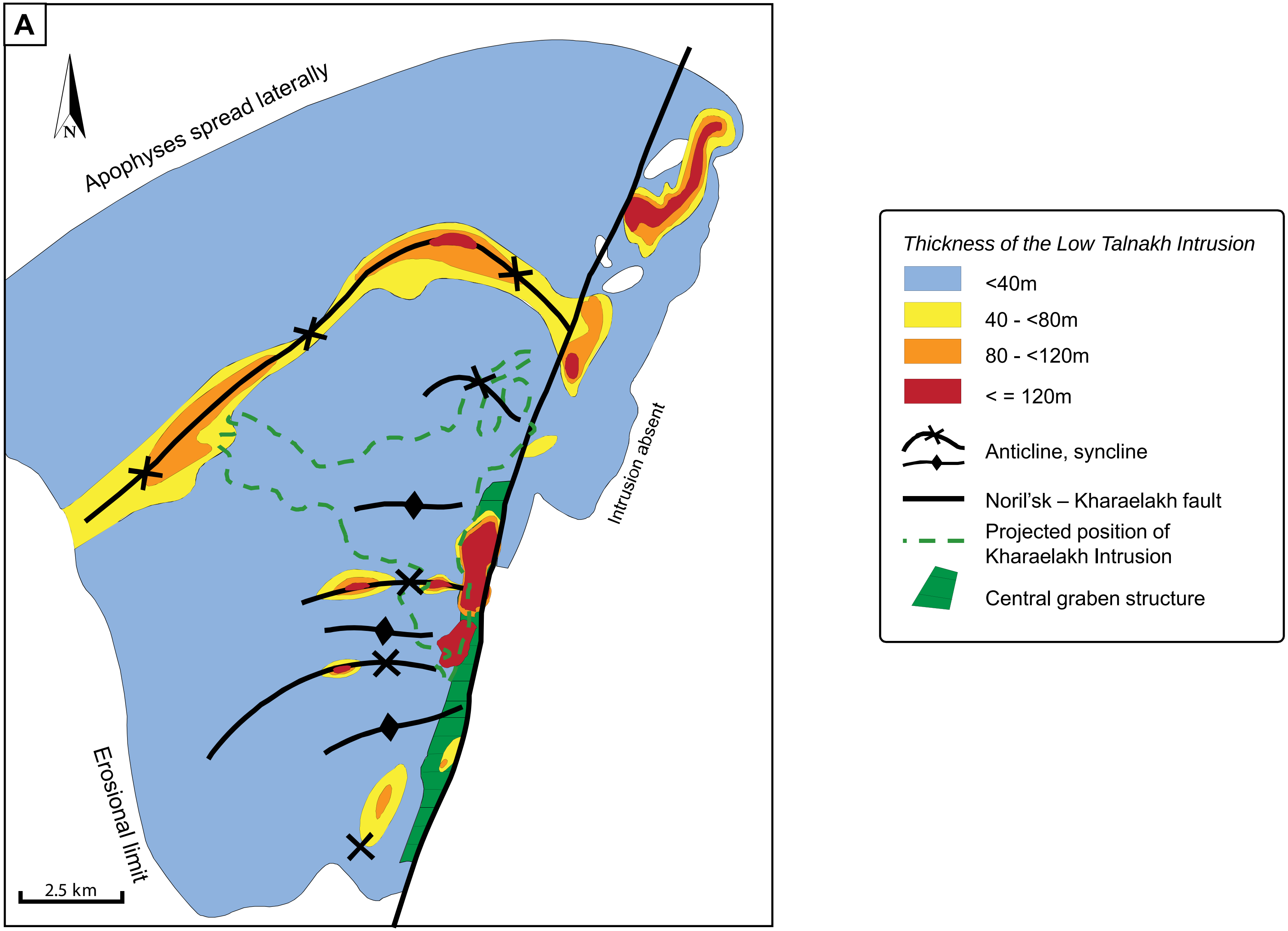


Skalisty and Gluboky Mines, Talnakh and Kharaelakh Intrusion: North-facing Section

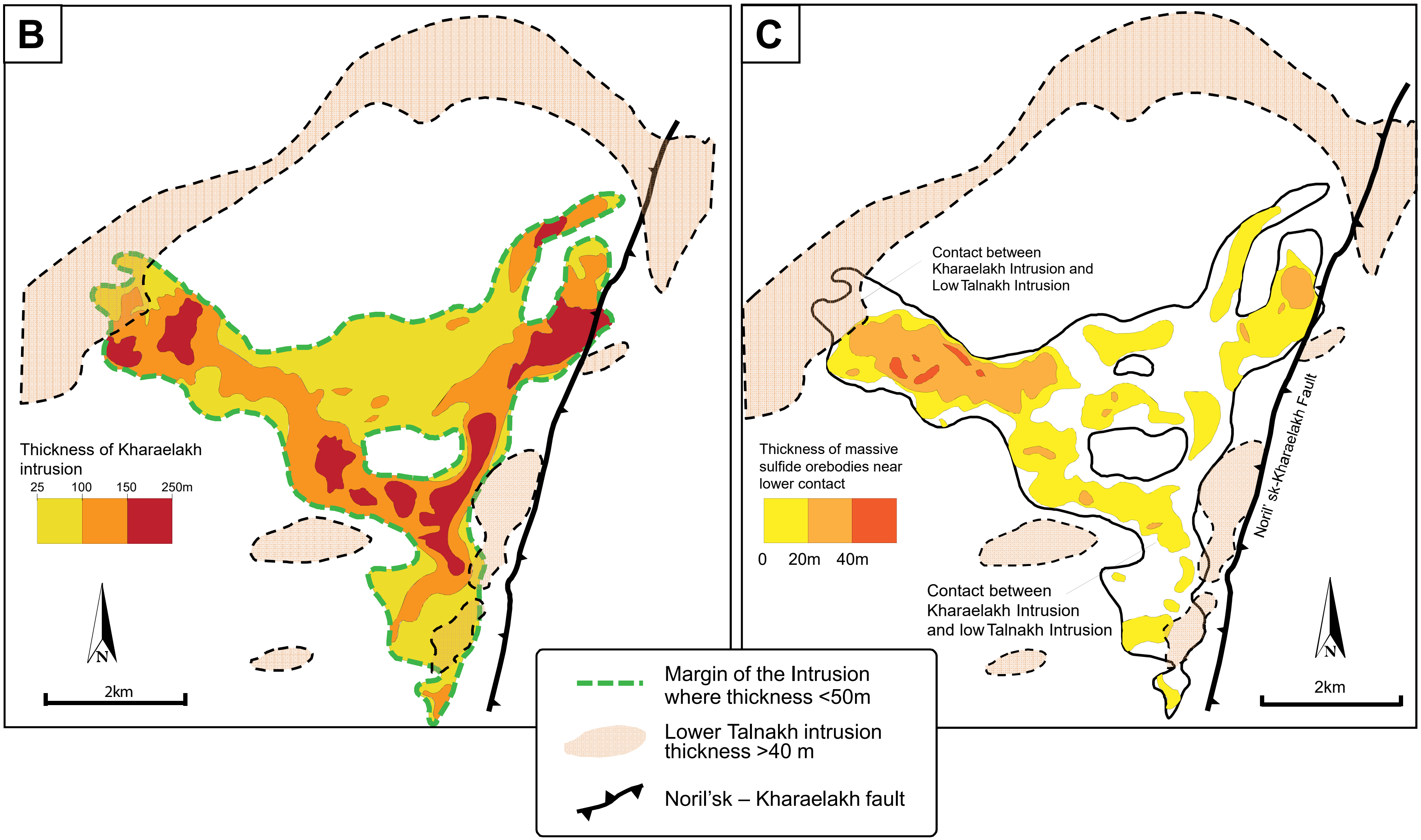


Lightfoot and Evans-Lamswood (2014)

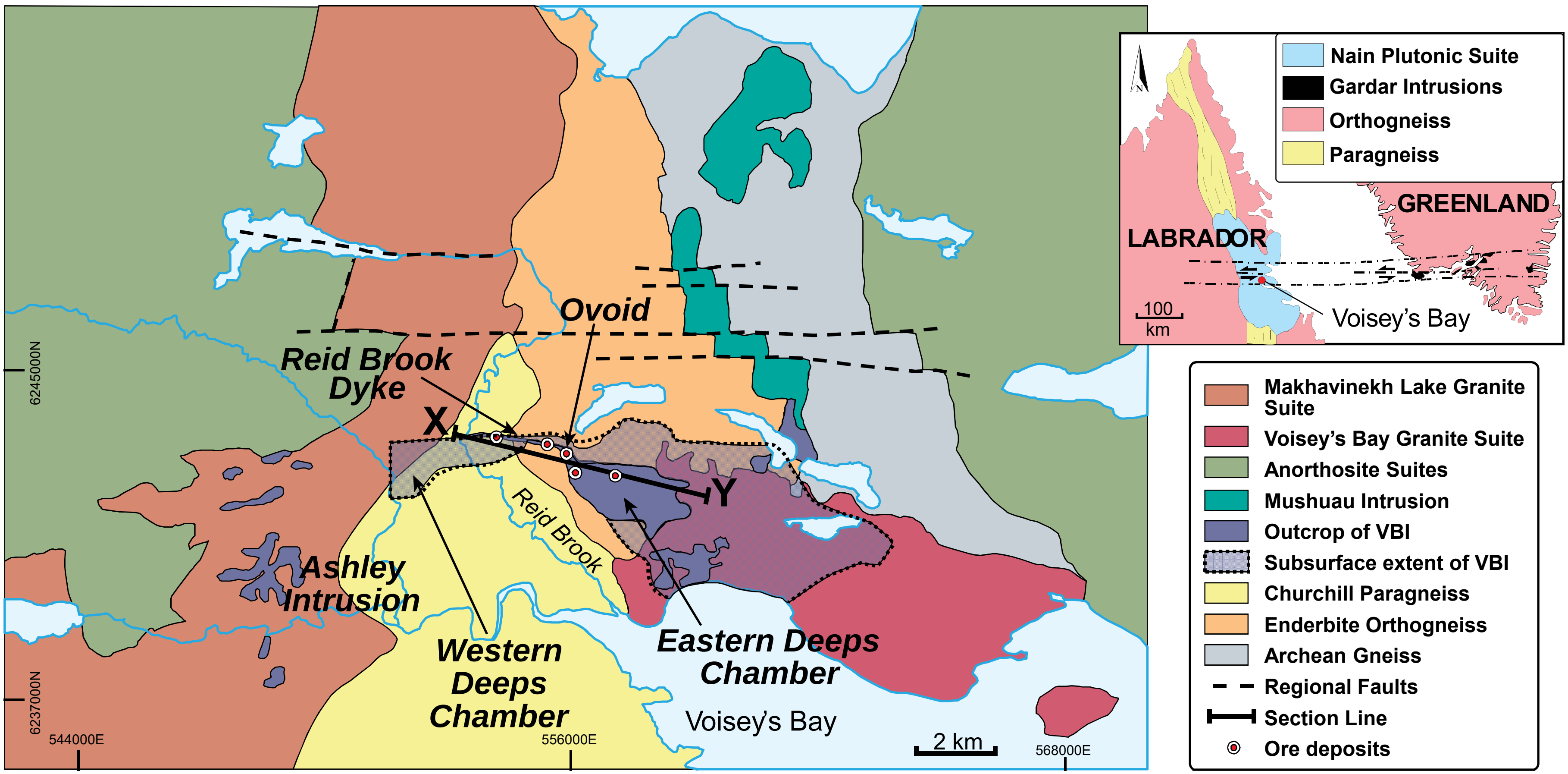
Morphology of the Low Talnakh chonolith



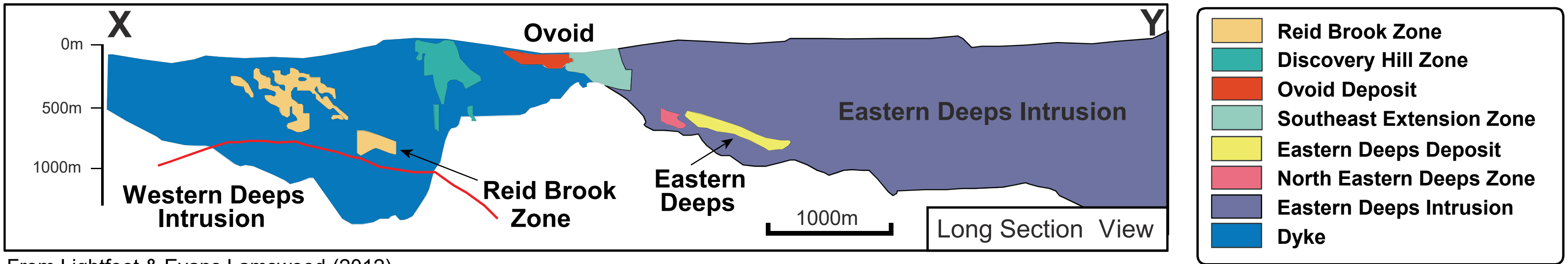
Morphology of the Kharaelakh chonolith



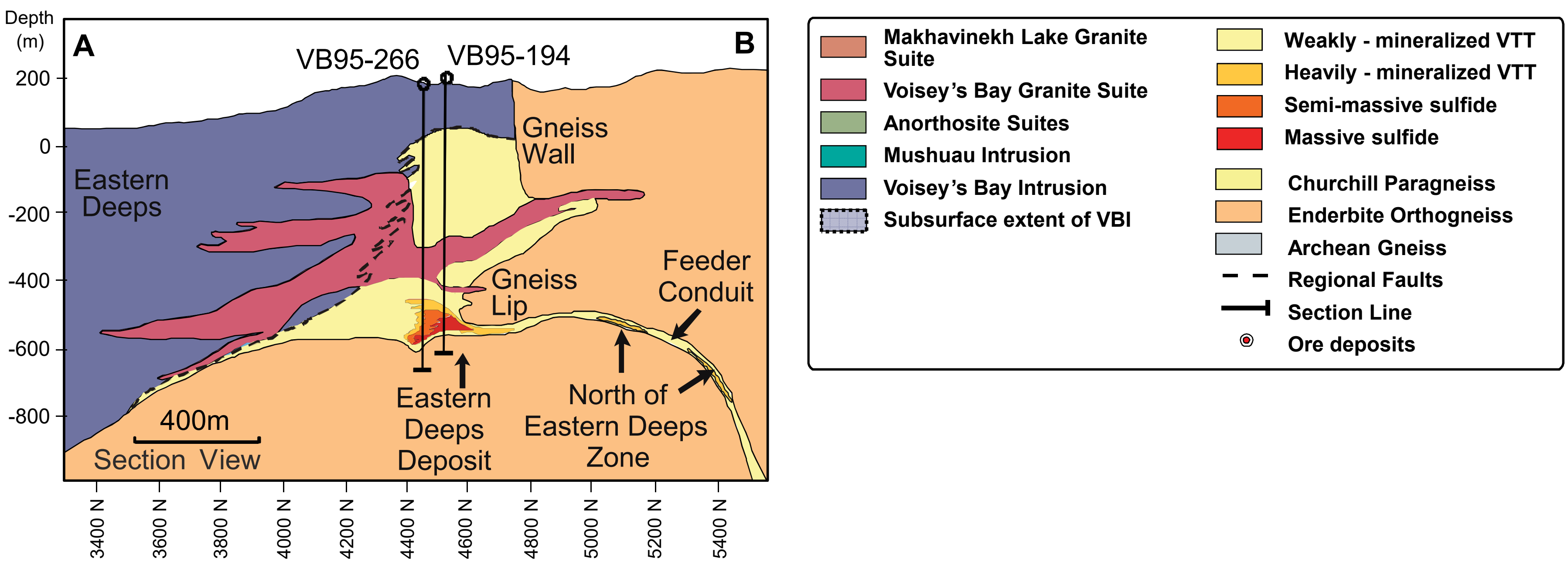
Geology of the Voisey's Bay Deposit



Geology of the Voisey's Bay Deposit



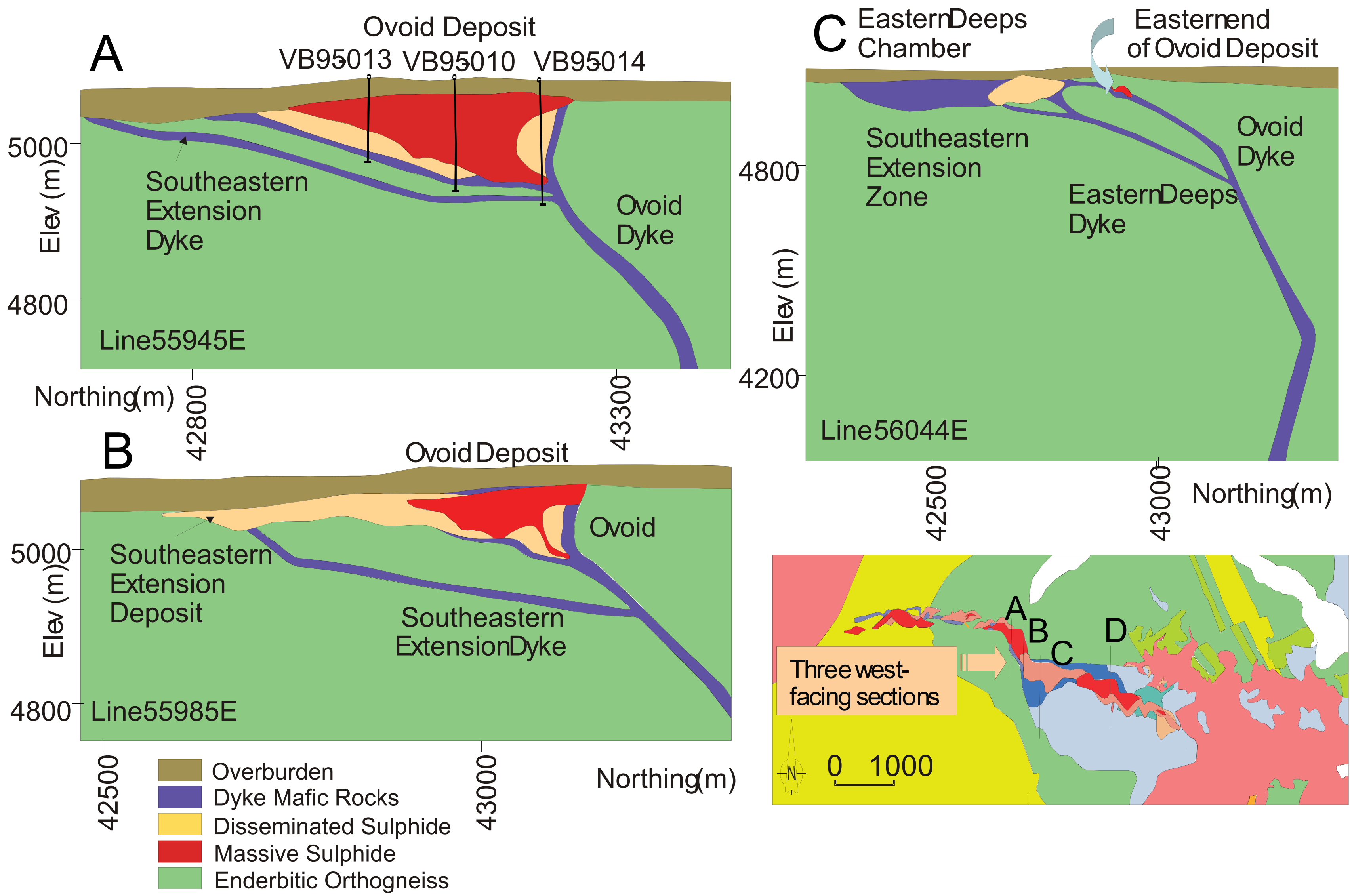
From Lightfoot & Evans Lamswood (2012)



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

Photograph: Peter Lightfoot, 1997

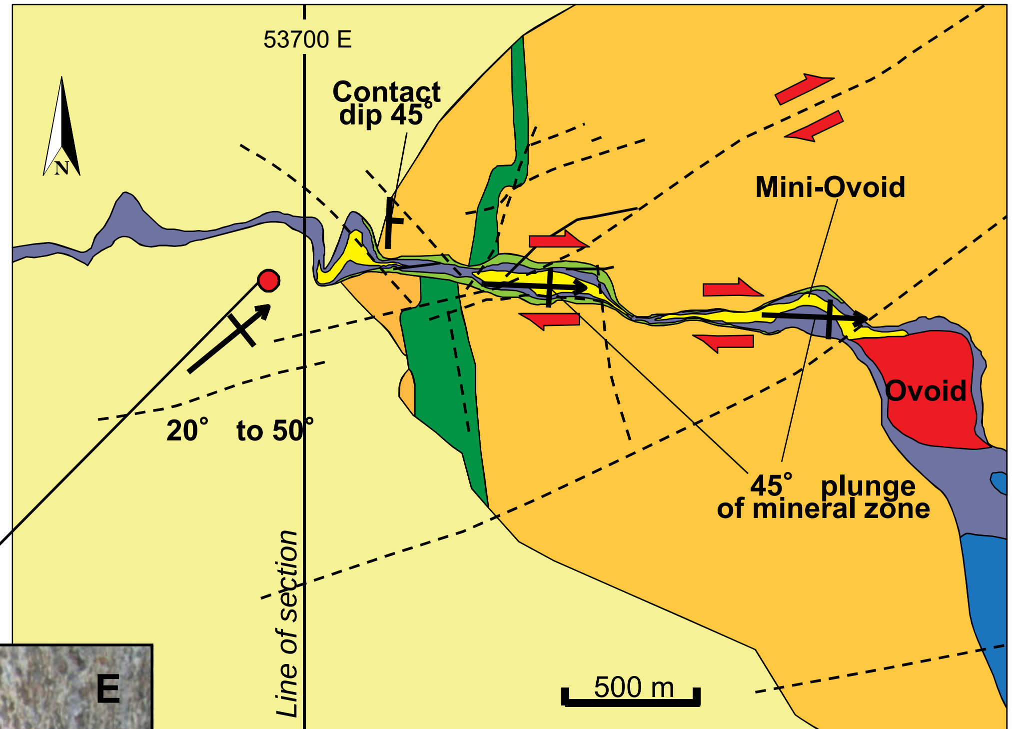
Geological relationships in the Ovoid

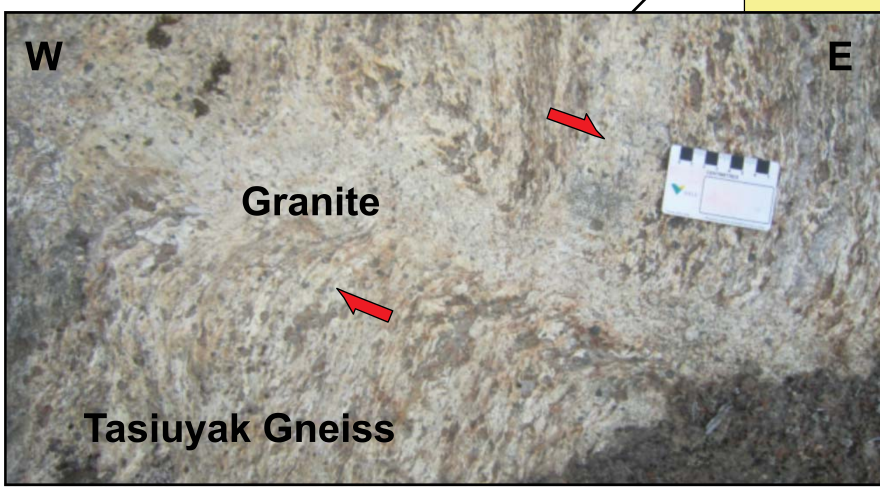


Lightfoot et al (2011)

Ovoid Deposit

Geology of the Reid Brook Zone



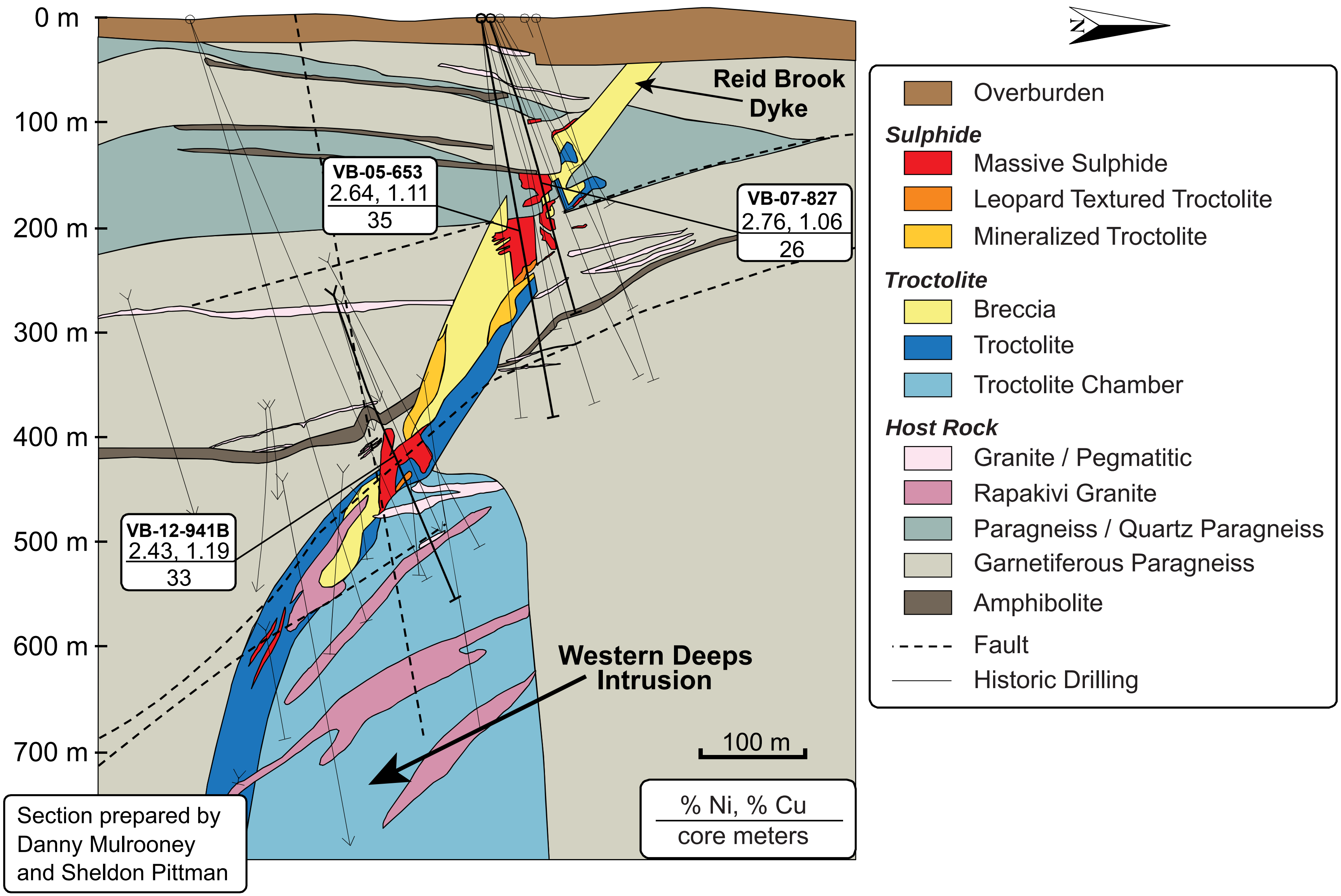


From Lightfoot & Evans Lamswood (2012)

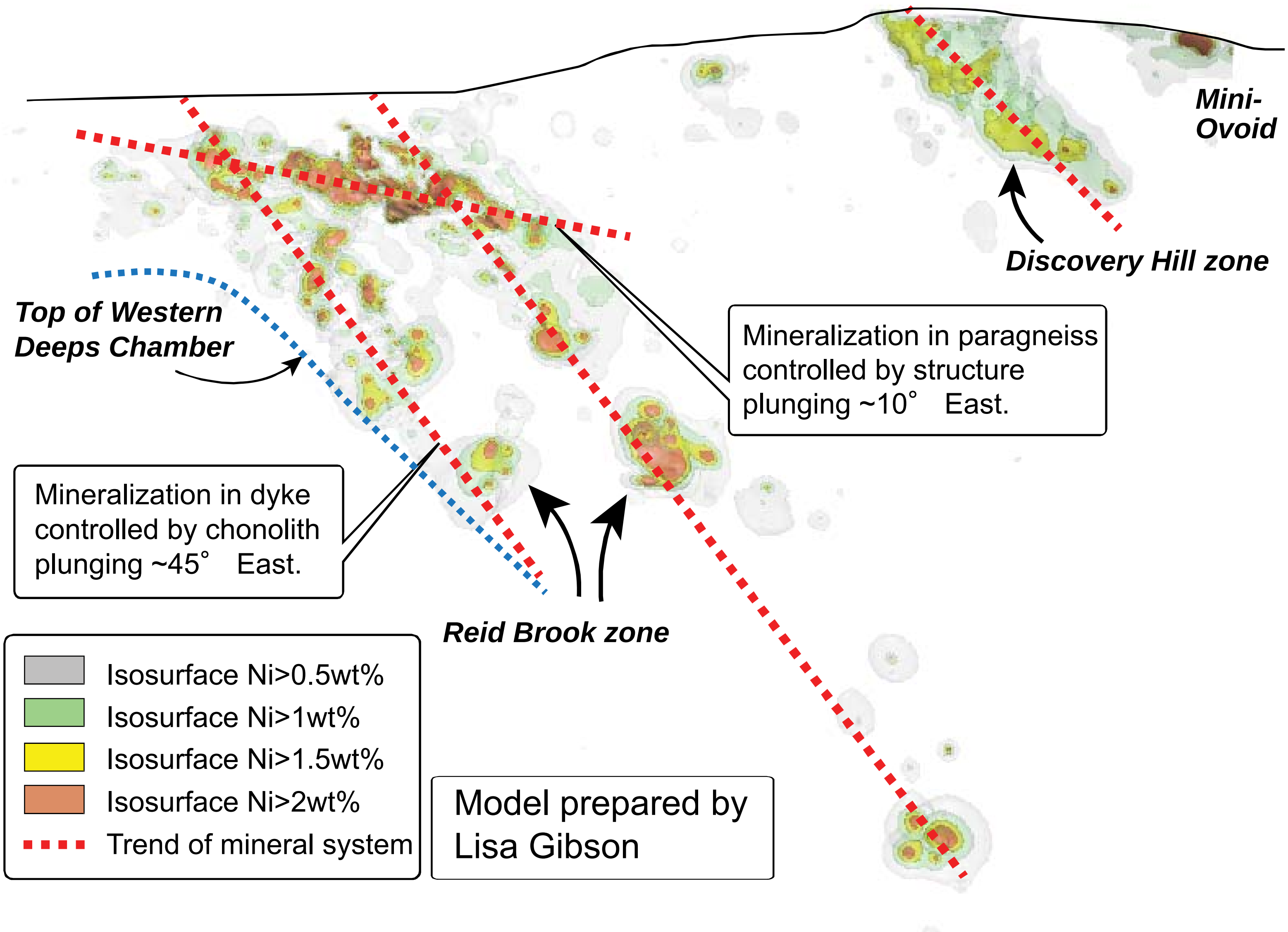
Evidence for syn-magmatic dextral transtension

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

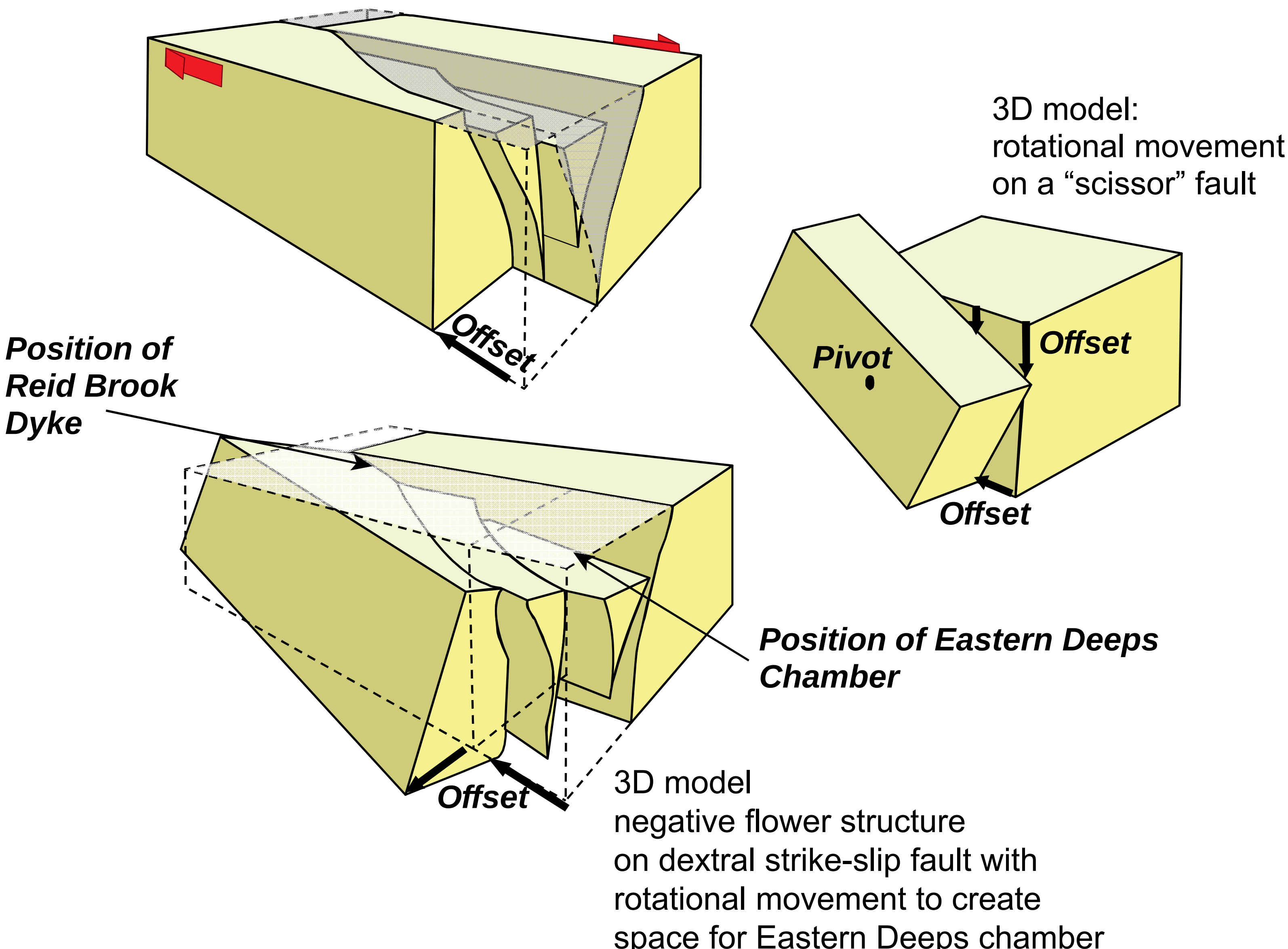
Reid Brook Zone: 53700E Section – Looking West



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

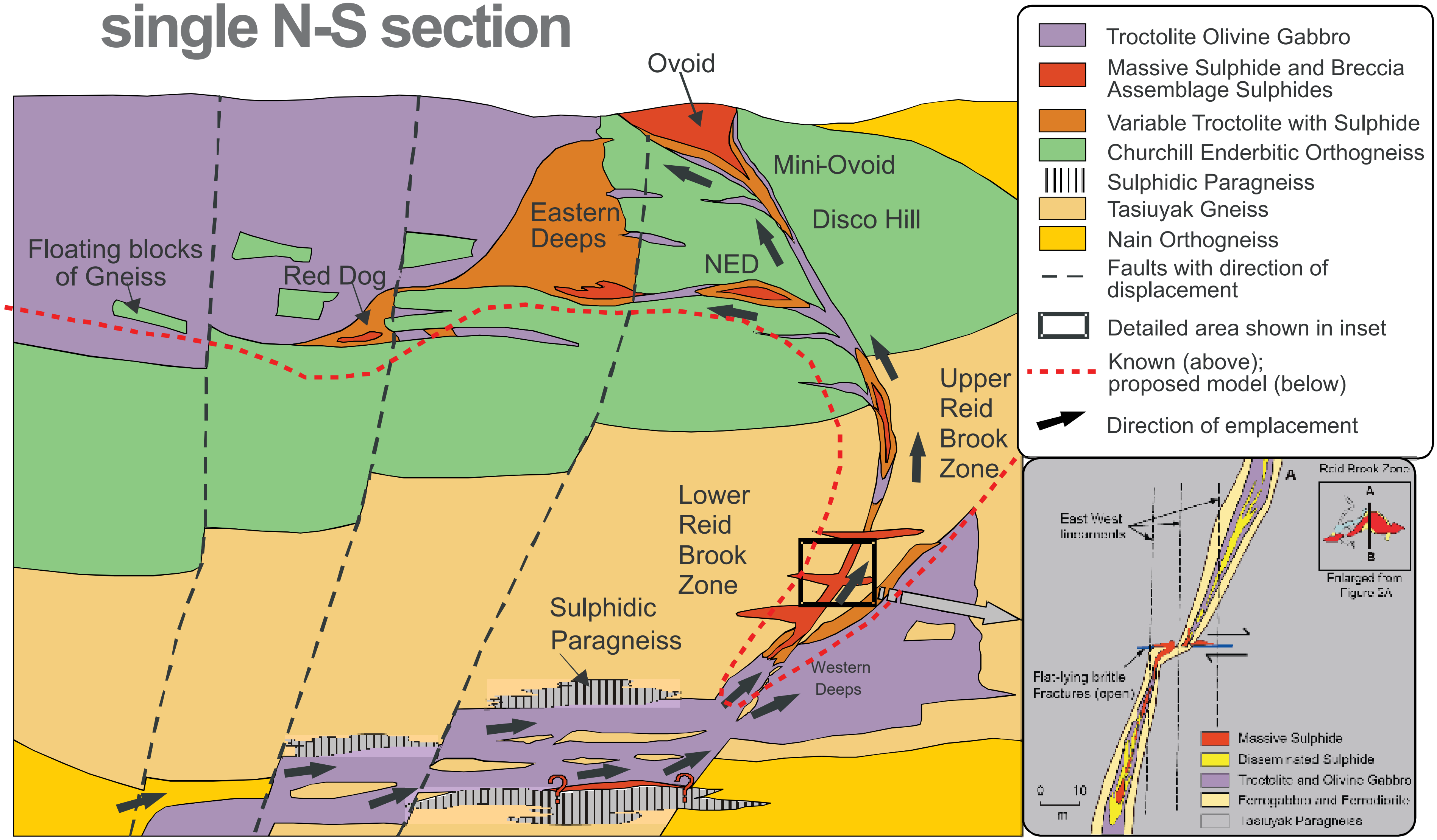


Kinematics: Summary for Voisey's Bay



From Lightfoot & Evans Lamswood (2012)

A Model for Voisey's Bay: Compressed into a single N-S section



Lightfoot et al (2011)

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:

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Alex Gagnon