Anatomy of an anomaly:

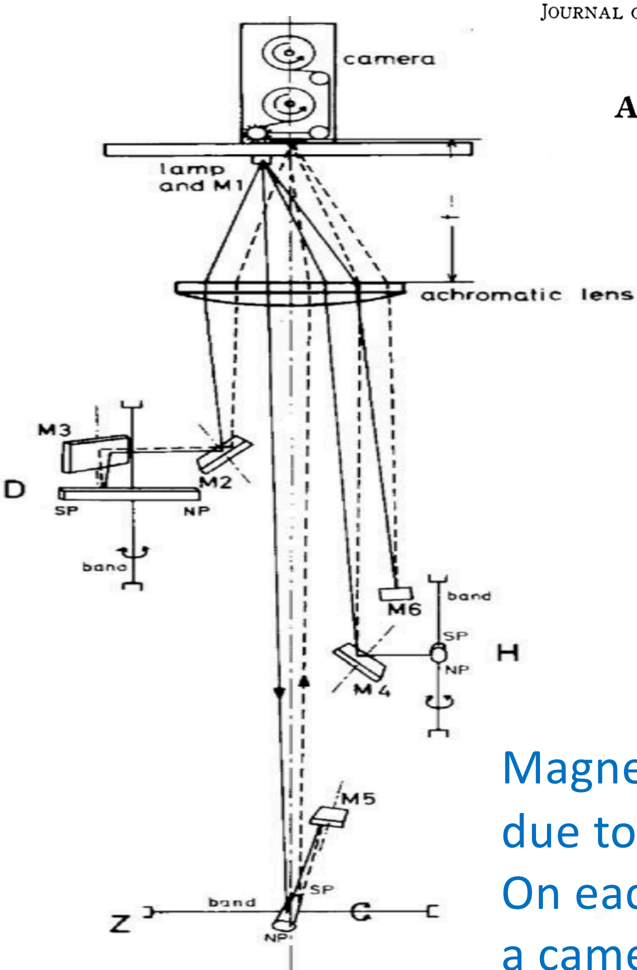
The North American Central Plains (NACP) conductivity anomaly from initial discovery to understanding, and from craton to grain scales

Alan G. Jones
Complete MT Solutions Inc.
Formerly: Geological Survey of Canada and Dublin Institute for Advanced Studies

EMinar, 20th October, 2021

EMinar series 2 MTNet

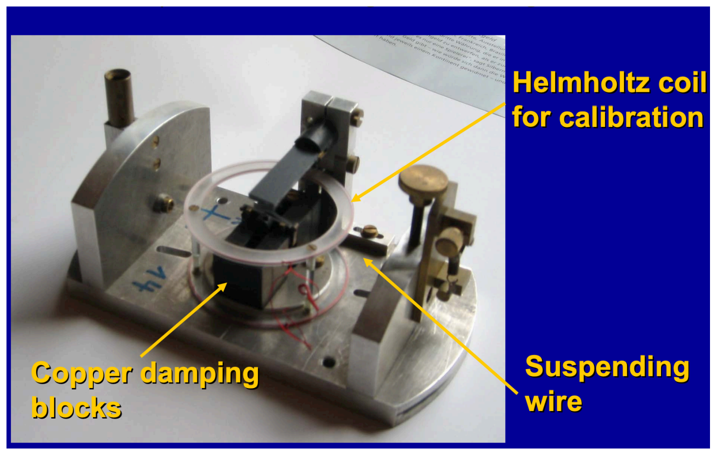
The first Geomagnetic Depth Sounding (GDS) instrument

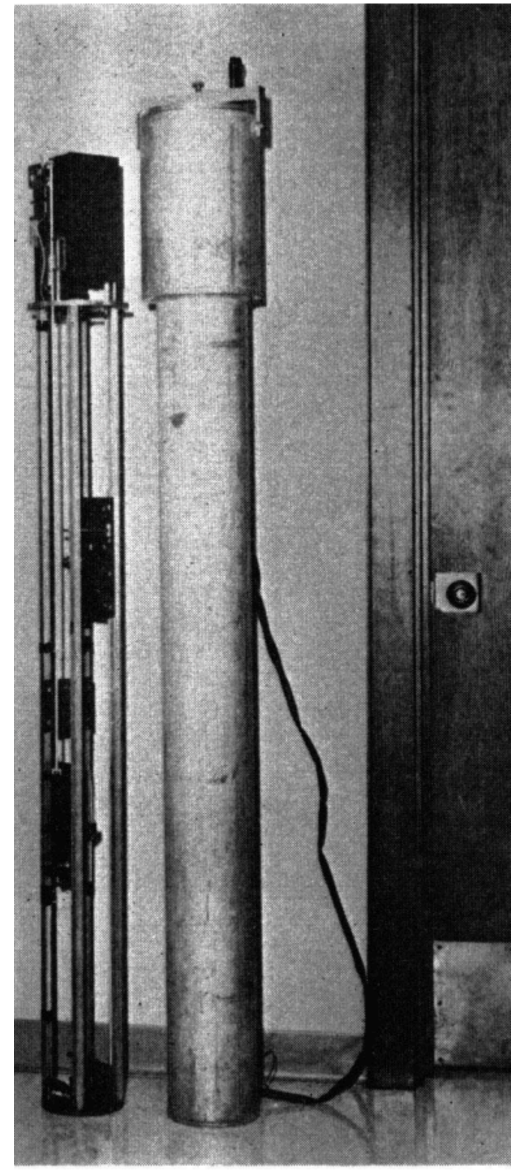


JOURNAL OF GEOMAGNETISM AND GEOELECTRICITY VOL. 19, NO. 3, 1967

A Portable Three-Component Magnetic Variometer**

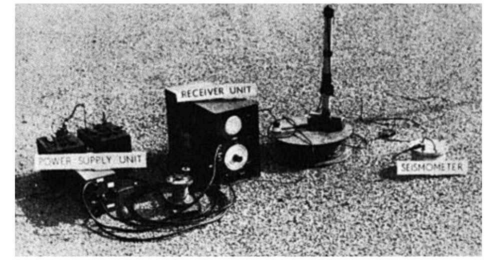
D.I. GOUGH* and J.S. REITZEL





Magnets suspended by a torsional wires rotate due to the time-varying Earth's magnetic field. On each magnet is a mirror that reflects light to a camera at the top of the magnetometer

Tribute to D. Ian Gough: 20 June, 1922 - 21 March, 2011



Geophysics, 1952, p. 311-333.

Ian Gough was an excellent scientist with impact in many areas of geophysics

- Seismology – both earthquake and source
  - Invented the hammer seismograph
- Geothermal studies
- Gravity and Isostacy
- Paleomagnetism
  - Invented the “spinner magnetometer”
- Geomagnetism
  - Invented the Gough-Reitzel magnetometer
- Stress and rheology
  - Most referenced work (337 citations)

A NEW INSTRUMENT FOR SEISMIC EXPLORATION AT VERY SHORT RANGES*

D. I. GOUGH†

JOURNAL OF GEOPHYSICAL RESEARCH VOL. 69, NO. 12 JUNE 15, 1964

A Spinner Magnetometer

D. I. GOUGH[1]

Physics Department
University College of Rhodesia and Nyasaland
Salisbury, Southern Rhodesia

Seismic reflectors, conductivity, water and stress in the continental crust

D. Ian Gough

Department of Physics, University of Alberta, Edmonton, Canada T6G 2J1

←Brought his broad understanding together in this paper
Nature, 1986

ELSEVIER
Earth and Planetary Science Letters
Volume 45, Issue 2, November 1979, Pages 475-482

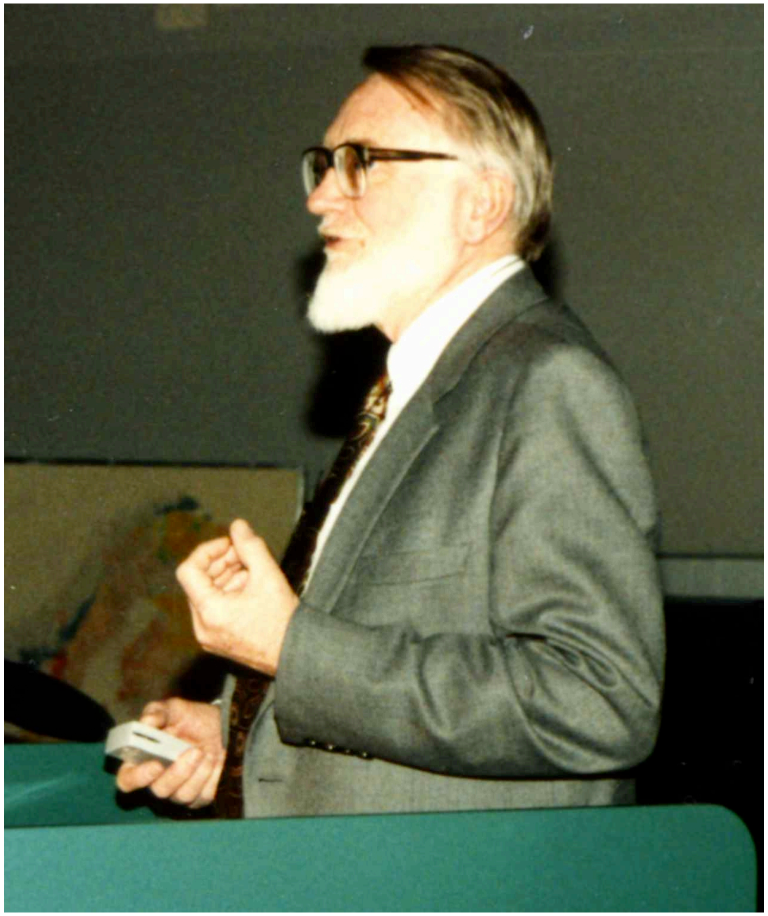
Northeast-southwest compressive stress in Alberta evidence from oil wells

J.S. Bell, D.I. Gough

Tribute to D. Ian Gough: 20 June, 1922 - 21 March, 2011

Ian Gough's impact "administratively" was also huge:

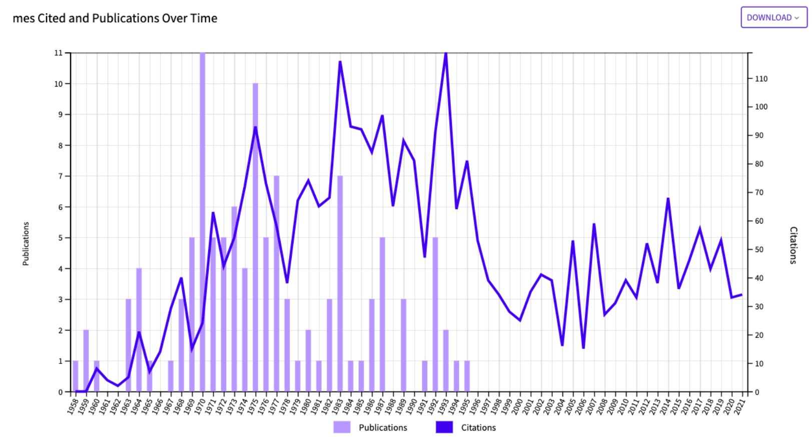
- President of IAGA (1983-1987)
- Was the champion of non-seismic geophysics, esp. for a strong EM component, in Lithoprobe



Tribute to D. Ian Gough: 20 June, 1922 - 21 March, 2011

His papers are still being referenced today – over 40 citations per year
– his last one with me (Jones & Gough, 1995)

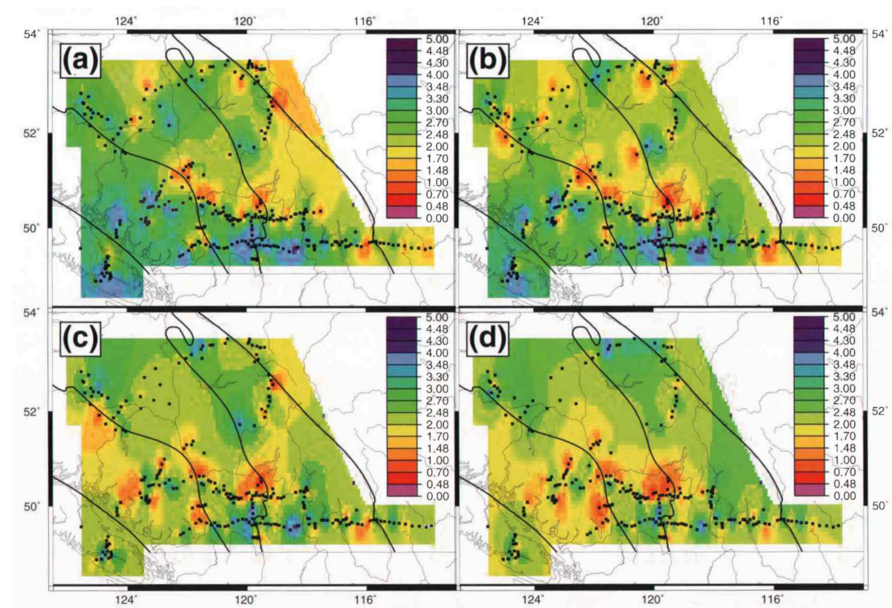
He turned to writing poetry on retirement
A true Renaissance scientist, and a true gentleman



Electromagnetic images of crustal structures in southern and central Canadian Cordillera[1]

Alan G. Jones and D. Ian Gough

Can. J. Earth Sci. 32: 1541–1563 (1995).



COMPLETE MT SOLUTIONS

First GDS (Geomagnetic Deep Sounding) array in 1967

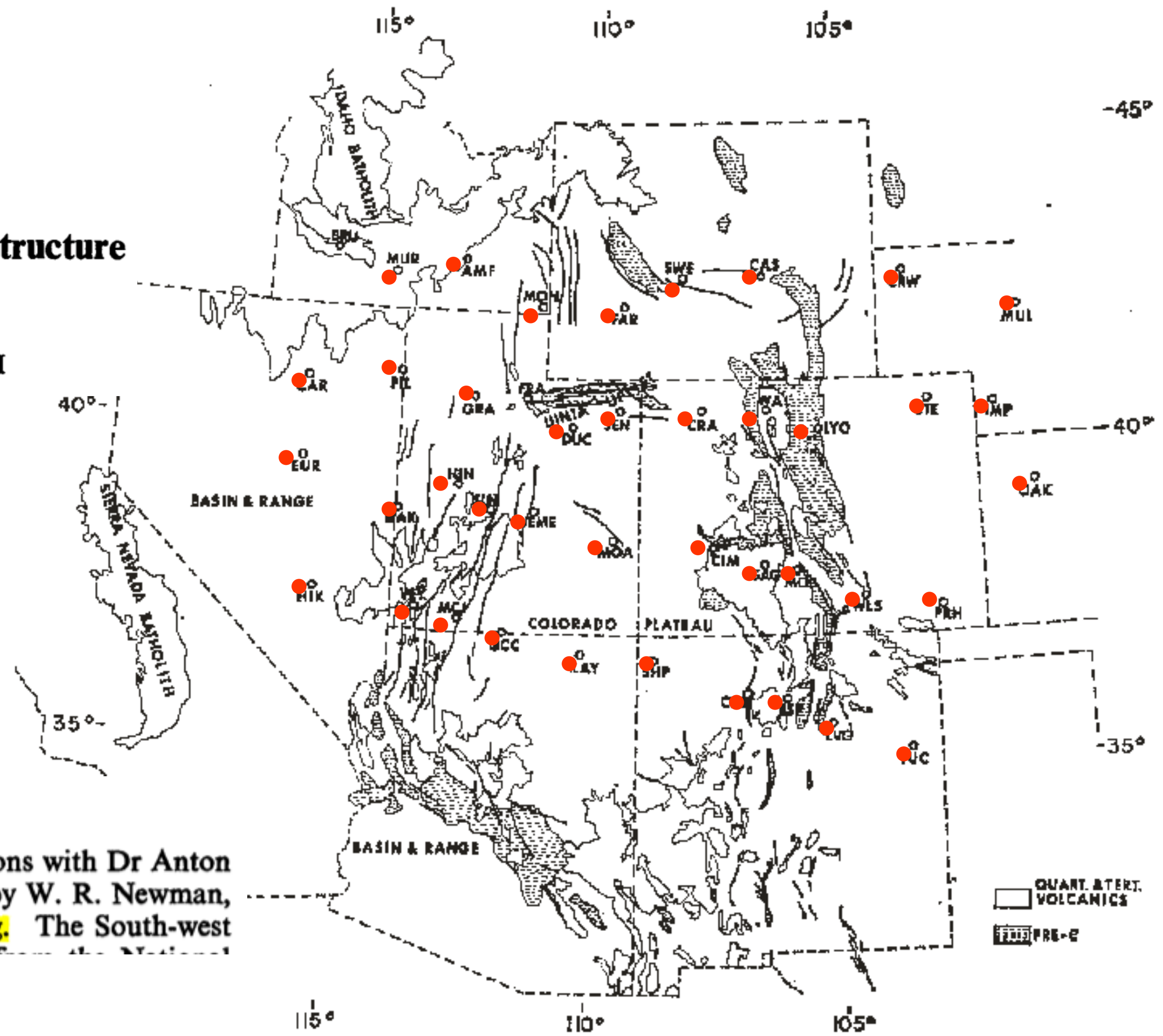
Geophys. J. R. astr. Soc. (1970) **19**, 213–235.

Geomagnetic Deep Sounding and Upper Mantle Structure in the Western United States

J. S. Reitzel, D. I. Gough, H. Porath and C. W. Anderson III

Acknowledgments

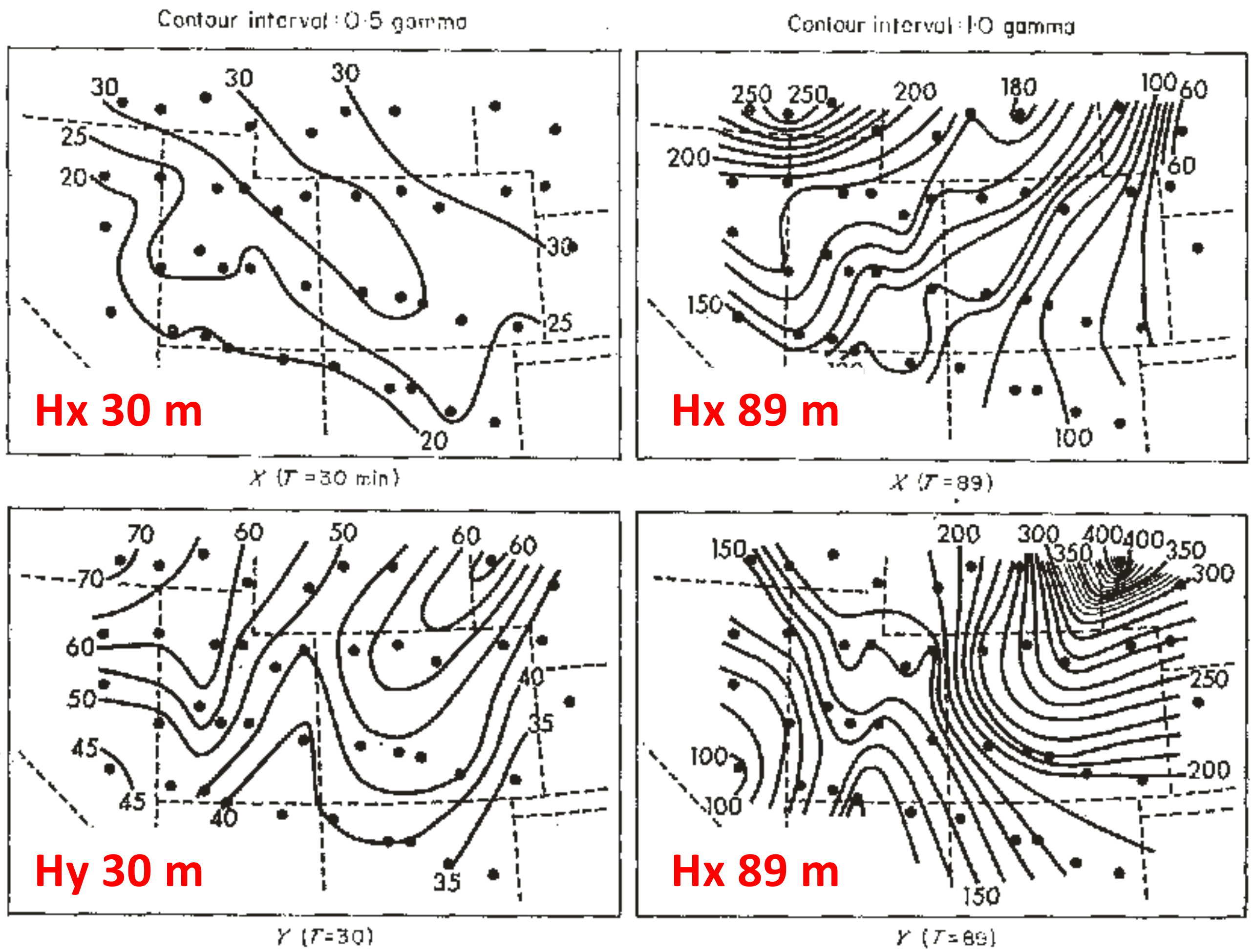
We have pleasure in acknowledging numerous helpful discussions with Dr Anton L. Hales. In the field work and data reduction we were assisted by W. R. Newman, H. J. McCullough, C. Cope, D. Galloway and D. W. Oldenburg. The South-west



COMPLETE MT SOLUTIONS

Fourier Hx & Hy amplitude maps at 30 min and 89 min for 1967 array from event on 1967-Sept-01: Strong event in northern Nebraska

That the biggest anomaly in magnetic variation occurred right at the edge of a magnetometer array became known as “Gough’s Law”, the EM equivalent to Murphy’s Law



COMPLETE MT SOLUTIONS

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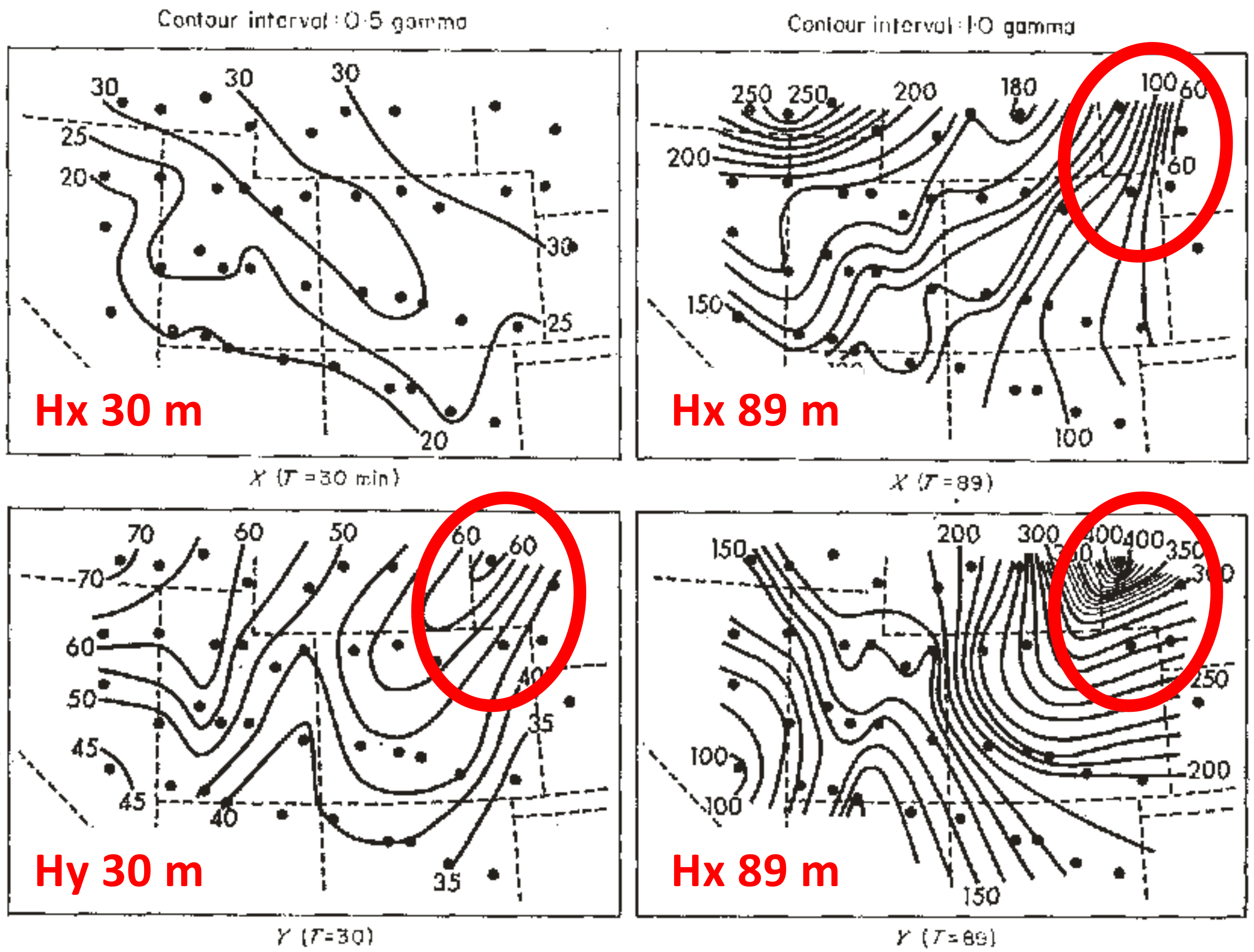
That the biggest anomaly in magnetic variation occurred right at the edge of a magnetometer array became known as "Gough's Law", the EM equivalent to Murphy's Law

Note the very long period of 89 min with a strongly anomalous response ➔ A very deep conductor



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Follow-up array - 1969 array locations (digitized slides from Ian Gough

Magnetometer Array Studies in the North-Western United States and South-Western Canada

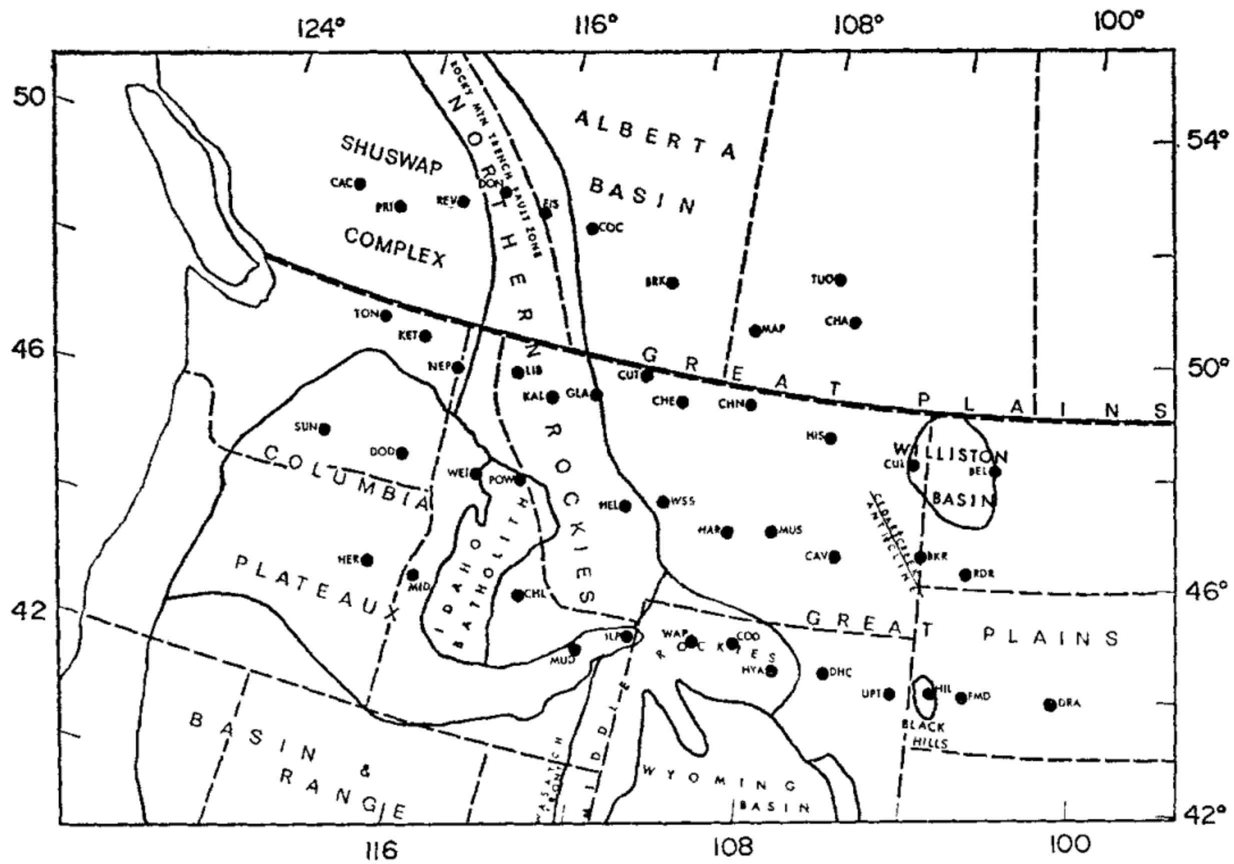
P. A. Camfield, D. I. Gough and H. Porath

Geophys. J. R. astr. Soc. (1970) **22,** 201–221.

Conductive Structures in the North-western United States and South-west Canada

H. Porath, D. I. Gough and P. A. Camfield

Geophys. J. R. astr. Soc. (1971) **23,** 387–398.



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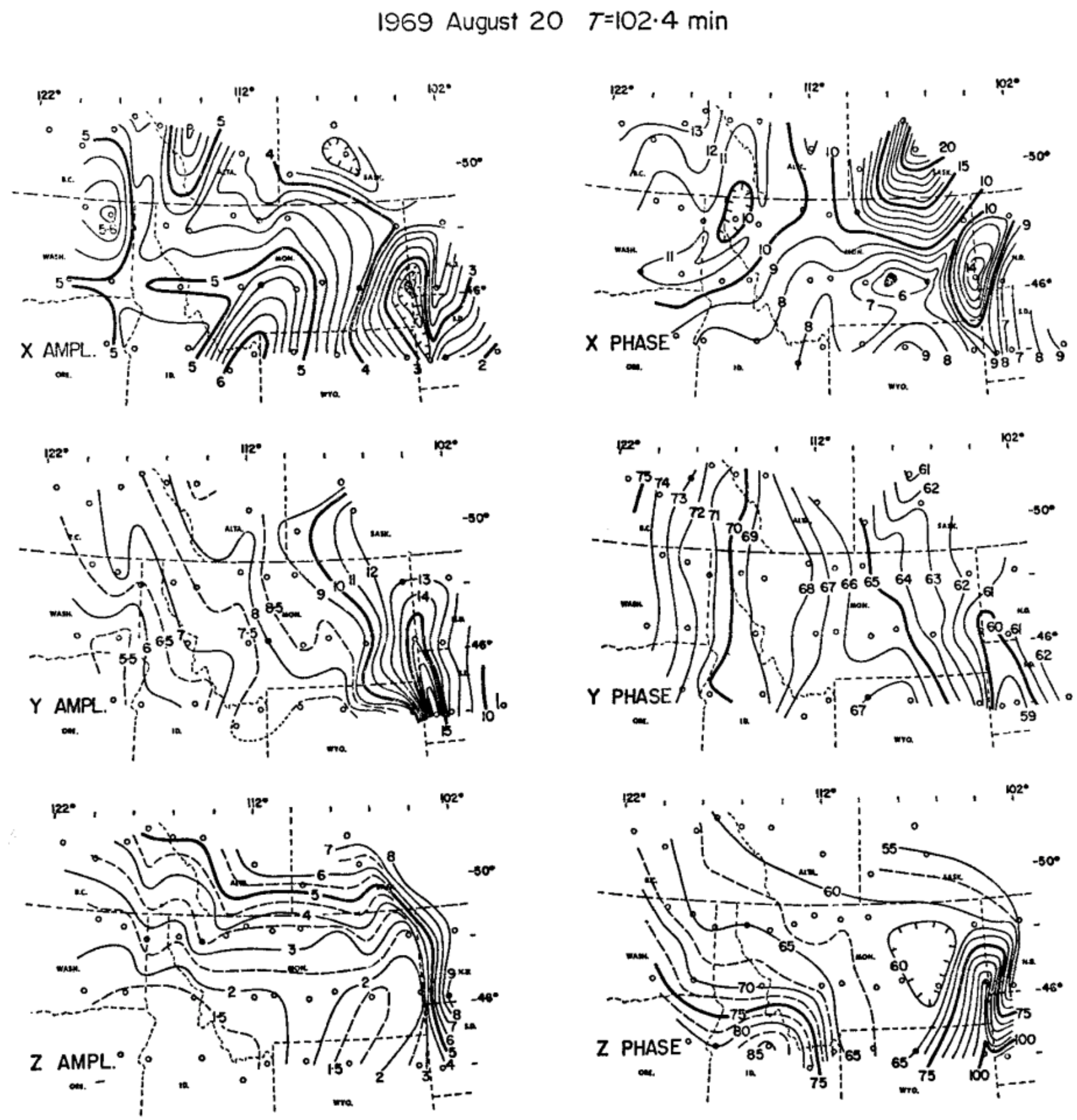
1969 August 20 event

Very strong intensification of amplitudes and strong phase anomalies in all components associated with easternmost edge of the array (Gough's Law!)

Spatially correlated with the Black Hills of South Dakota

Note again the very long period of 102.4 min
➔ A very deep conductor



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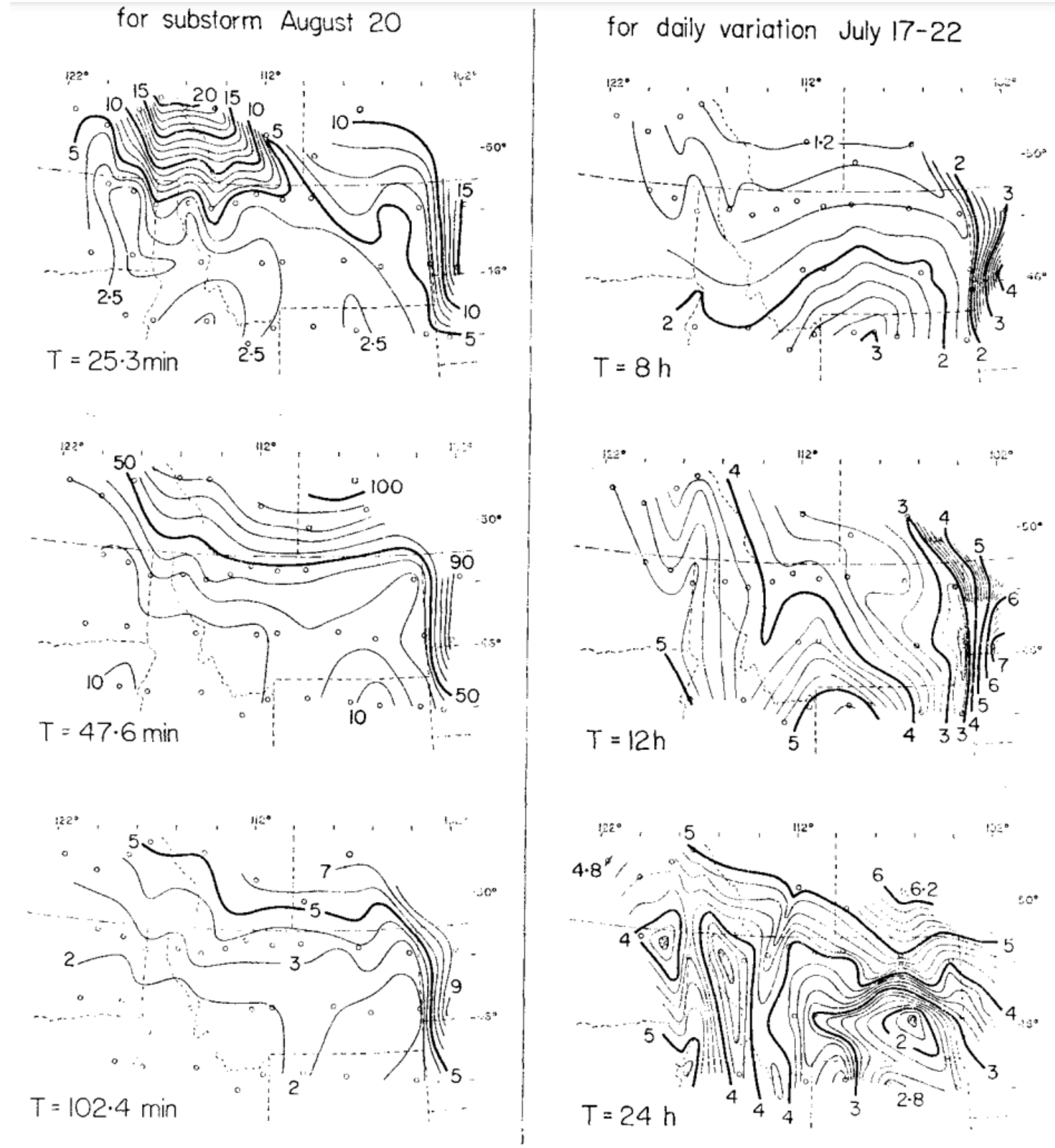
VERY long periods

Camfield and Gough (1975) looked at very long periods of Quiet days and compared the Fourier maps to those of active days at shorter periods, and found a strong amplification at the location of the anomalous region on the eastern side of the array at periods up to 12 hours

Anomalies in Daily Variation Magnetic Fields and Structure Under North-western United States and South-western Canada*

P. A. Camfield and D. I. Gough

Geophys. J. R. astr. Soc. (1975) **41**, 193–218.



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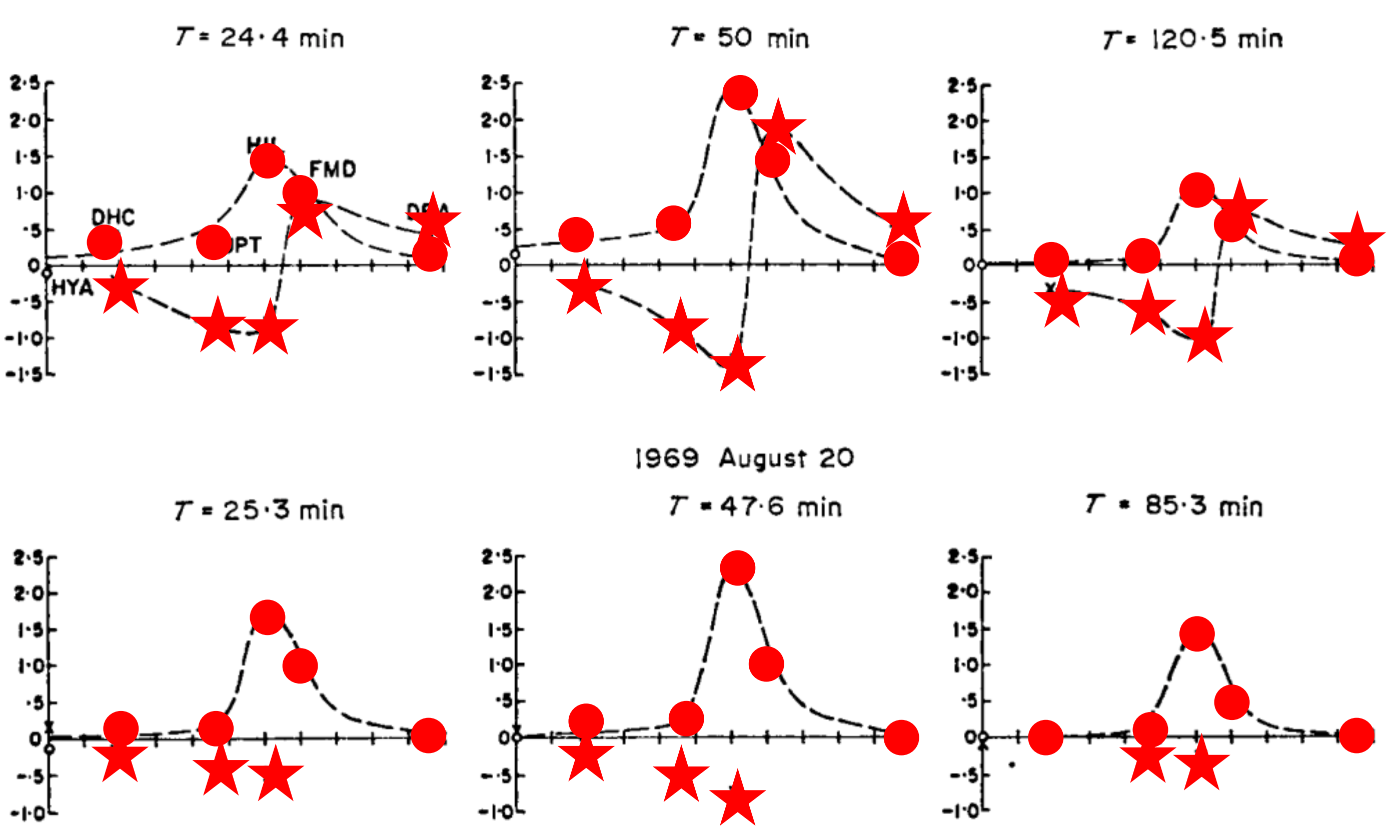
Normalized fields across the Black Hills from 1969 array



● = Da/Dn

★ = Z/Dn

Note the very strong vertical field response – greater than the normal horizontal field in some cases.

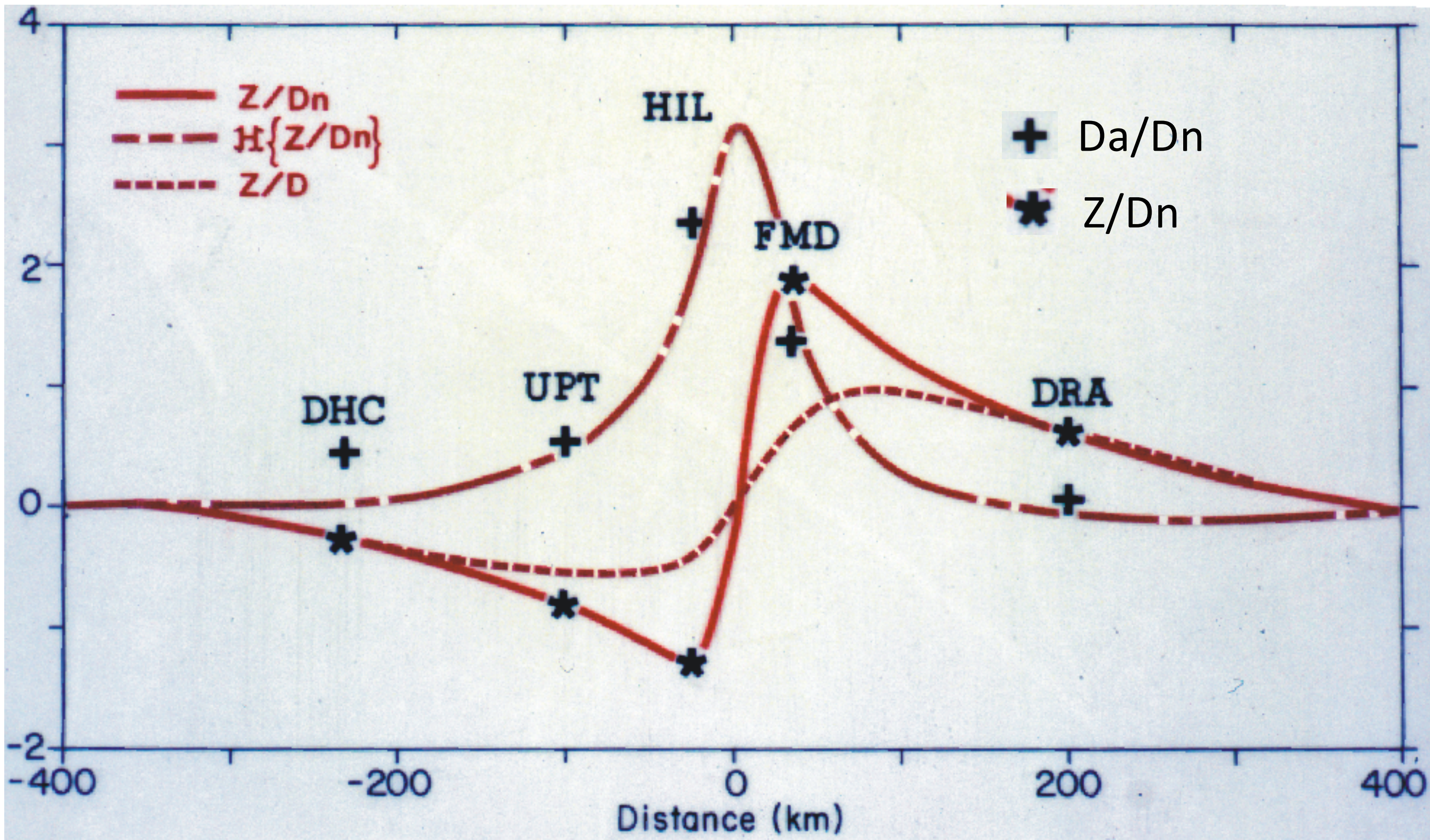
This was thought impossible and "current channelling" was invoked

Normalized fields (Z/Dn and Da/Dn) across the Black Hills from 1969 array and Hilbert transform

I derived the Hilbert Transform of Z/Dn and showed it fits exactly Da/Dn

This was (and still is by some) known as the "Kertz Operator" in geomagnetism

(Kertz, 1954)



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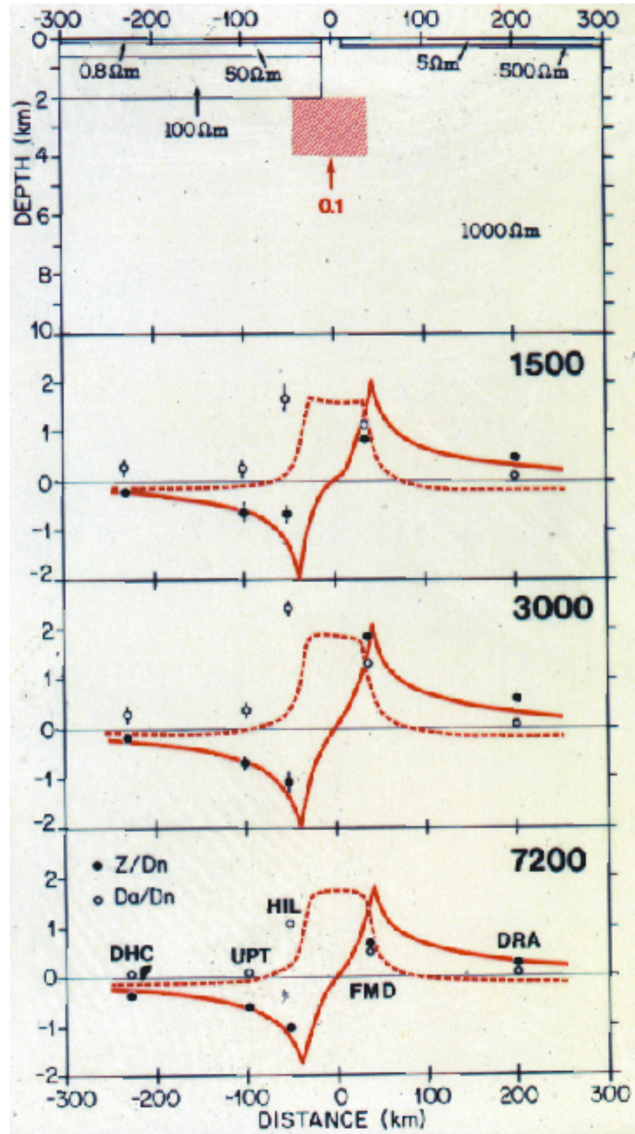
Simple (but extreme!) 2-D model of a conductor below the Black Hills to explain the GDS observations

An extensive highly-conducting (0.1 Ωm) block of conducting material 2 km thick (=20,000 S integrated conductivity) and 100 km wide right at the edge of the sedimentary basin explains the observations to first-order, even to very long periods

→ A conductivity model can be found that explains the observations, one does not need to appeal to "current channelling"

→ The model is completely geologically implausible though…



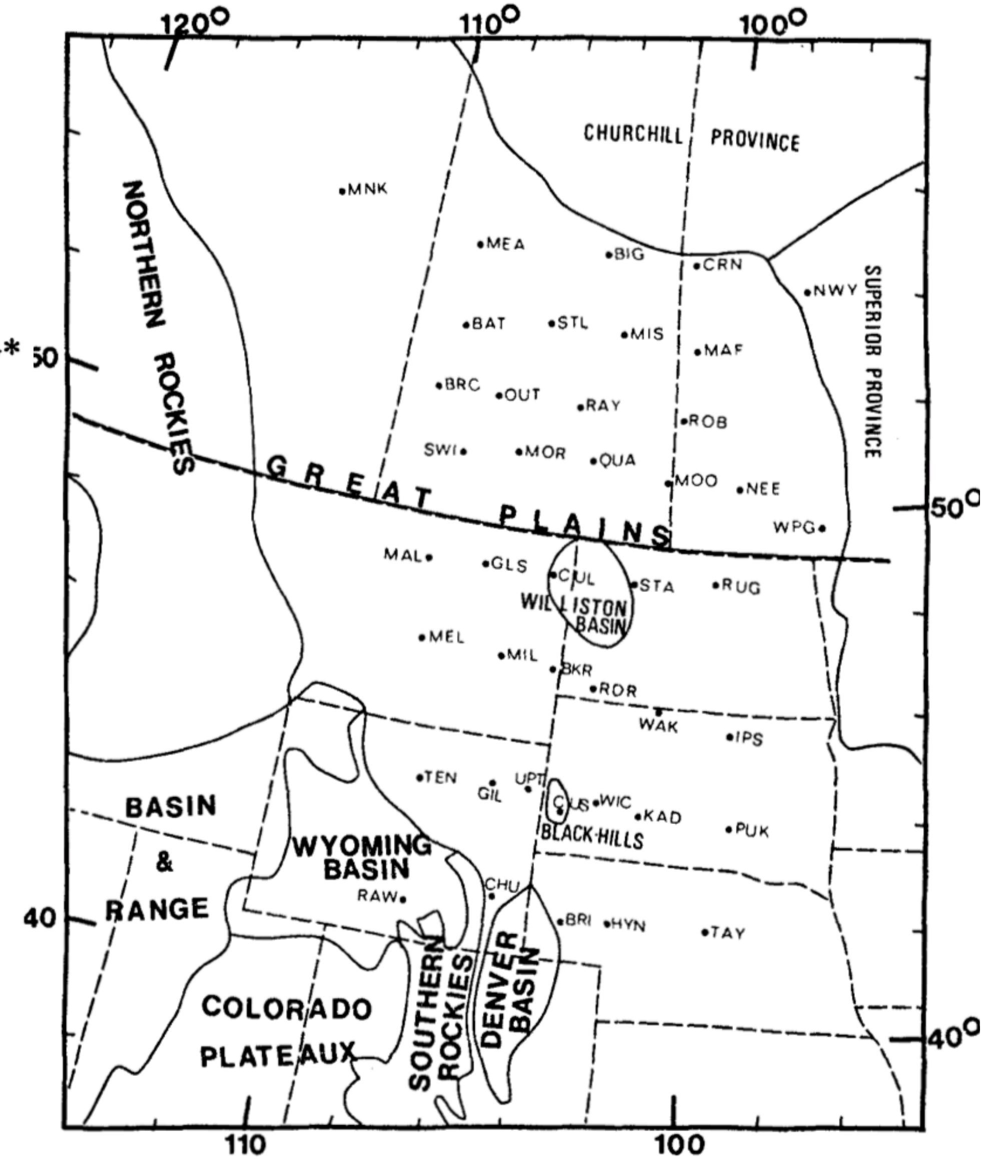
GDS array in 1972 by Alabi, Camfield and Gough followed up on Black Hills anomaly

The North American Central Plains Conductivity Anomaly*

A. O. Alabi, P. A. Camfield and D. I. Gough

Geophys. J. R. astr. Soc. (1975) **43**, 815–833.

First use of the name “North American Central Plains Conductivity Anomaly”, abbreviated to NACP



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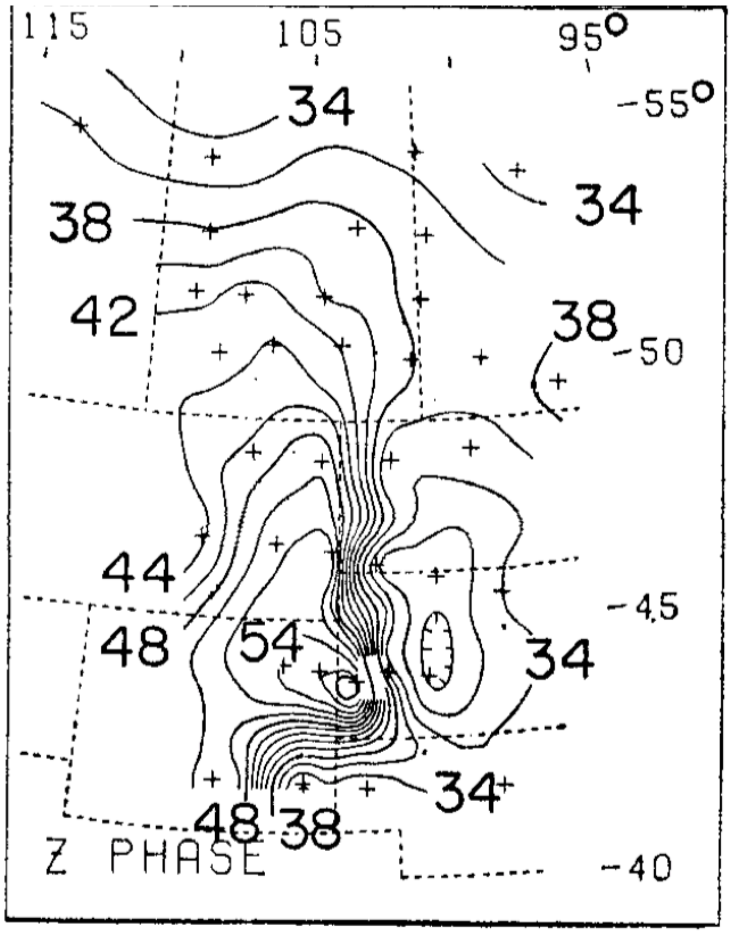
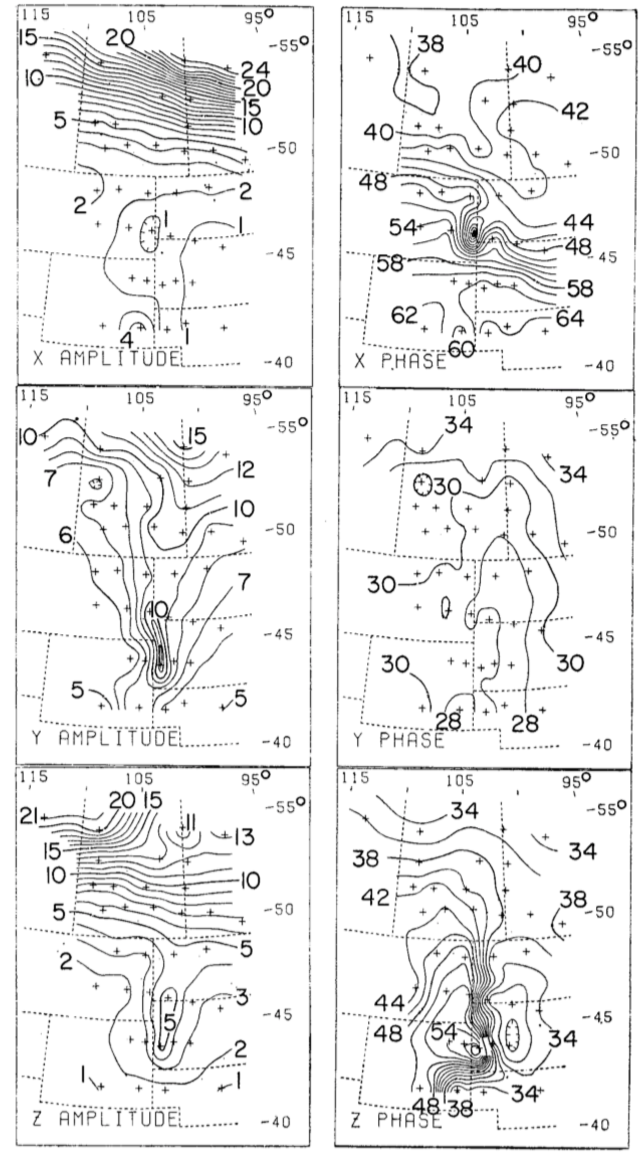
Fourier maps for event from 1972 array (1972-Aug-28) at 68 min period

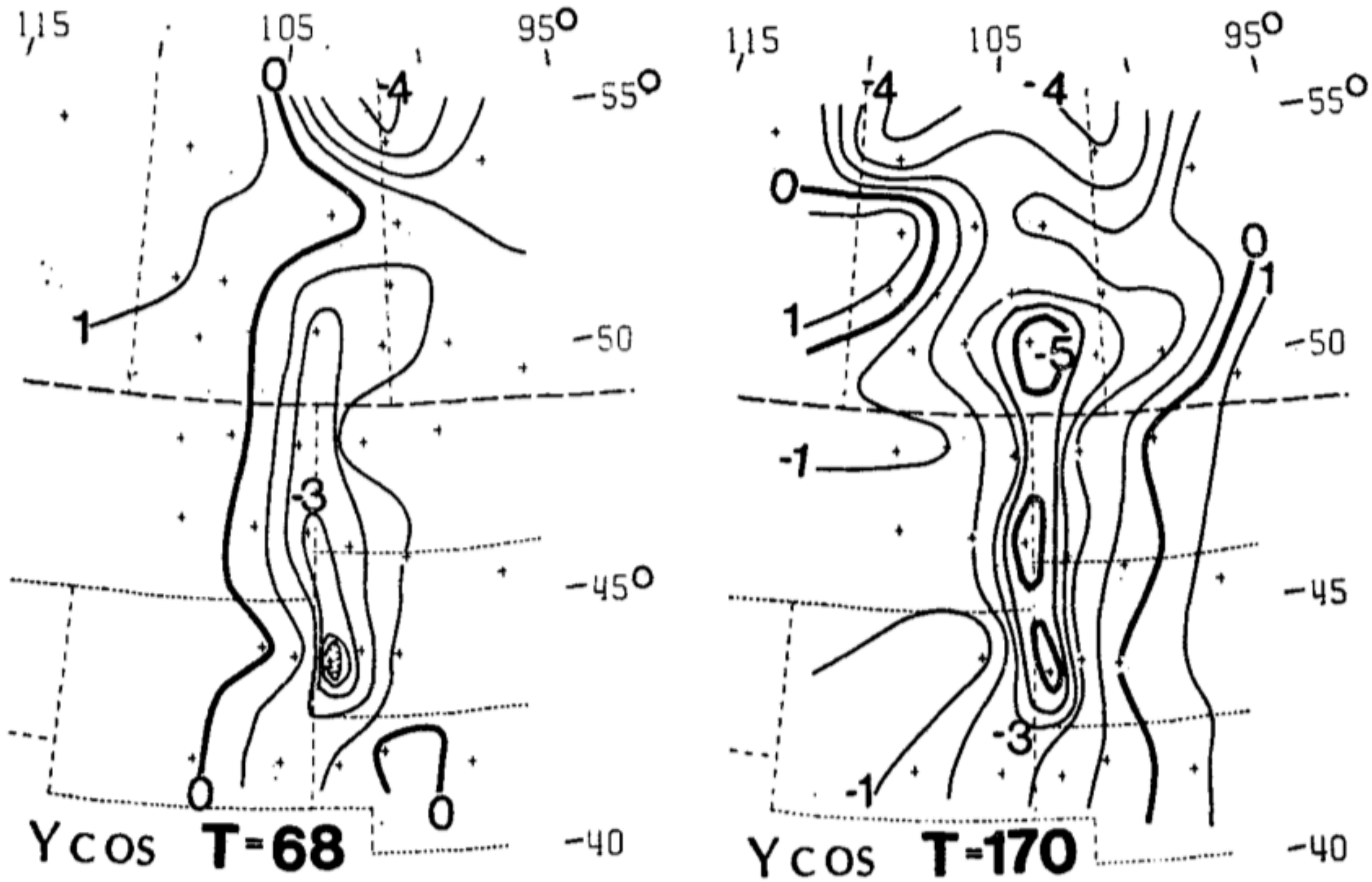


Fourier maps at 31.5 m, particularly Hz phase, show the presence of a linear conductor from southern Dakota into northern Canada



Residual Fourier cosine Hy coefficient maps for event from 1972 array (1972-Aug-28 and 1972-Aug-31) at periods of 68 mins and 170 mins

Residual coefficient maps constructed assuming the end stations for each E-W line can be taken as “normal” and subtracting the cos coeff at each station



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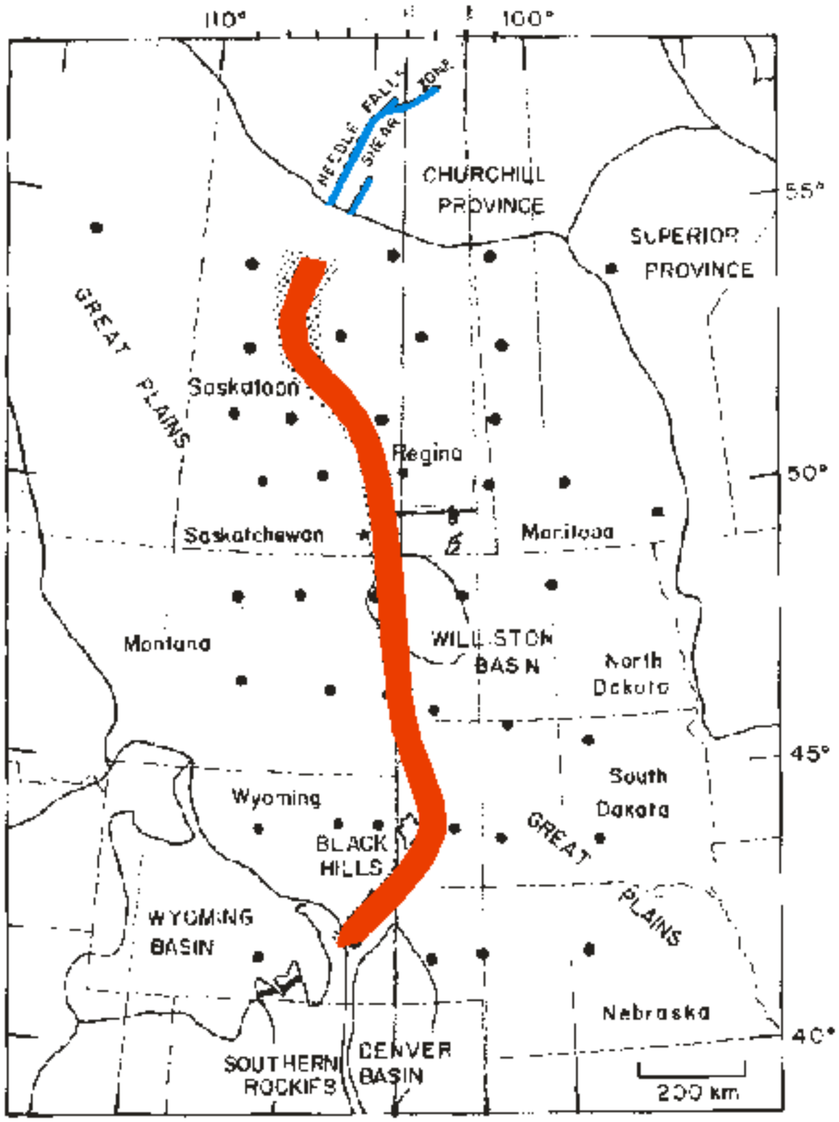
Trace of the North American Central Plains (NACP) conductivity anomaly based on GDS responses



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Camfield and Gough's 1977 suggestion that there is a Proterozoic continental collision zone or geosuture beneath the Central Plains

A possible Proterozoic plate boundary in North America[1,2]

P. A. CAMFIELD

Earth Physics Branch, Energy, Mines and Resources Canada, Ottawa, Ont., Canada K1A 0Y3

AND

D. I. GOUGH

Institute of Earth and Planetary Physics, Department of Physics, University of Alberta, Edmonton, Alta., Canada T6G 2E1

Received 27 September 1976

Revision accepted for publication 5 January 1977

Can. J. Earth Sci., **14**, 1229–1238 (1977)

This was the FIRST paper published to suggest that a major continental-scale plate boundary existed from exposed rocks in northern Canada to beneath the Williston Basin

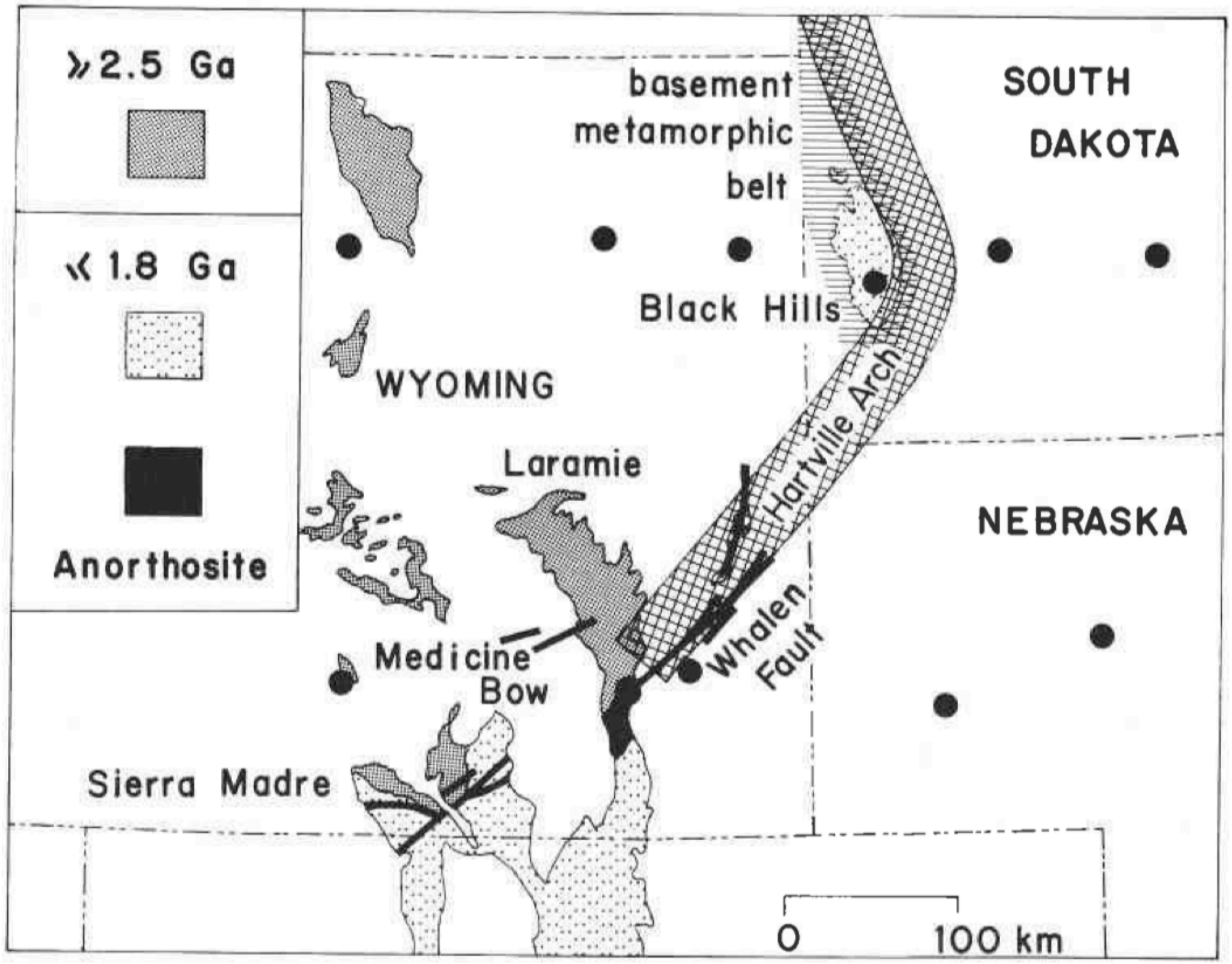
Came before any geological model

They further went on to propose that the cause of the NACP is graphite

NACP spatially related to Proterozoic-aged structures at southern end

Proterozoic-aged Black Hills, Hartville Arch, and Whalen Fault

Camfield and Gough note that “Graphite occurs in some of these exposures (Osterwald et al. 1959).:



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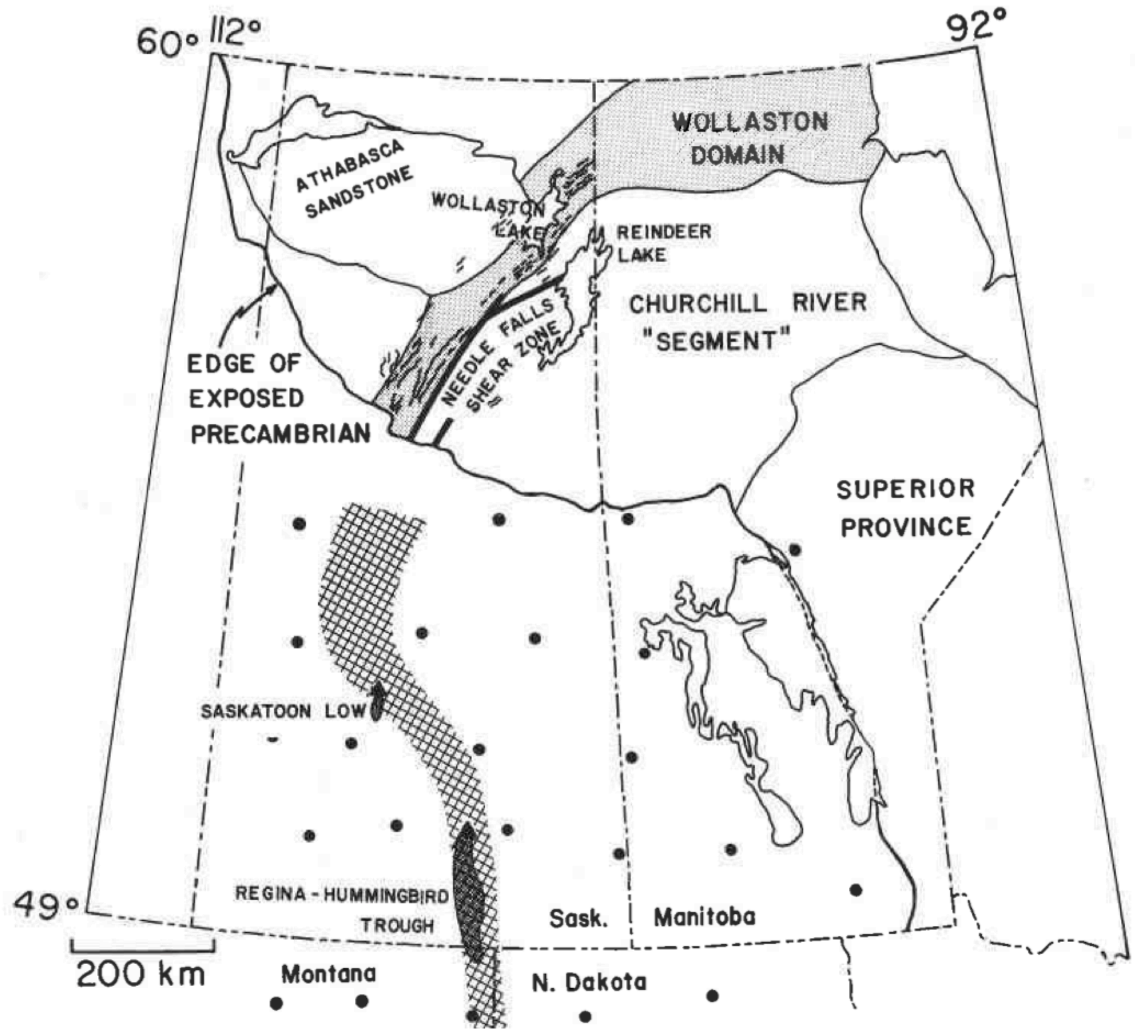
NACP spatially related to Proterozoic-aged structures at northern end

Proterozoic-aged Needle Falls Shear Zone was thought to be the northern projection of the NACP

On the Wollasaton Domain, Camfield and Gough report that "conductive anomalies form definite linear belts with generally southwesterly strike", and that "almost invariably they coincide with graphitic garnet-biotite gneiss units". (R.J.C. Munday, Saskatchewan Mining Development Corporation, personal communication, 1976



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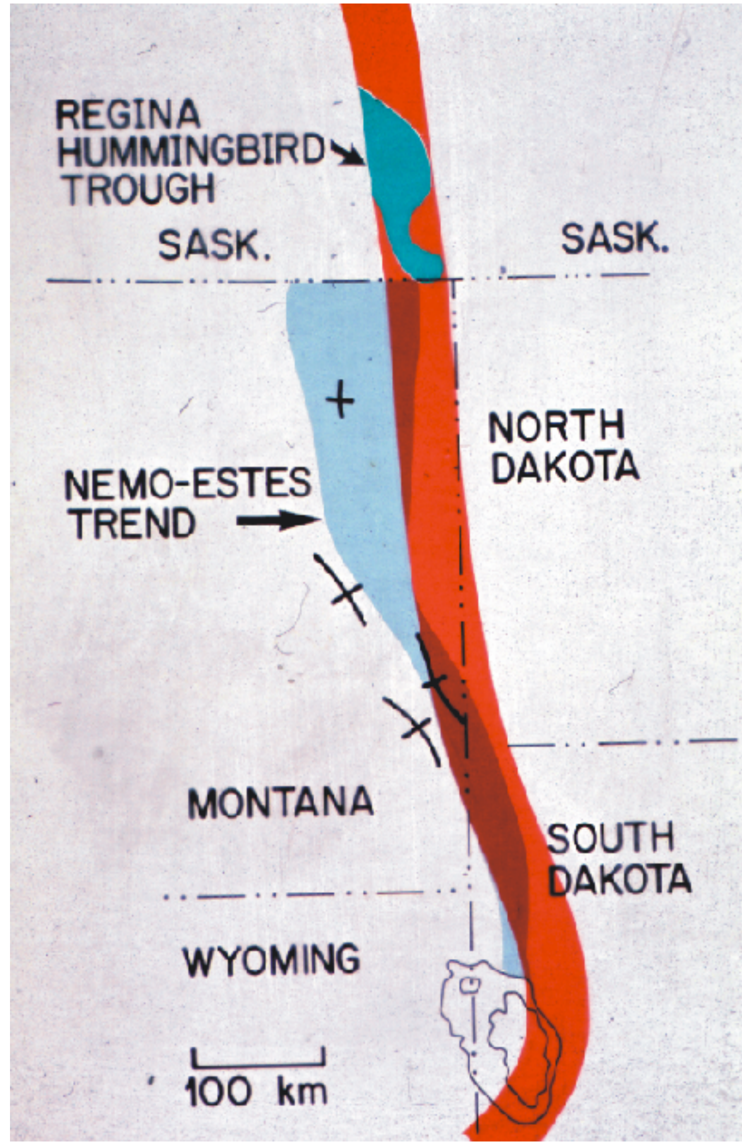
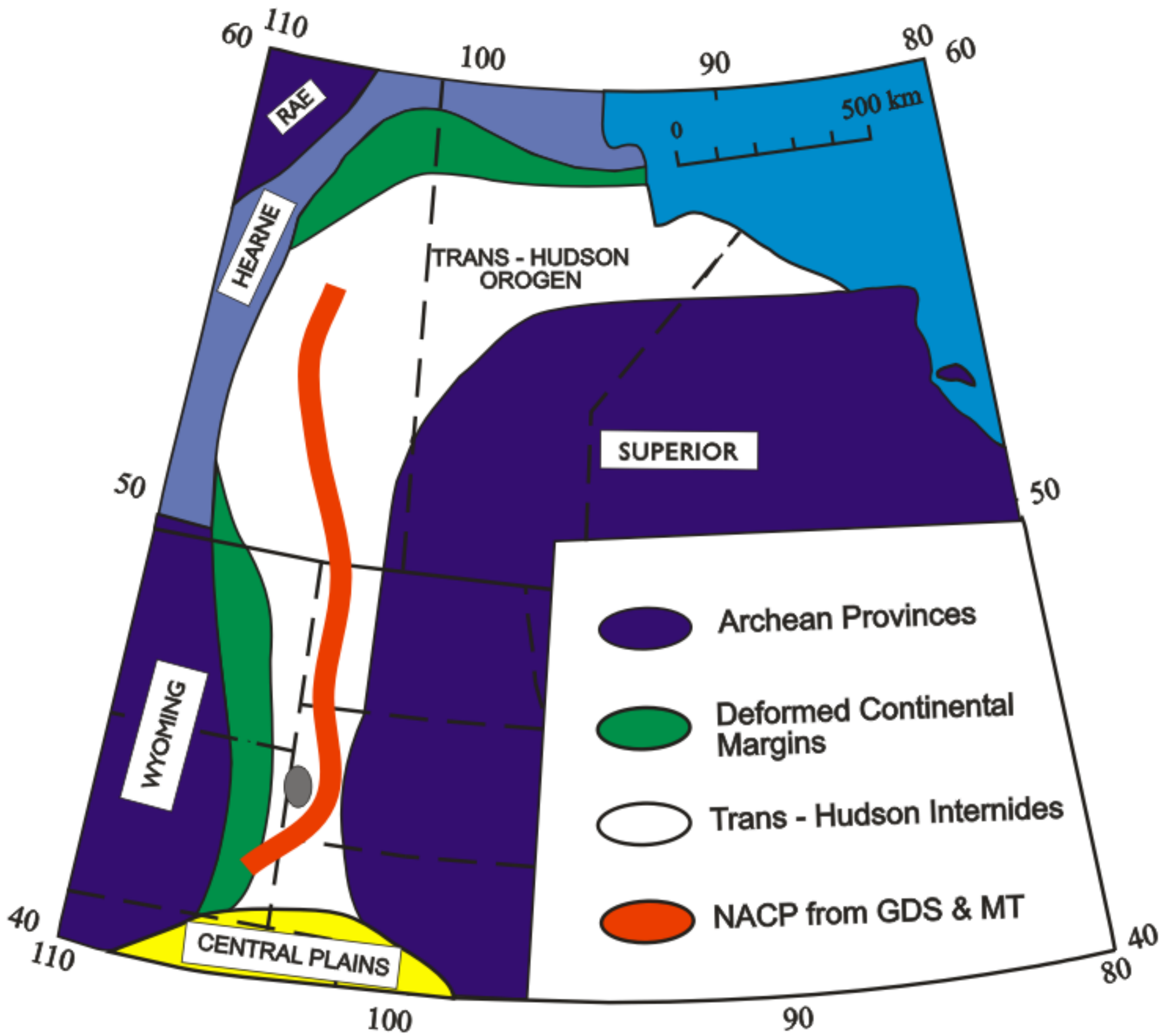
Suggestion that structures in the Phanerozoic basin are controlled by Proterozoic-aged basement features related to the NACP



Trace of NACP after GDS array of Alabi, Camfield and Gough (1975) on the now-known extent of the Paleoproterozoic Trans-Hudson Orogen (THO) that coalesced the Superior craton (east) with the Rae-Hearne and Wyoming cratons (west)



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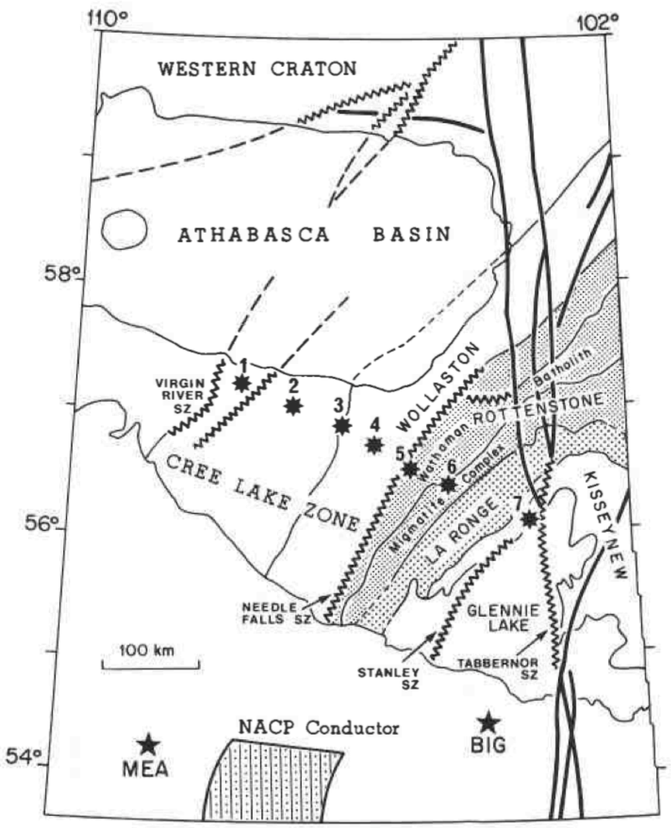
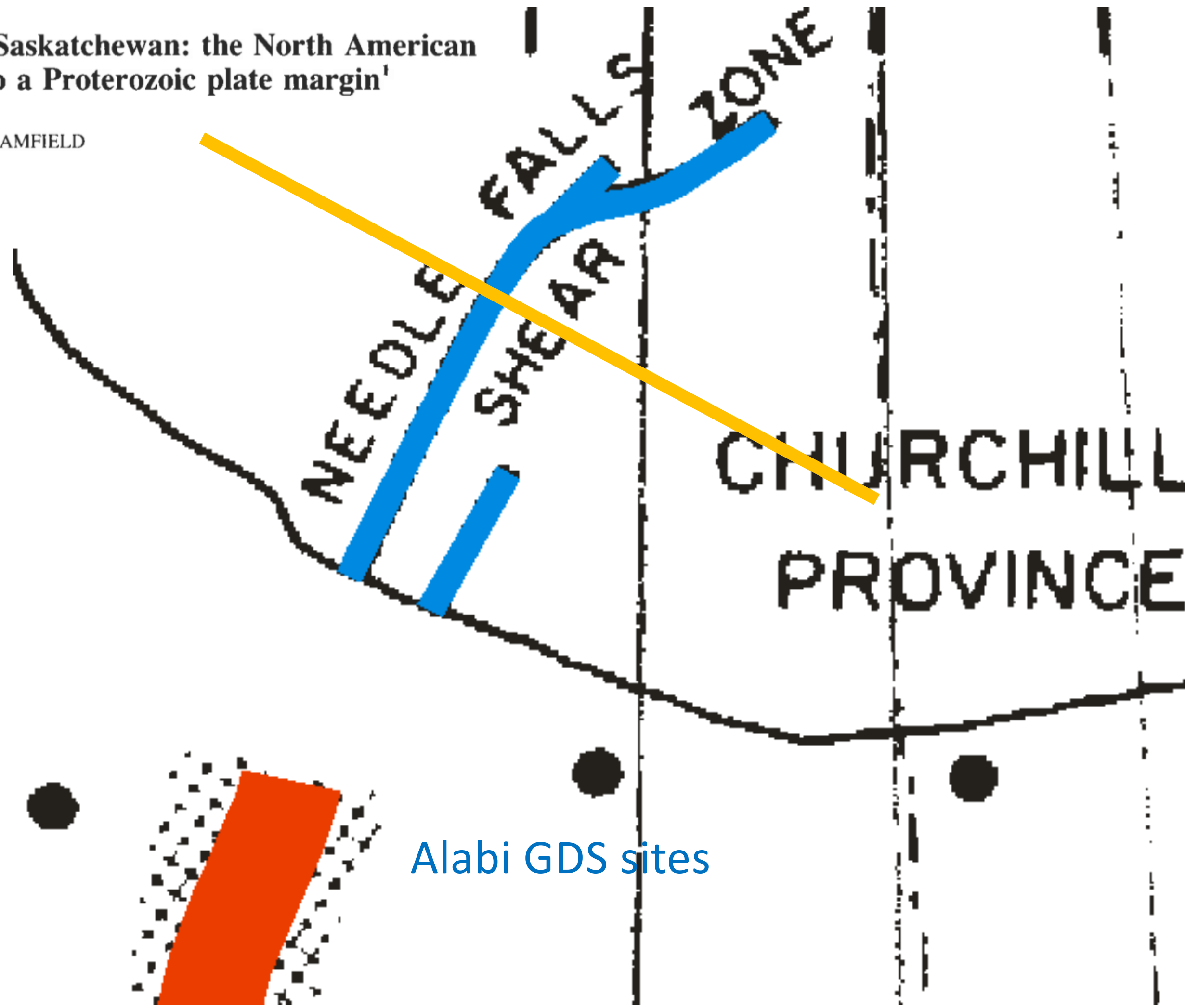
Handa and Camfield GDS profile in N. Saskatchewan

Crustal electrical conductivity in north-central Saskatchewan: the North American Central Plains anomaly and its relation to a Proterozoic plate margin[1]

S. HANDA[2] AND P. A. CAMFIELD

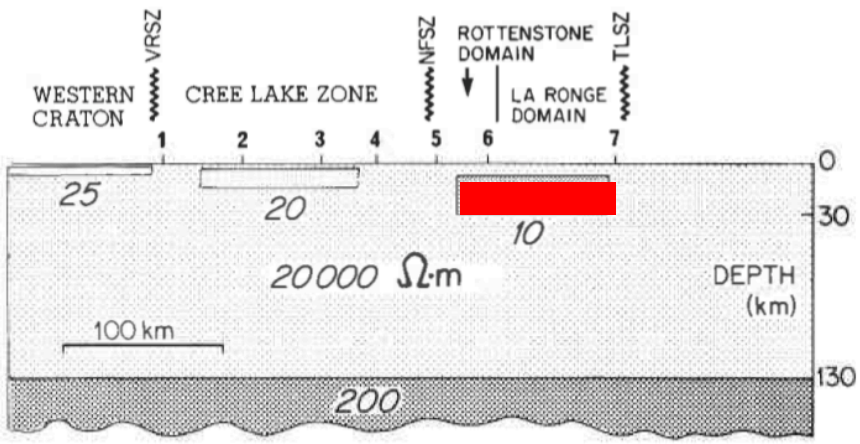
Can. J. Earth Sci. 21, 533–543 (1984)

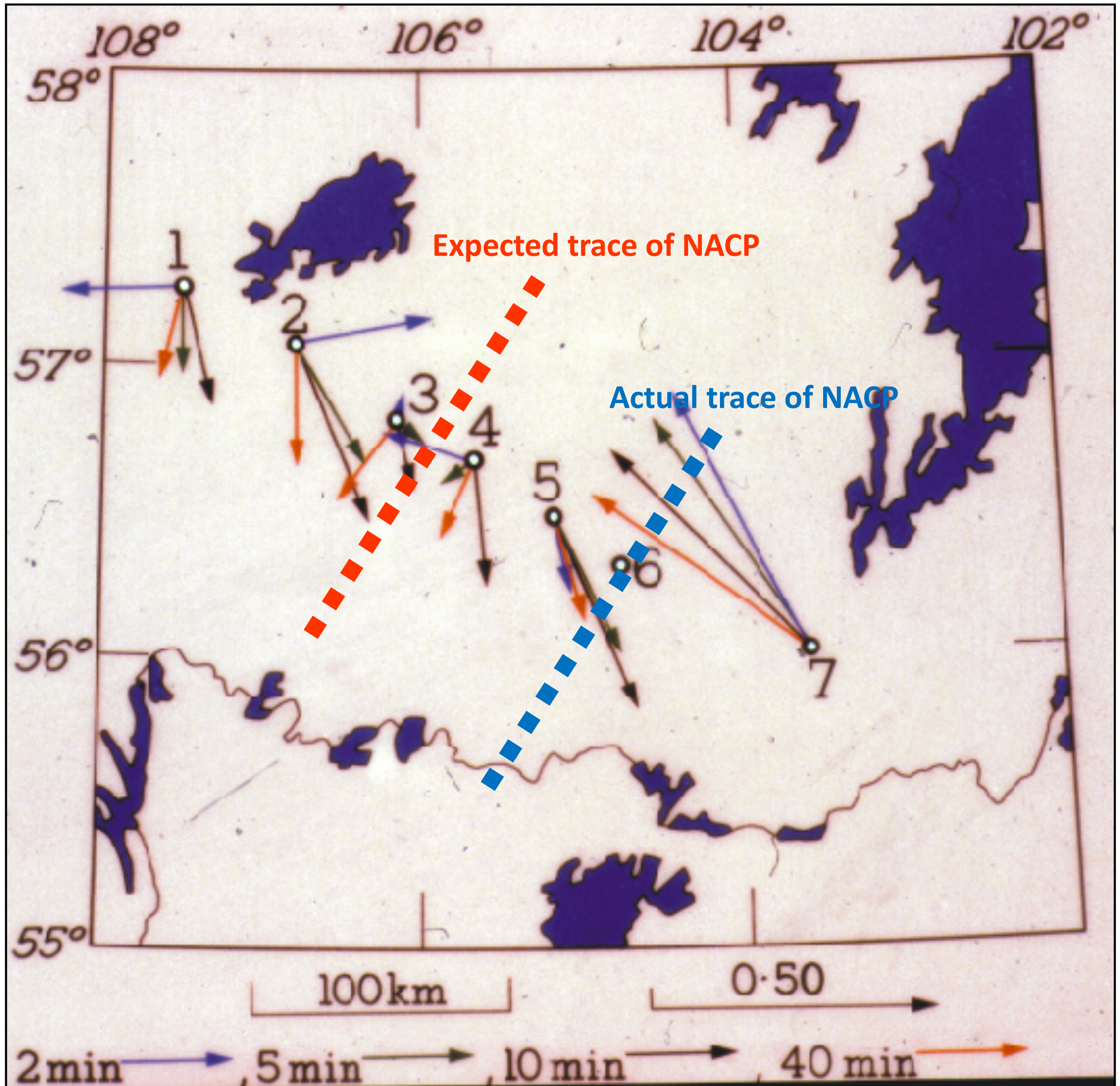




Handa & Camfield followed up with a GDS profile across the NFSZ

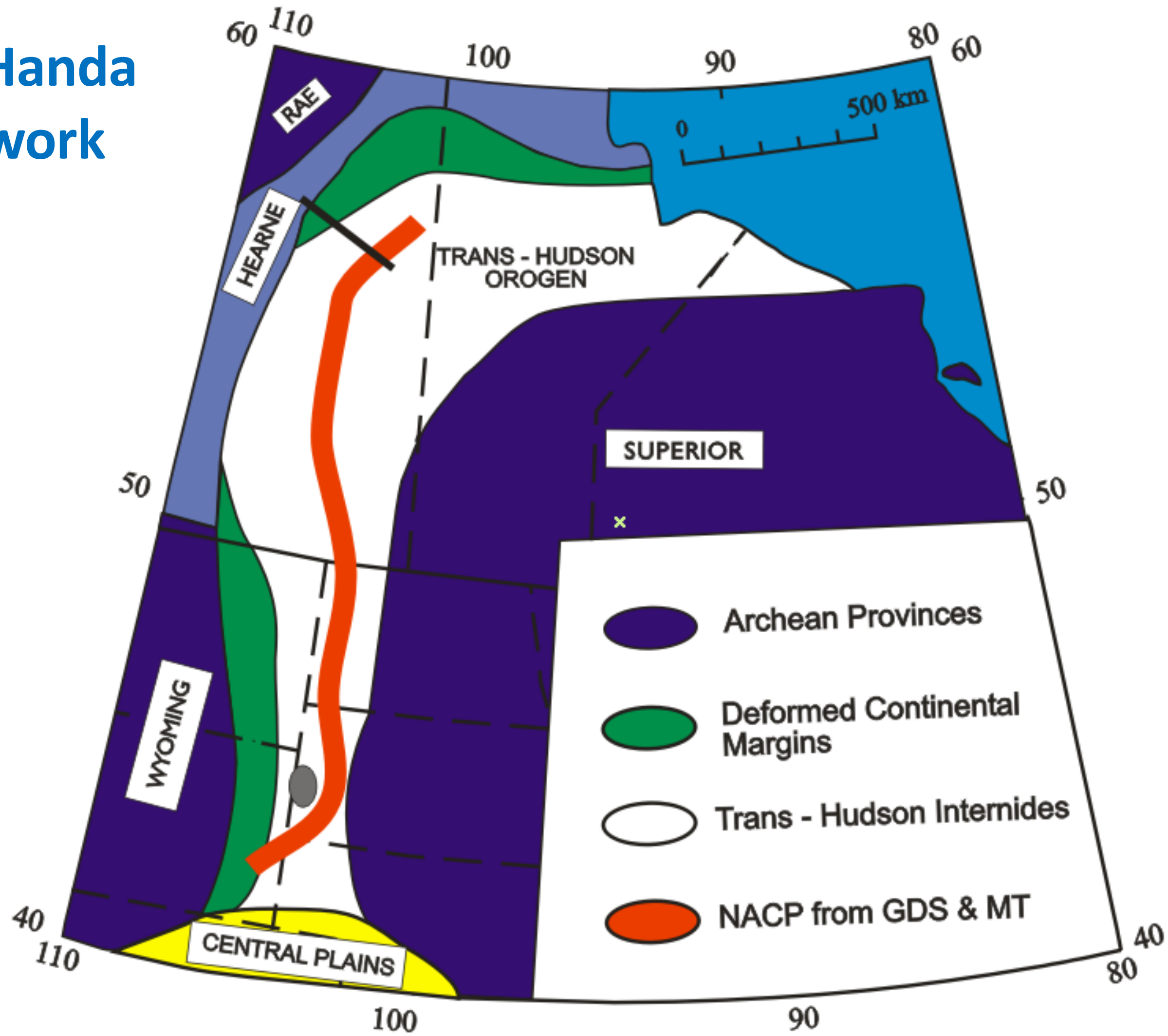
Anomaly at SE end of profile, not in middle as expected
2D forward model of 2 min and 20 min data shows large crustal conductor beneath the La Ronge Domain





SOLUTIONS

Trace of NACP after Handa & Camfield's (1984) work

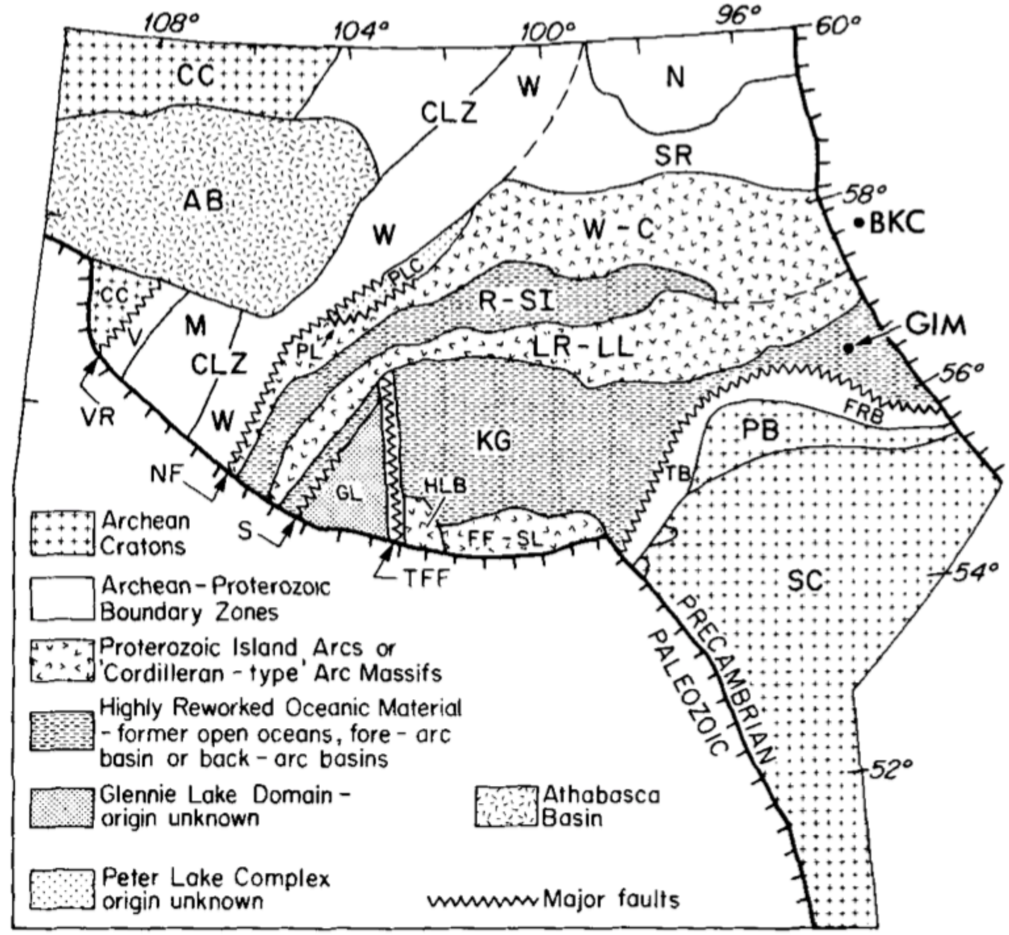


Gupta et al. (1985)

A geomagnetic induction anomaly from IMS data near Hudson Bay, and its relation to crustal electrical conductivity in central North America

J. C. Gupta, R. D. Kurtz, P. A. Camfield and E. R. Niblett *Division of Seismology and Geomagnetism, Earth Physics Branch, Energy, Mines and Resources, Ottawa, Ontario K1A 0Y3, Canada*

Geophys. J. R. astr. Soc. (1985) 81, 33–46



Gupta et al. mapped a conductor found between two IMS geomag stations GIM and BKC and related it to the NACP b/c of along-strike continuity of La Ronge belt (LR-LL)

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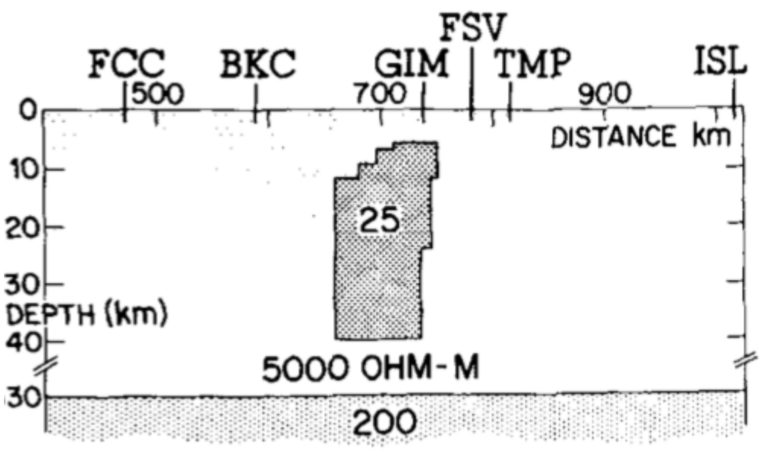
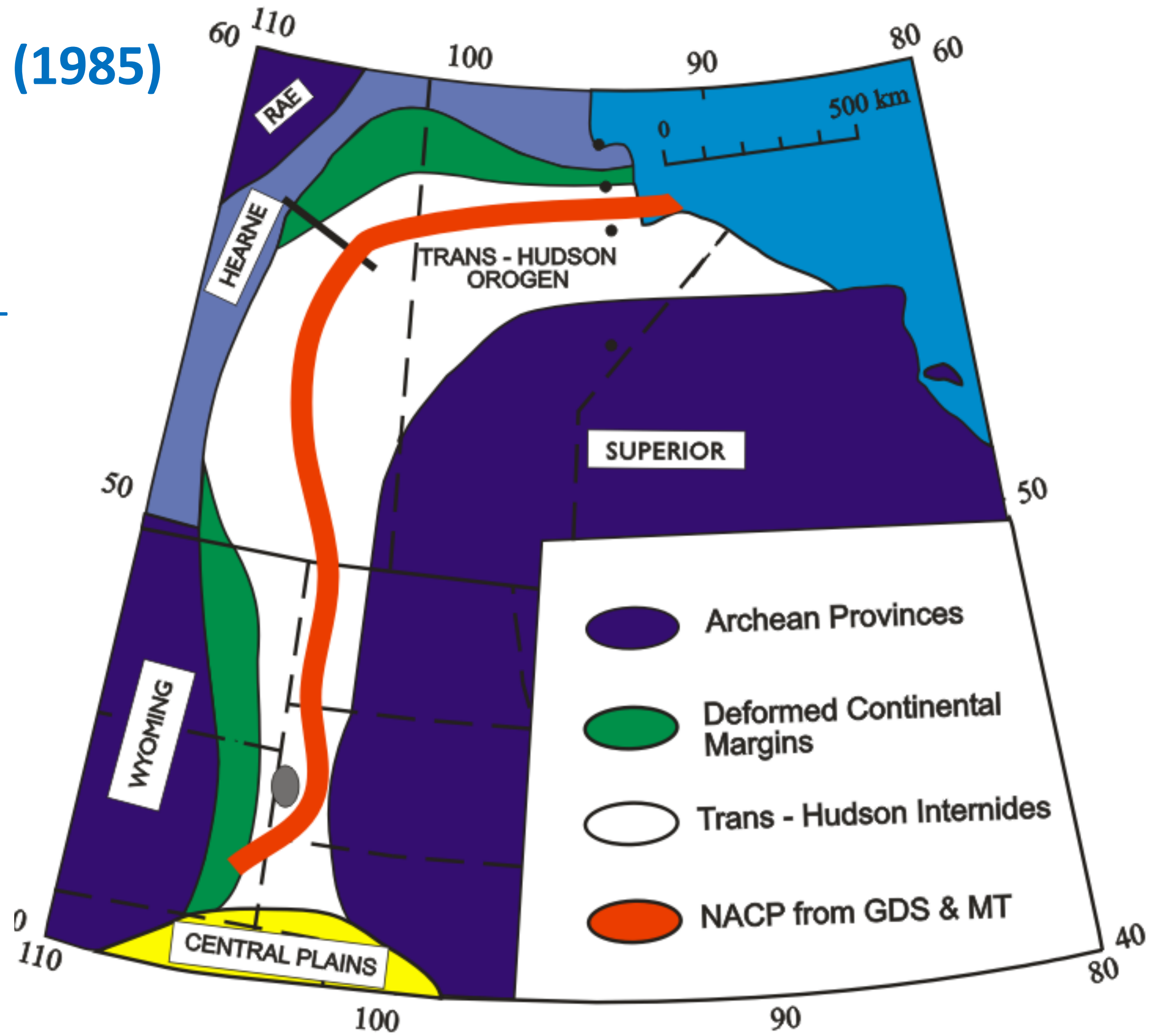
Trace of NACP after Gupta et al. (1985)

2D forward model shows strong crustal conductor of 25 Ωm from 5 – 40 km (1,400 S conductance)





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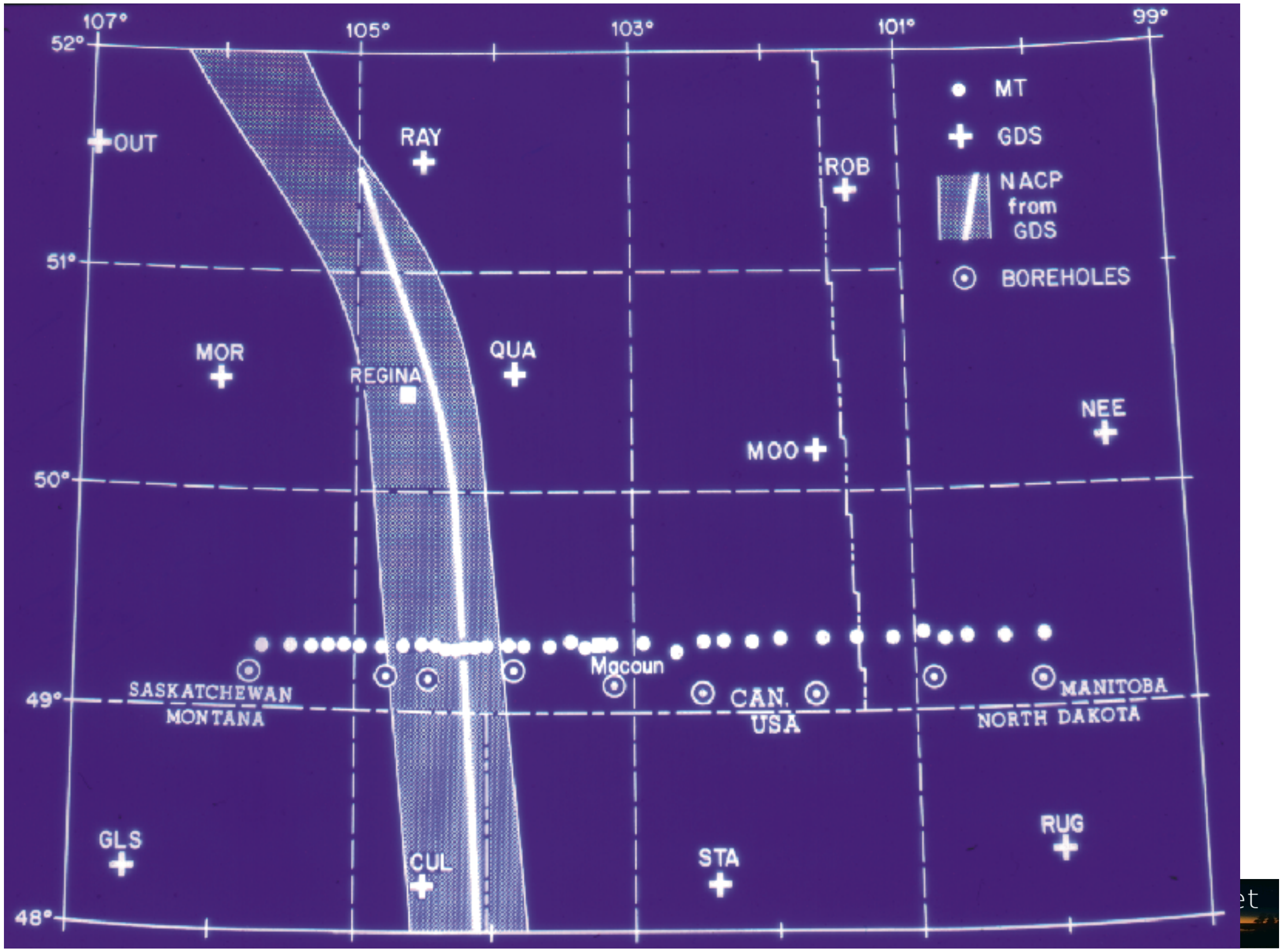
PanCanadian undertook MT surveys in 1984 and 1985 to follow up on basement-control by NACP

1984 MT site locations based on GDS location of NACP at 104.5° W

Did not cross anomaly. Had to conduct 1985 survey



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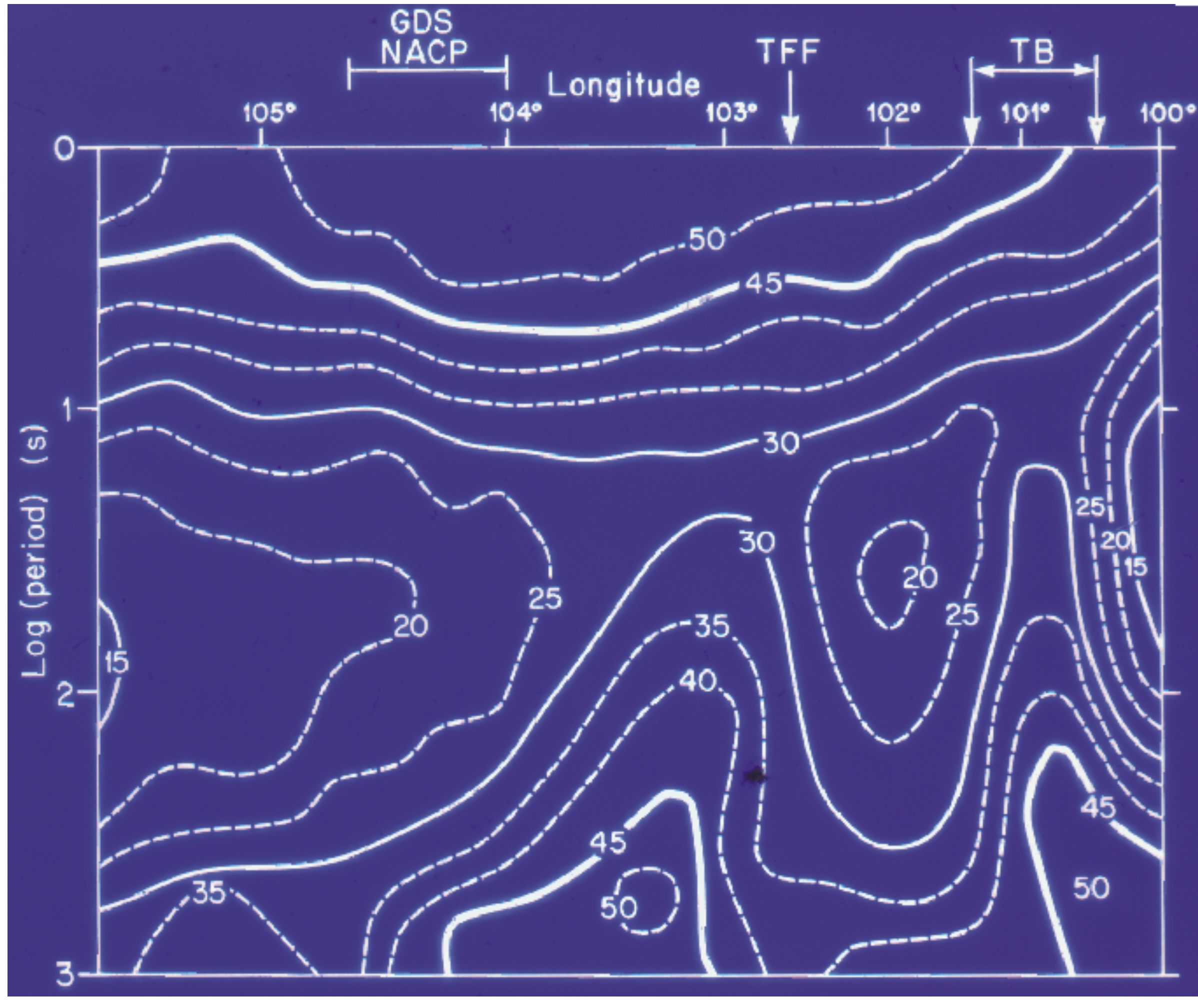
TE phase pseudosection shows maximum response at 103º W, not at proposed GDS location

NORTH AMERICAN CENTRAL PLAINS CONDUCTIVITY ANOMALY GOES EAST

Alan G. Jones[1] and Peter J. Savage[2]

GEOPHYSICAL RESEARCH LETTERS, VOL. 13, NO. 7, PAGES 685-688, JULY 1986



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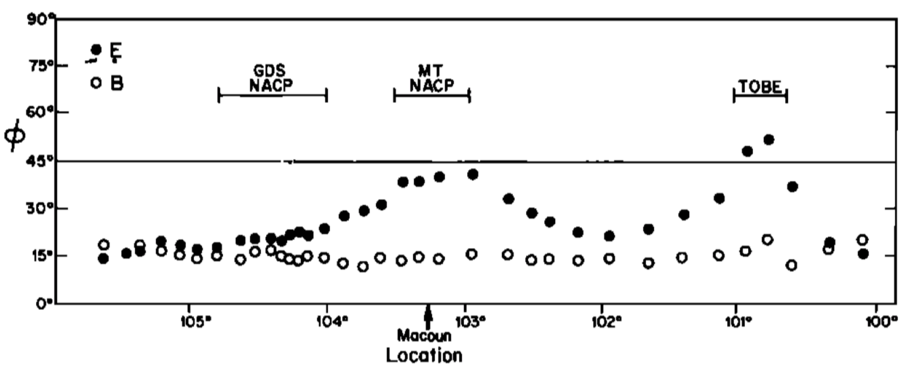
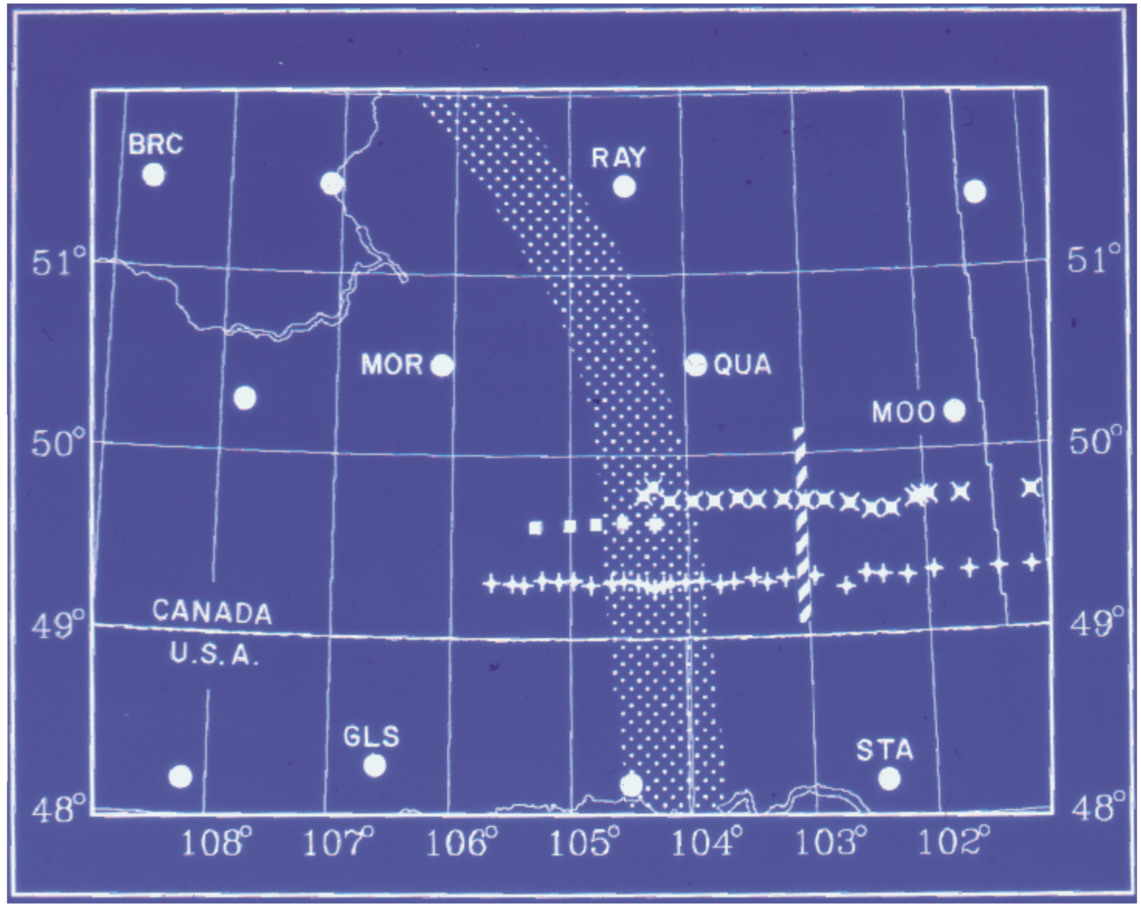
Relocated top of NACP based on MT at 103º W at 49º N

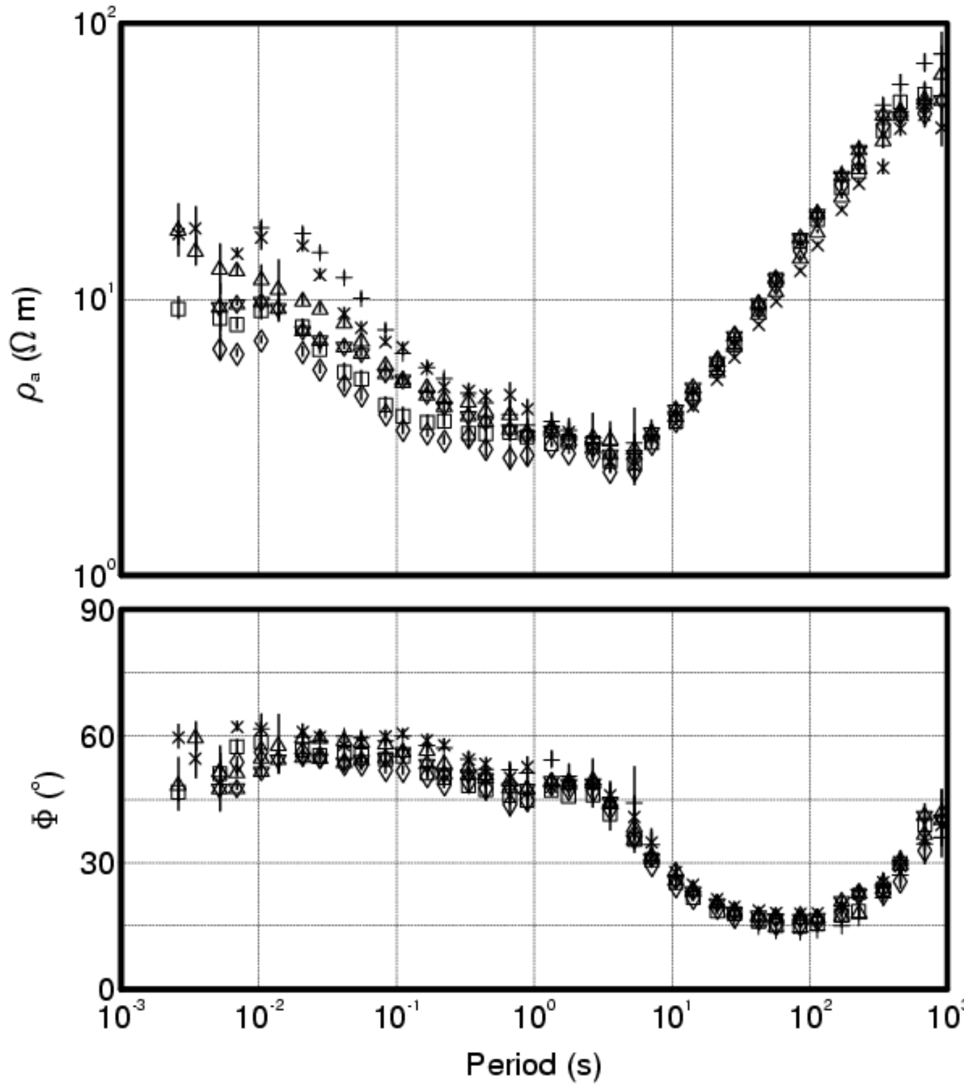
TE & TM phases at 100 s





Sites at western end of profile isotropic

RhoXY = RhoYX
PhaXY = PhaYX



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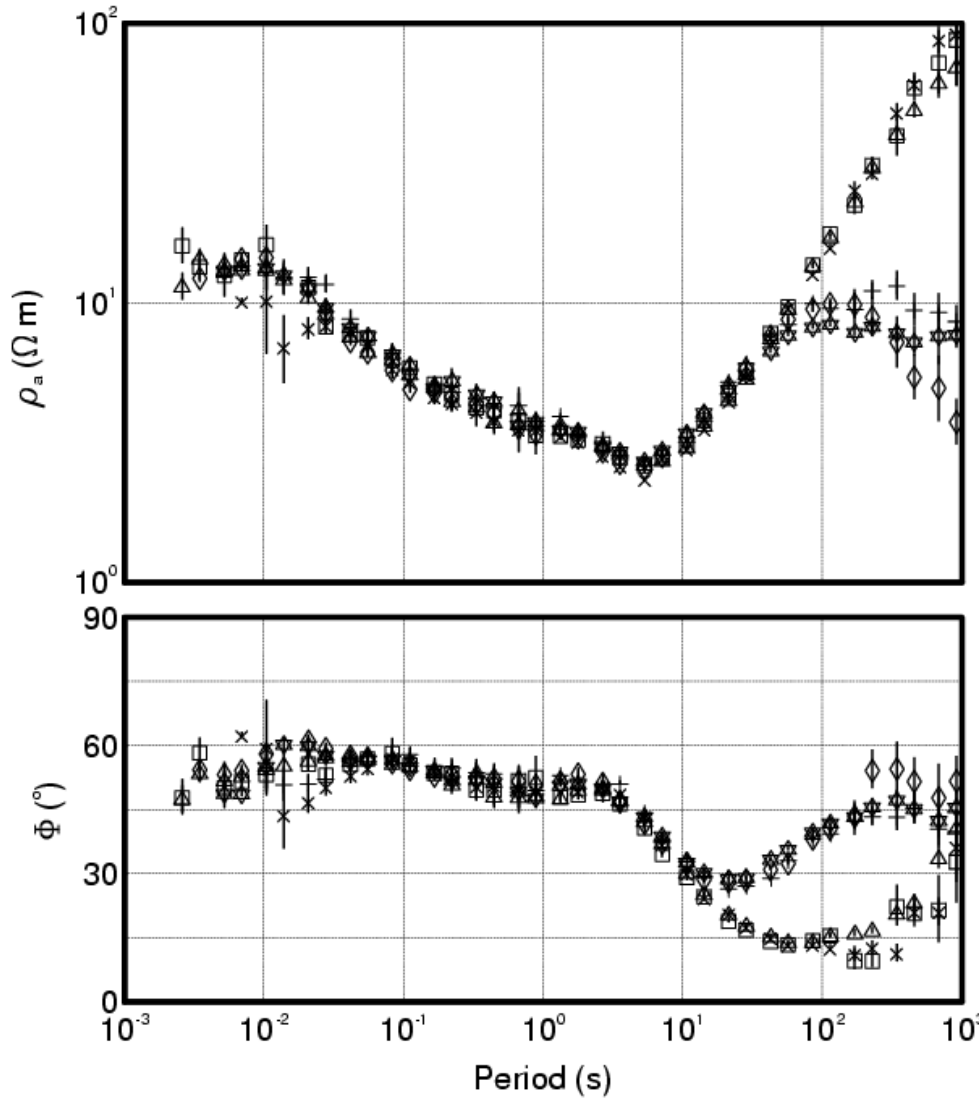
Central sites near Macoun <u>anisotropic</u>

RhoXY ≠ RhoYX
PhaXY ≠ PhaYX

and Ryx and Pyx same as to west



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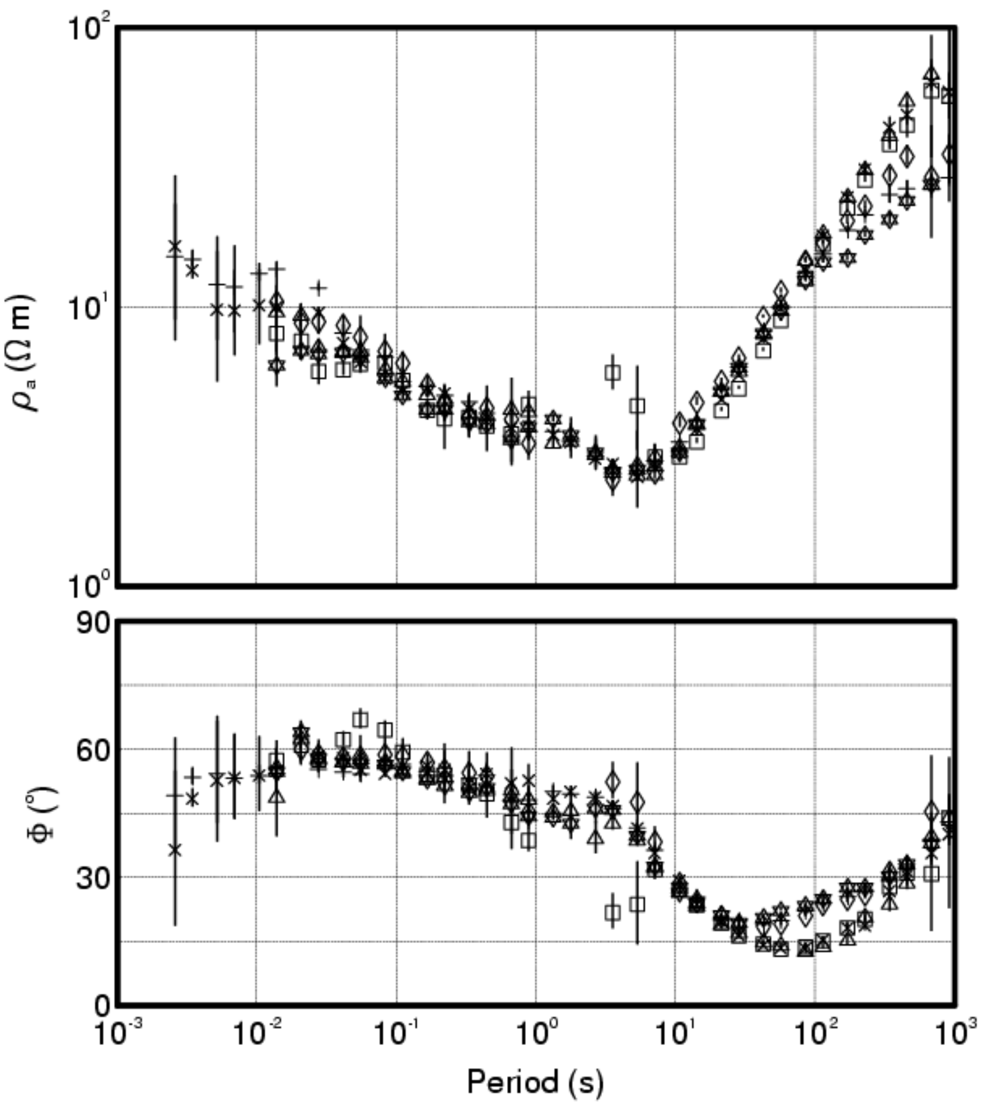
Sites to east of Macoun again <u>isotropic</u>

RhoXY = RhoYX
PhaXY = PhaYX

and RhoXY, RhoYX and PhaXY, PhaYX same as western end



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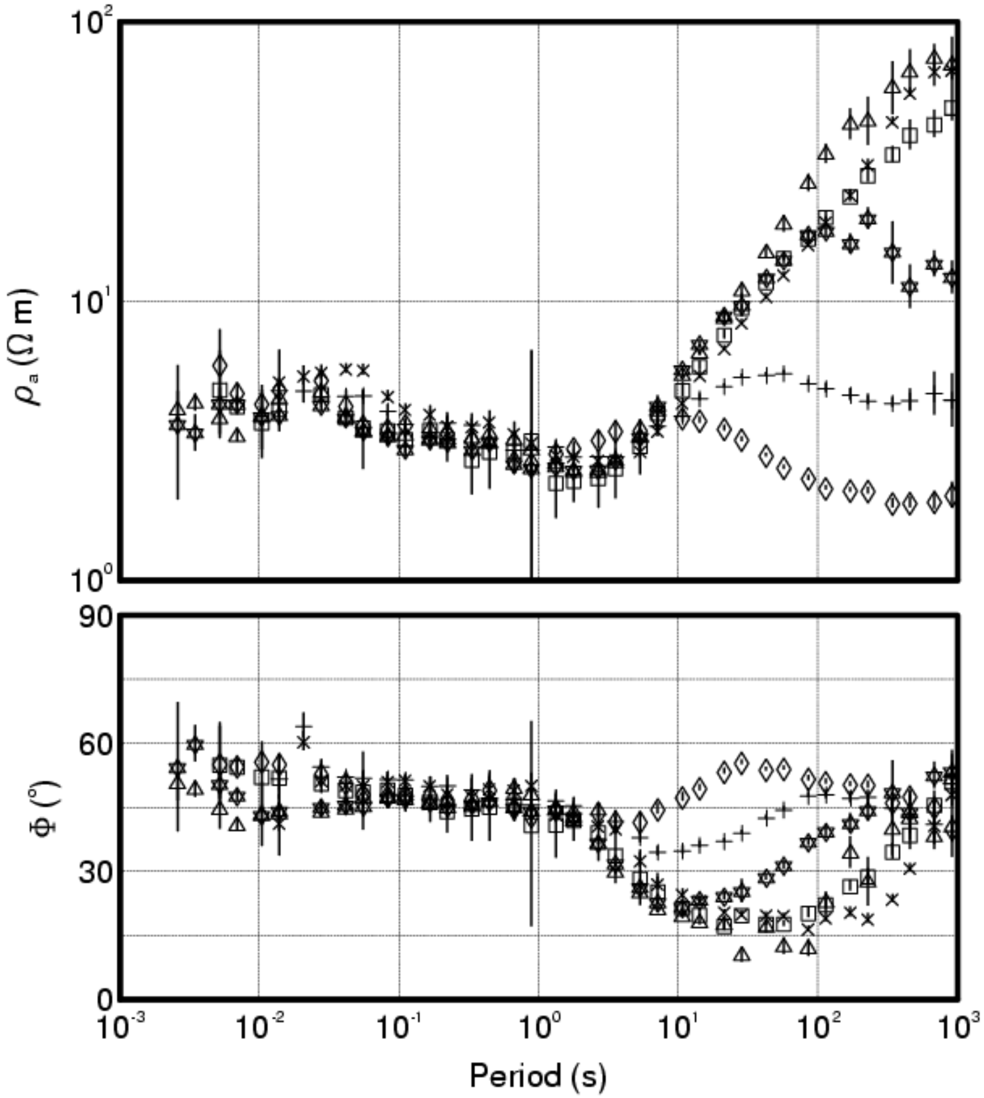
Another **anisotropic** anomaly found further west

RhoXY ≠ RhoYX
PhaXY ≠ PhaYX

Called TOBE, for Thompson Nickel Belt



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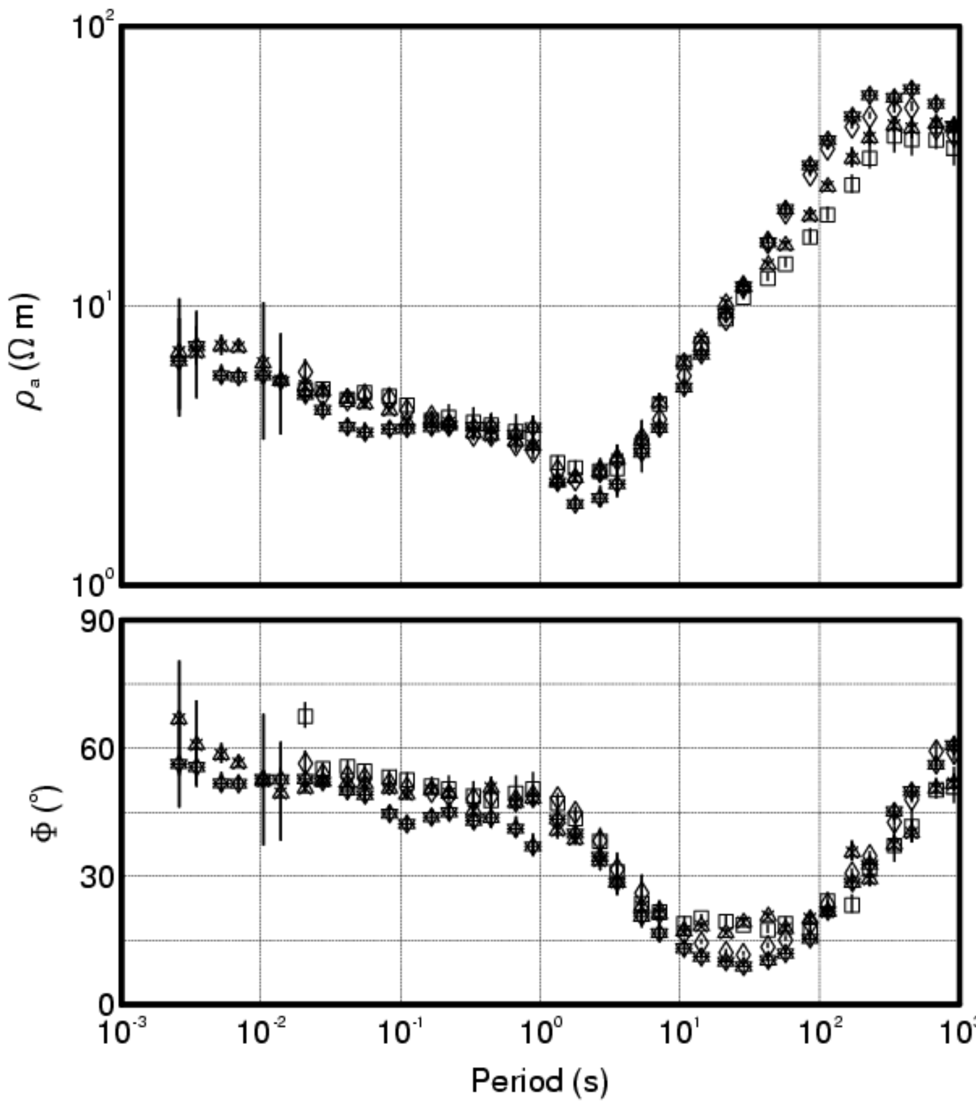
Sites at eastern end of profile isotropic

RhoXY = RhoYX

PhaXY = PhaYX



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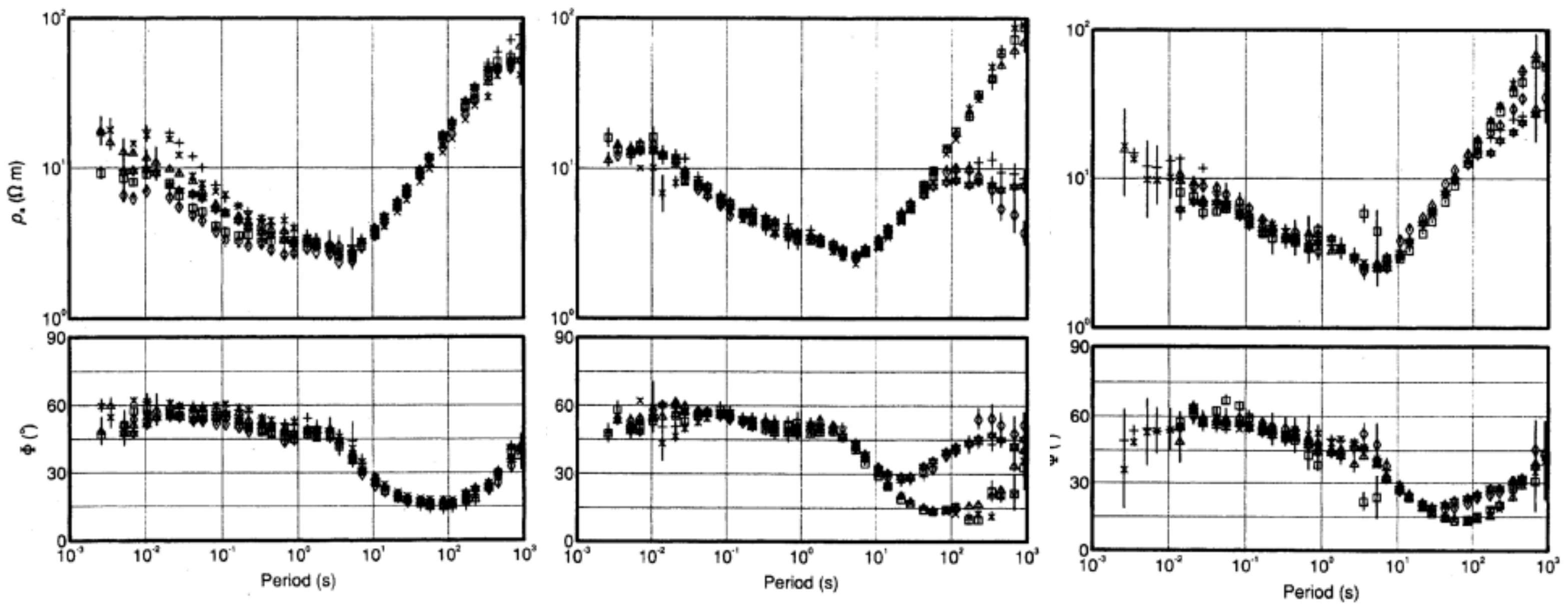
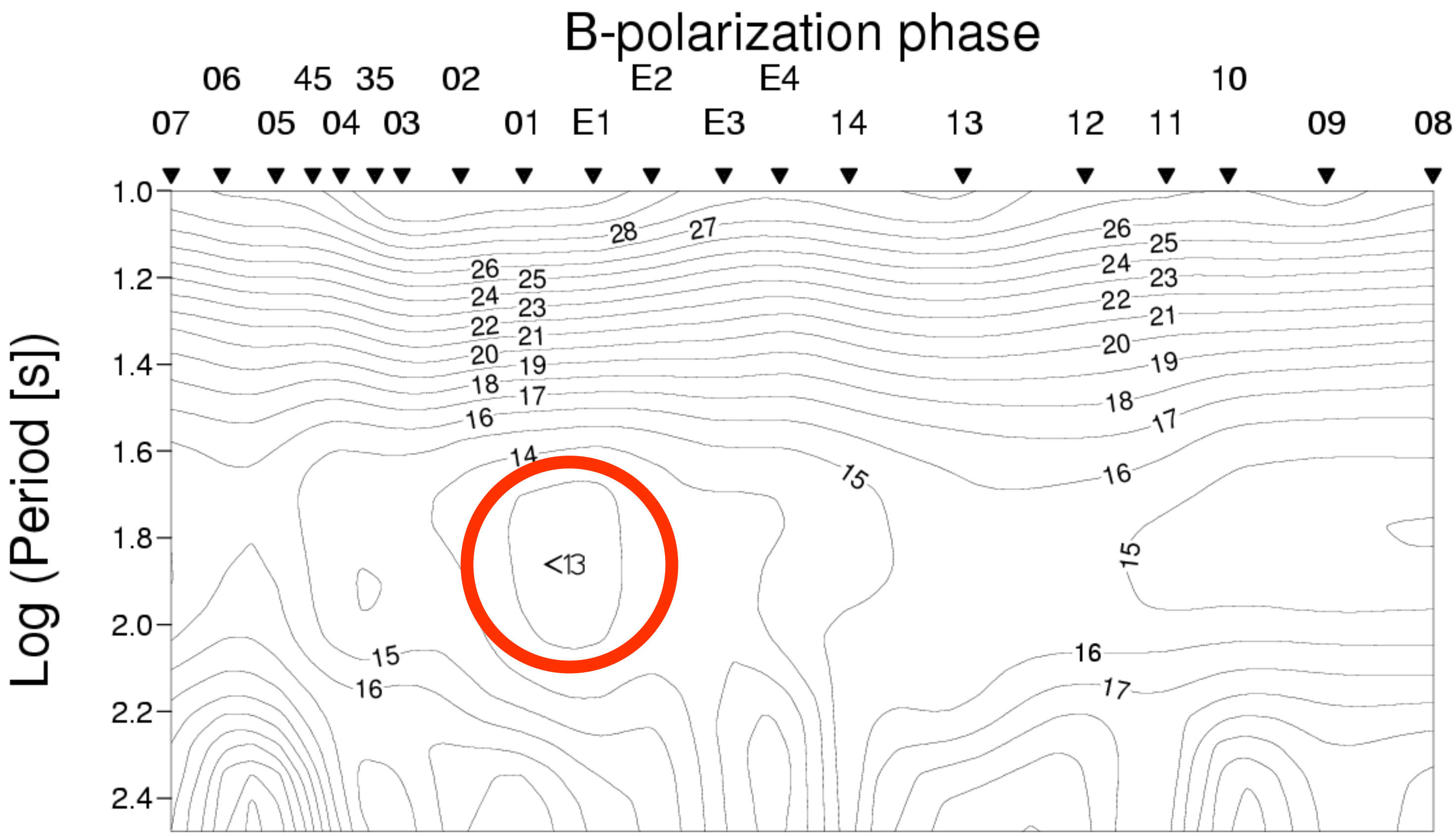
MT responses of the NACP

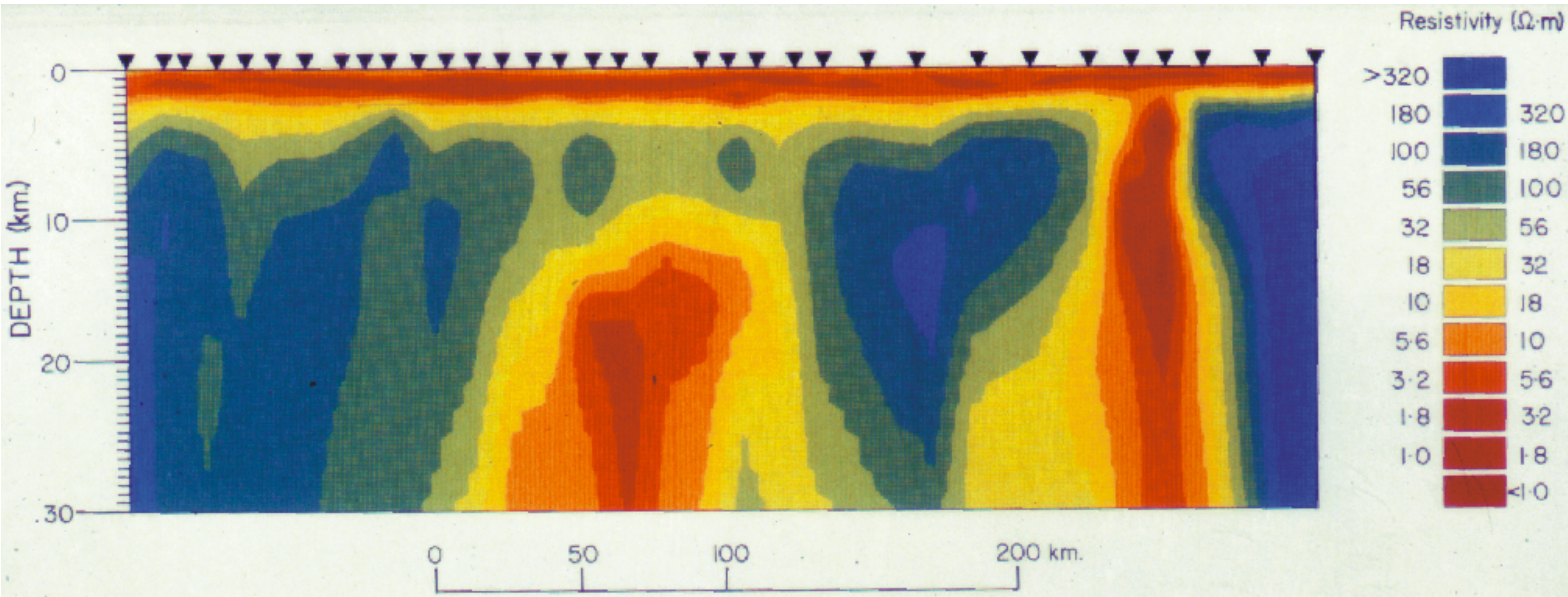
West Centre East



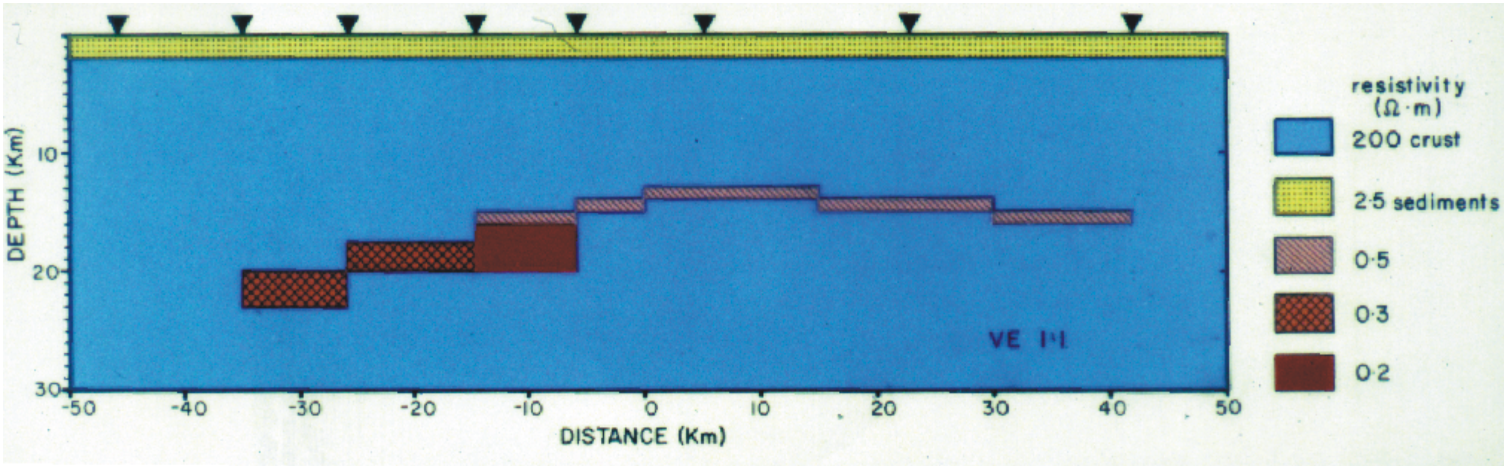
TM phase shows a local minimum at the location of the NACP. This requires discrete conductors

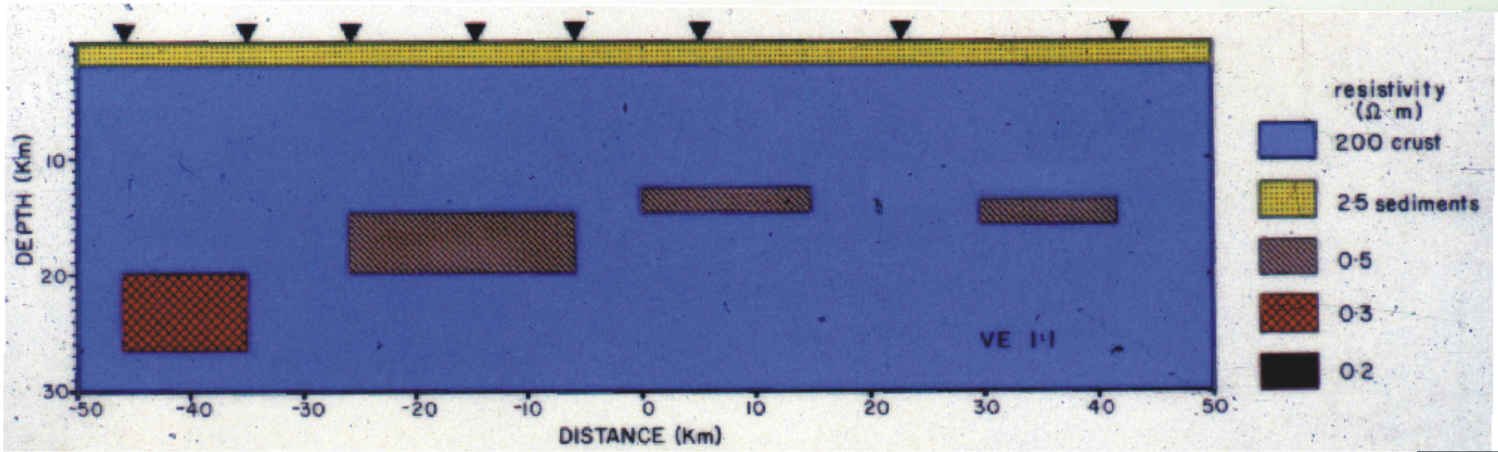


One-dimensional inversion of the PanCanadian data show the NACP and TOBE anomalies

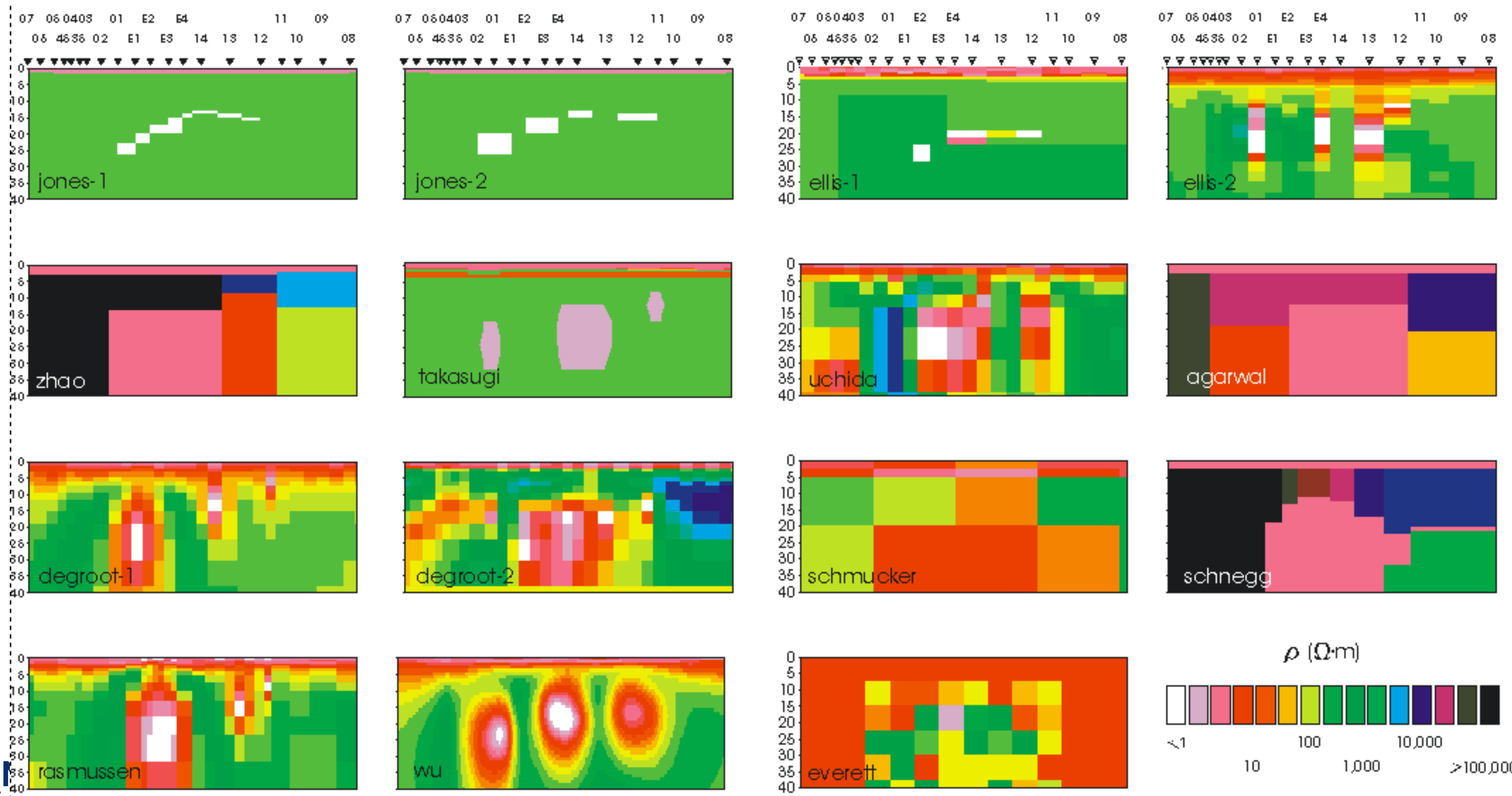


Two-dimensional forward modelling of NACP PanCanadian shows two end-member models





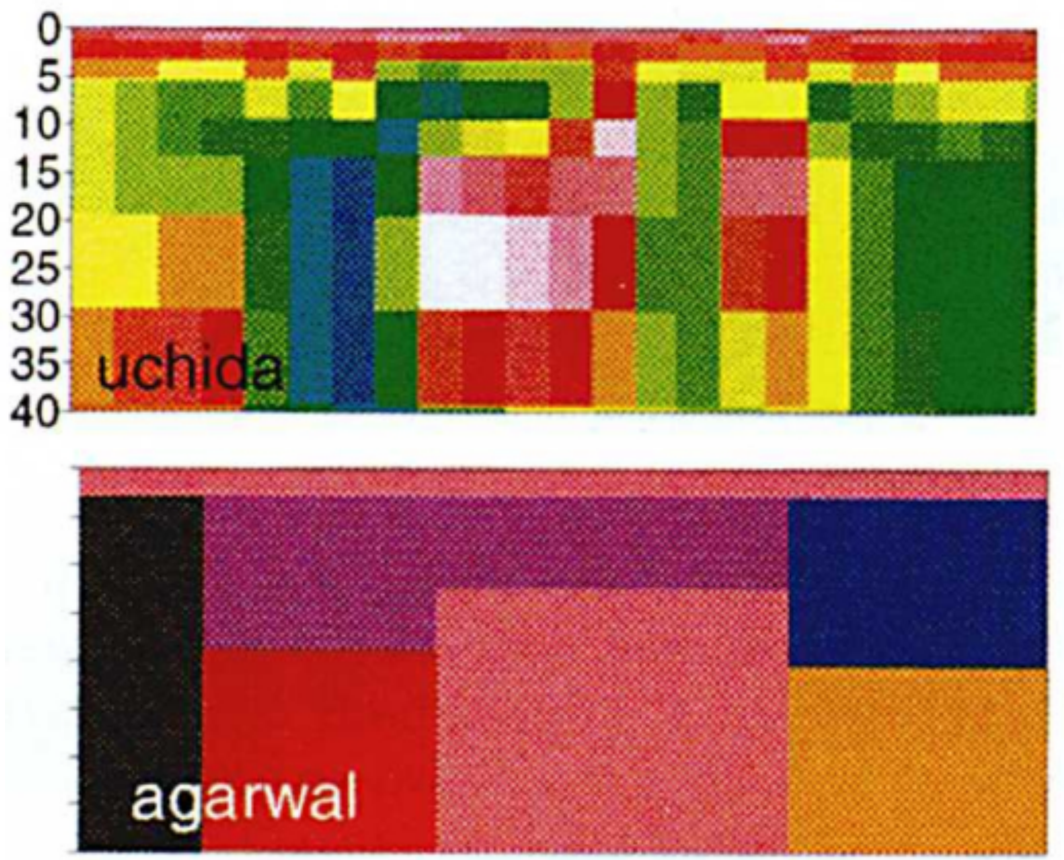
These data used in a comparison of 2-D inversion codes – COPROD2
The models that fit the data best had discrete conductors



Two families of "minimum structure" model

Smallest gradient and smallest number of blocks

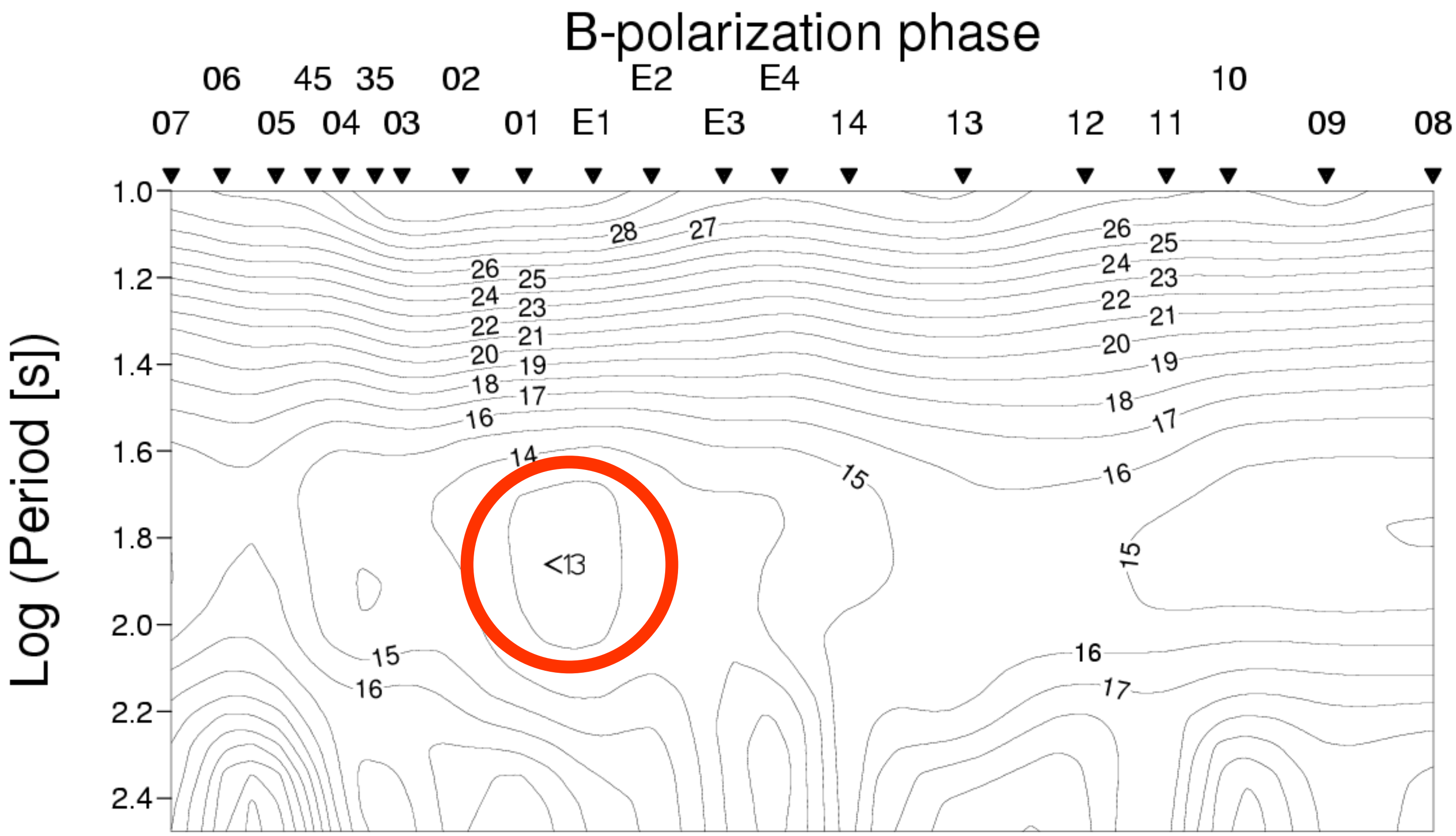
These two models fit equally well according to nRMS misfits



COMPLETE MT SOLUTIONS

EMinar series 2 MTNet

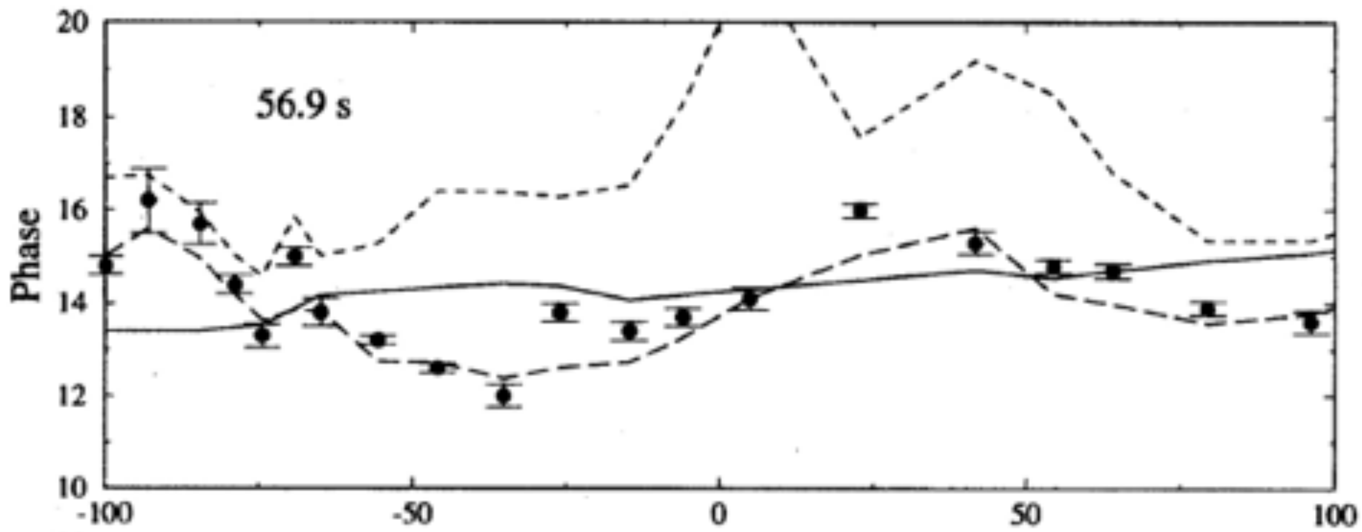
TM phase shows a local minimum at the location of the NACP. This requires discrete conductors



COMPLETE SOLUTIONS

ar series 2 MTNet

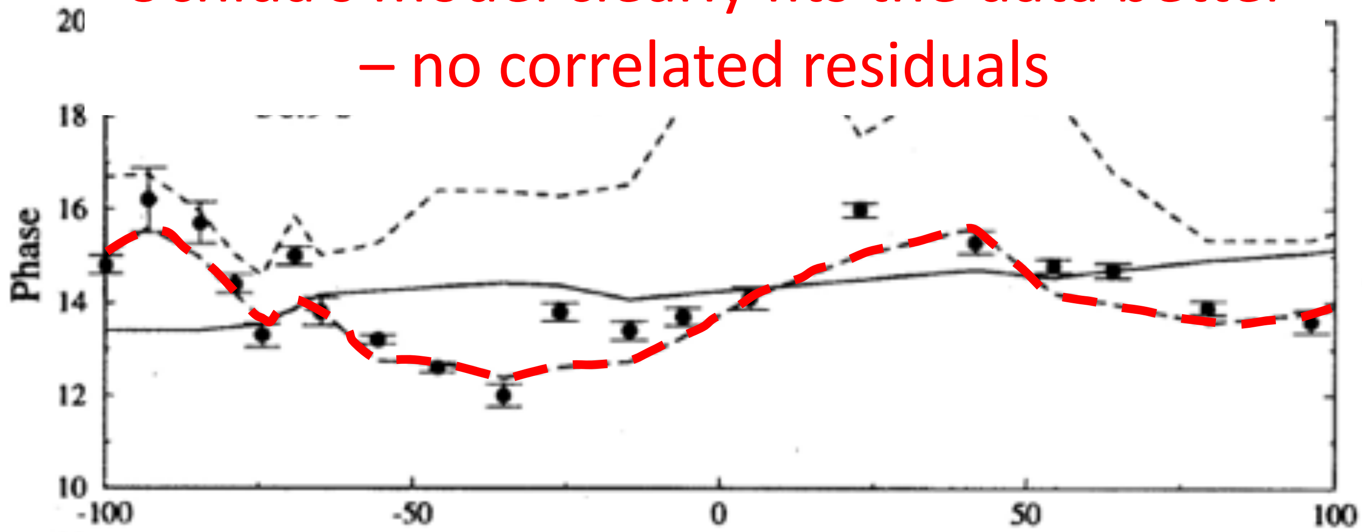
Fit of uchida & agarwal models to TM phase at phase minimum over NACP



-- -- -- -- Uchida --------- Agarwal - - - - - - - Wu

Fit of uchida & agarwal models to TM phase at phase minimum over NACP

Uchida's model clearly fits the data better – no correlated residuals



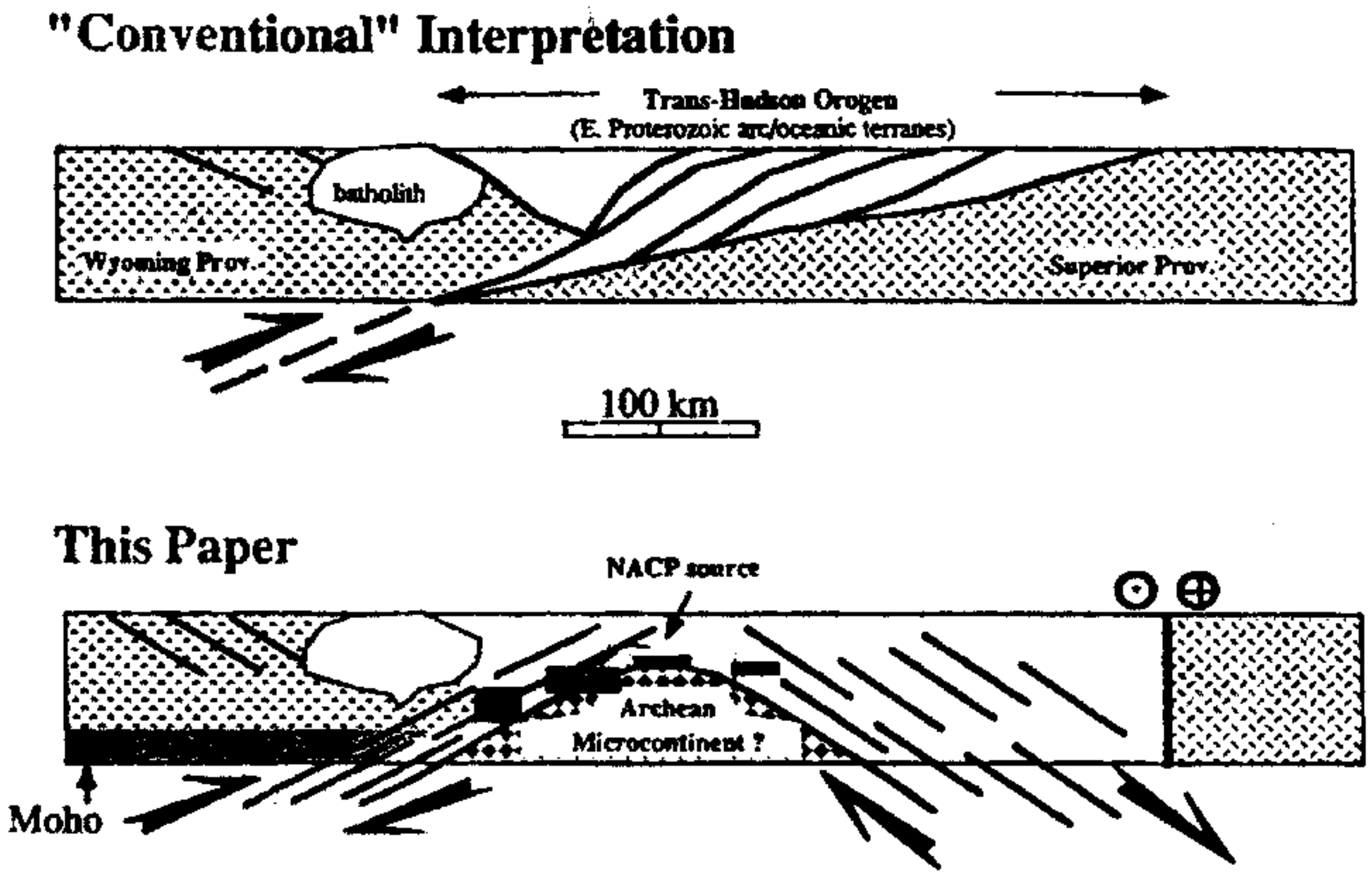
- - - - - - - Uchida --------- Agarwal - - - - - - - Wu

Geometry of NACP used by Nelson et al. (1993) in their interpretation of COCORP reflection data from northern North Dakota

Trans-Hudson orogen and Williston basin in Montana and North Dakota: New COCORP deep-profiling results

K. D. Nelson* Department of Geology, Syracuse University, Syracuse, New York 13224
D. J. Baird
J. J. Walters
M. Hauck
L. D. Brown
J. E. Oliver
Institute for the Study of the Continents, Cornell University, Ithaca, New York 14853
J. L. Ahern School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma 73019
Z. Hajnal Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0, Canada
A. G. Jones Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario K1A 0Y3, Canada
L. L. Sloss Department of Geological Sciences, Northwestern University, Evanston, Illinois 60201

GEOLOGY, v. 21, p. 447–450, May 1993



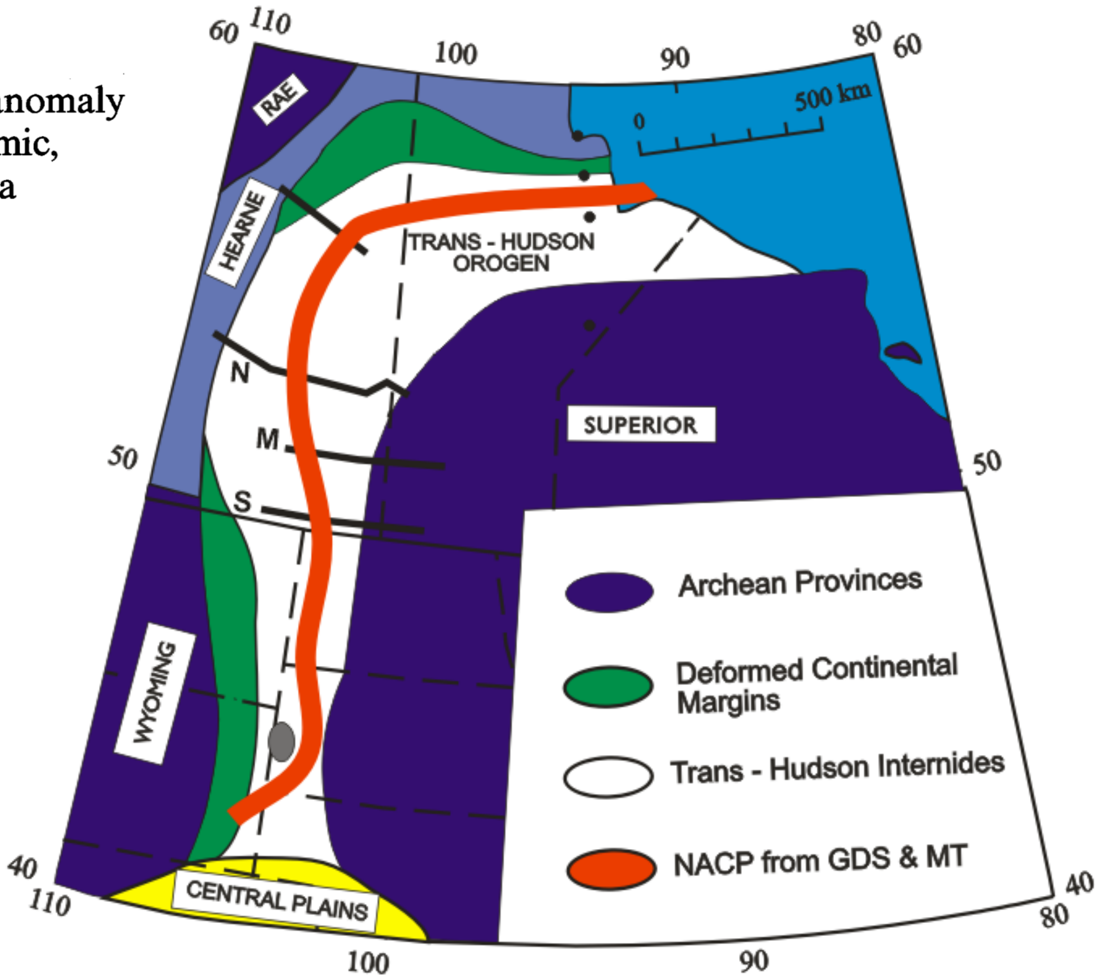
COMPLETE MT SOLUTIONS

MT measurements at 35 sites by Jones and Craven in 1987 along profiles *M* and *N*

The North American Central Plains conductivity anomaly and its correlation with gravity, magnetic, seismic, and heat flow data in Saskatchewan, Canada

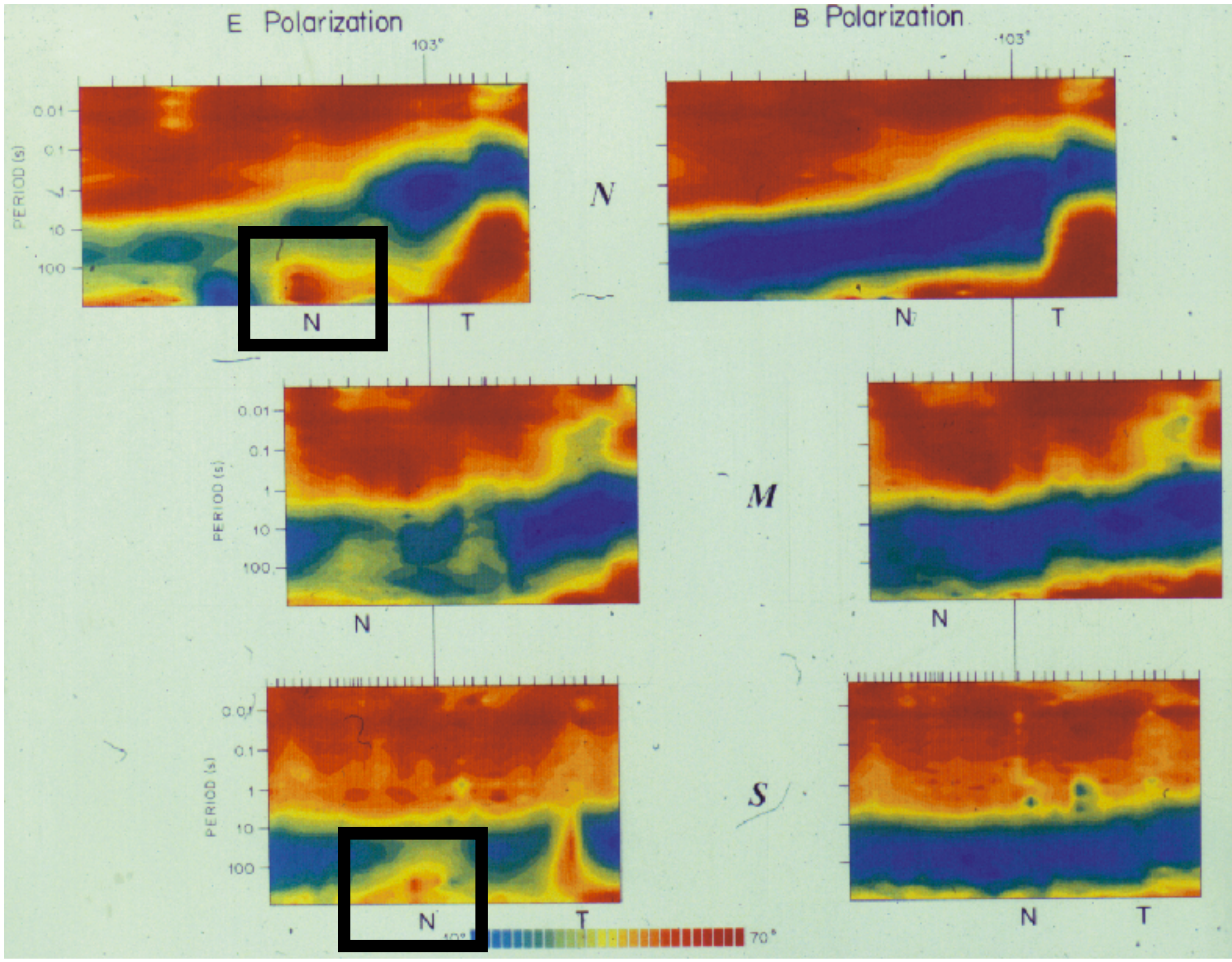
Alan G. Jones and James A. Craven

Physics of the Earth and Planetary Interiors, 60 (1990) 169–194



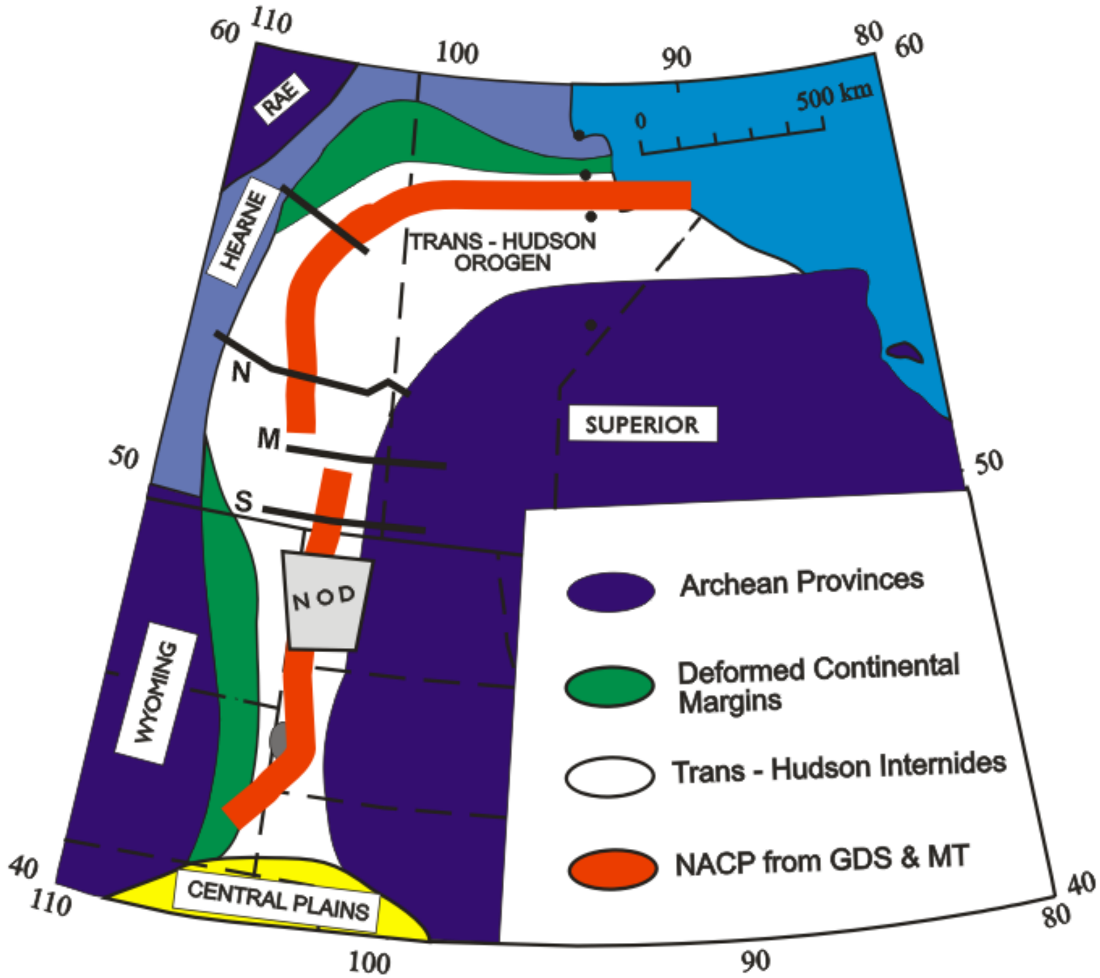
COMPLETE MT SOLUTIONS

TE phases show NACP on profiles *S* and *N*, but not *M*



Break in NACP beneath profile *M*?

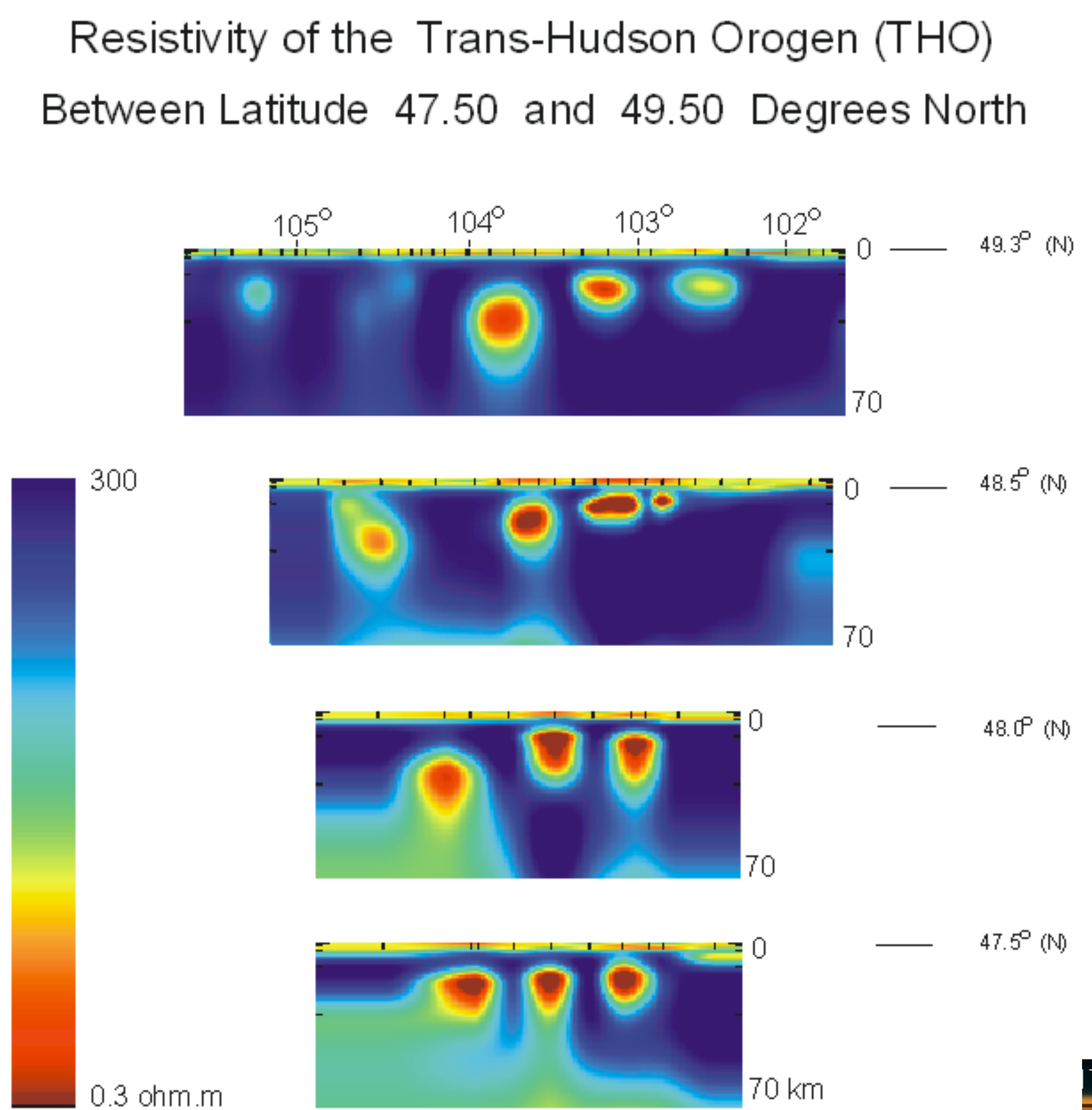
MT in North Dakota in 1992 (NOD)



COMPLETE MT SOLUTIONS

2-D inversions of all 3 NoD lines and line S show separated structures

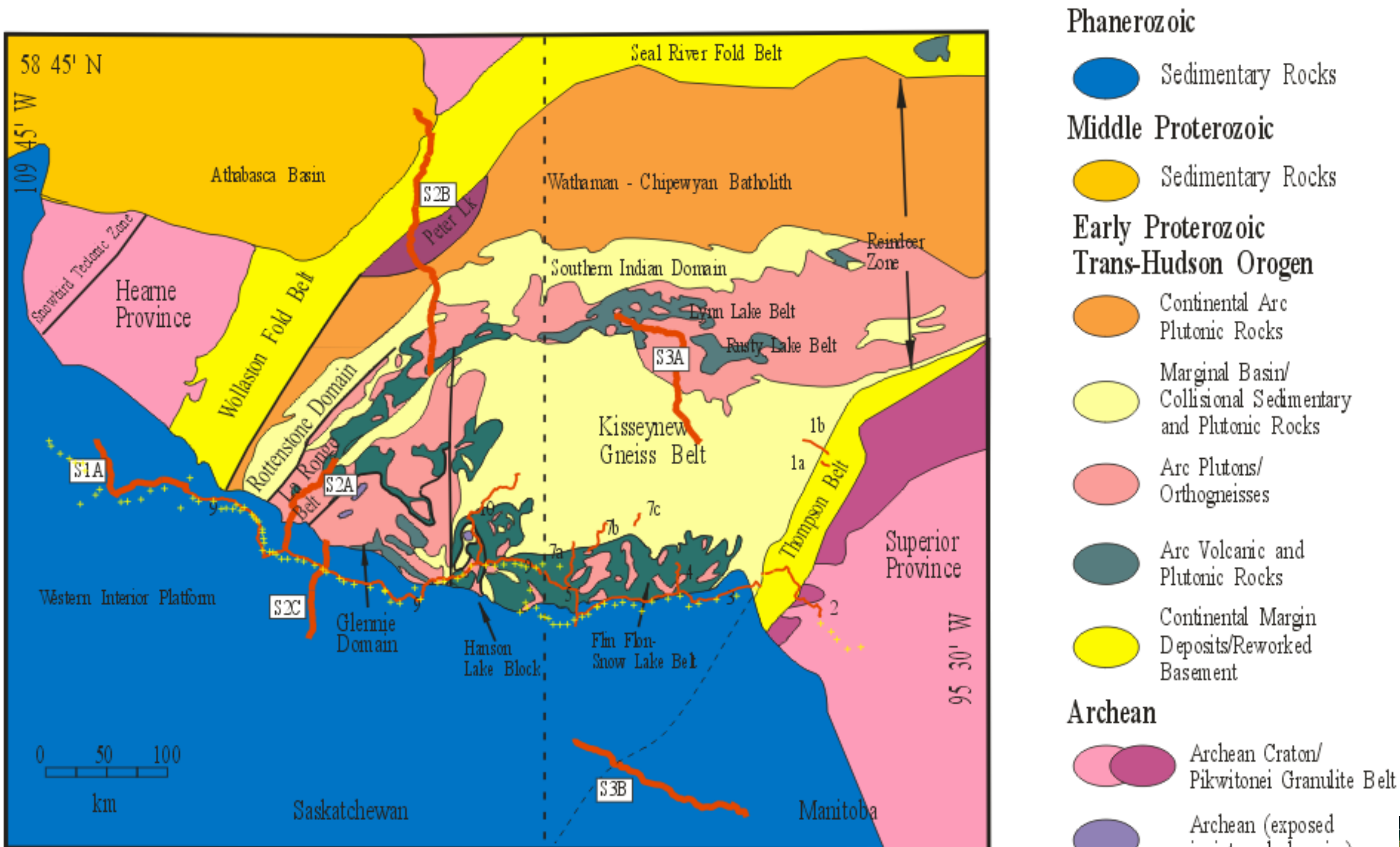
Numerical expression of anisotropy



COMPLETE MT SOLUTIONS

TNet

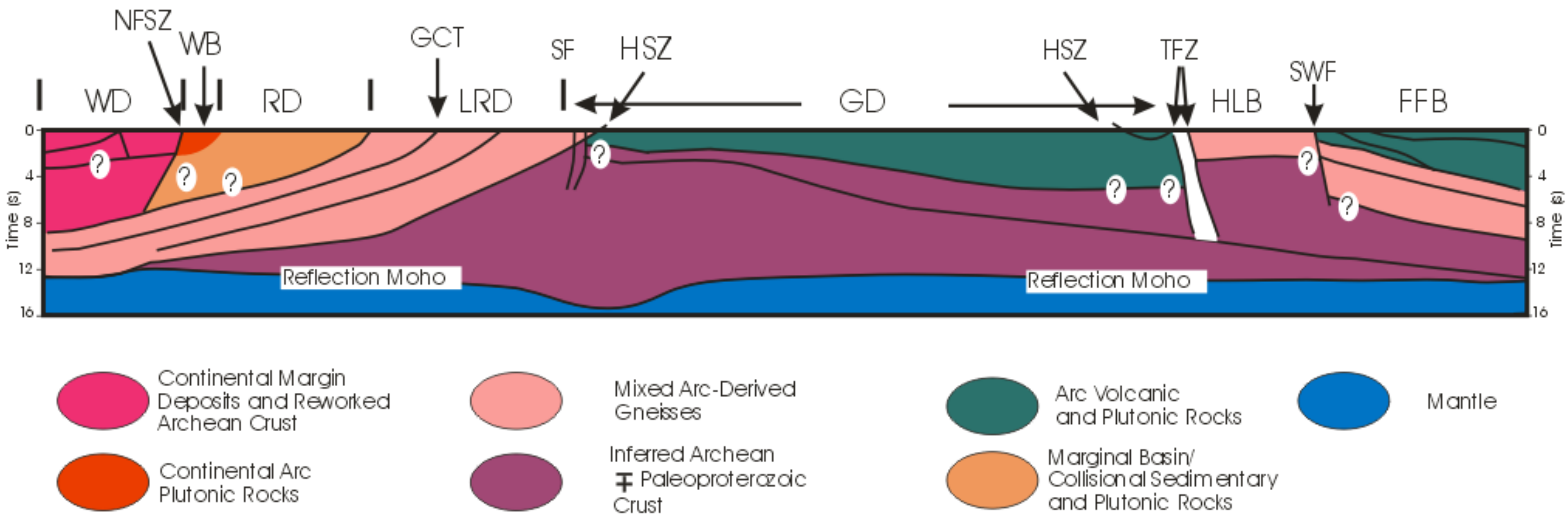
Lithoprobe surveys: Main profile 1992. Along S2B in 1994



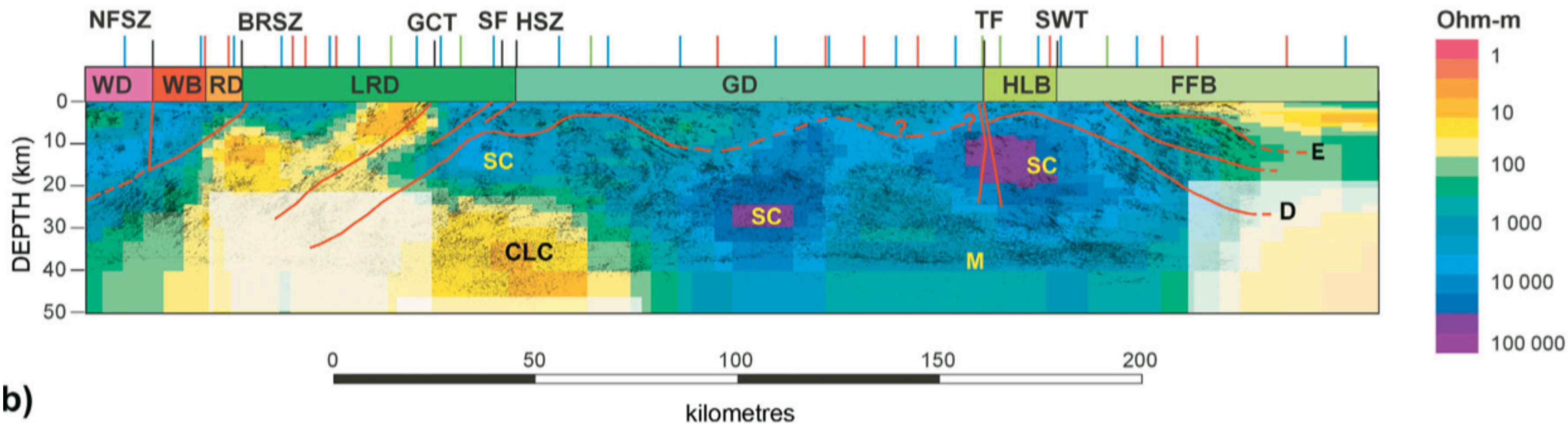
series 2 MTNet

Seismic reflection identified “Sask craton”

Some questions about western geometry and NFSZ



MT model of the whole profile L



Electrical-resistivity imaging of the central Trans-Hudson orogen[1, 2]

Ian J. Ferguson, Kevin M. Stevens, and Alan G. Jones

Can. J. Earth Sci. **42**: 495–515 (2005)

COMPLETE MT SOLUTIONS

Ferguson et al. (2005) presented a 2-D model along the whole profile.

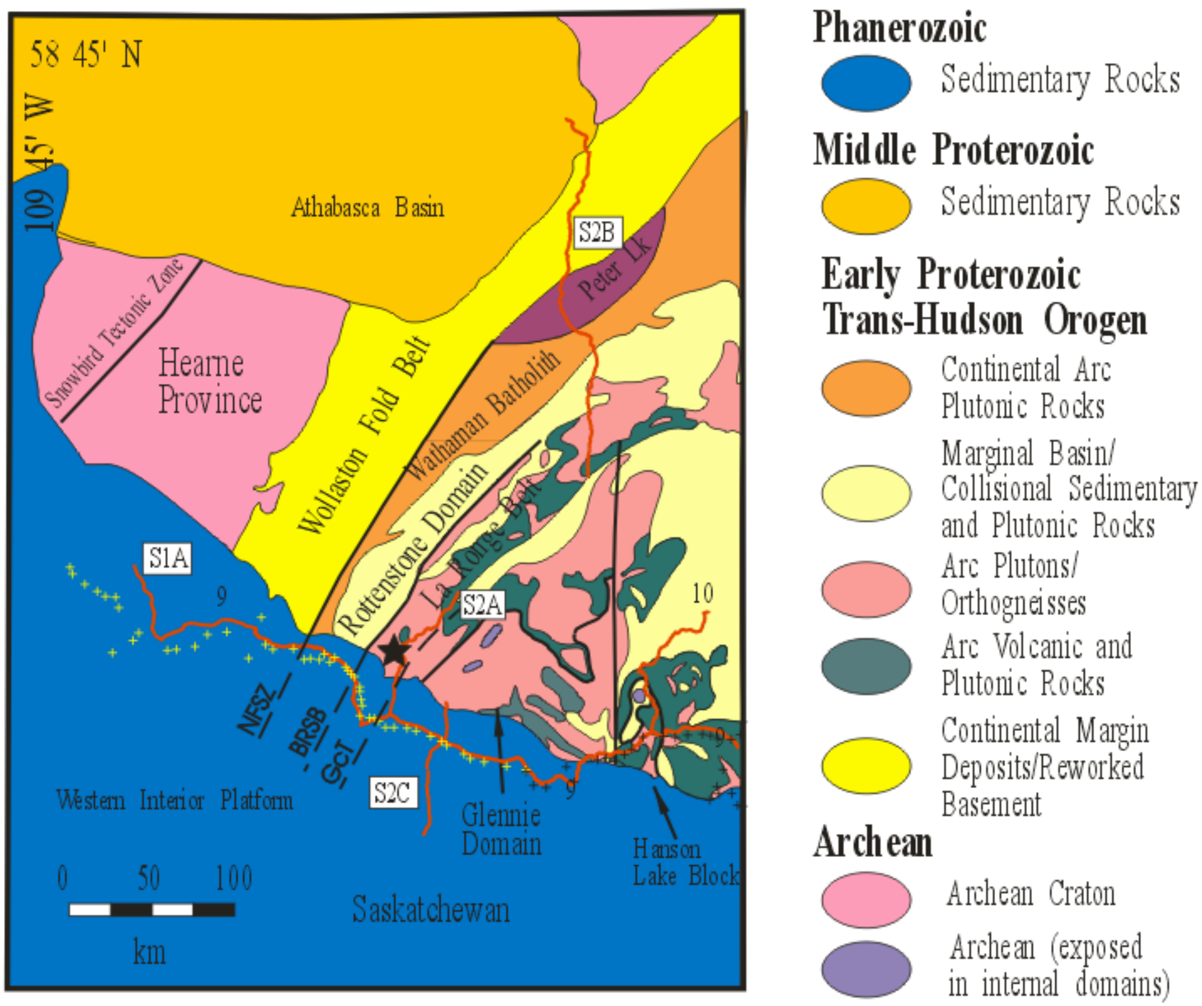
In this model the NACP has two features:

1) Dipping strata within the La Ronge Domain

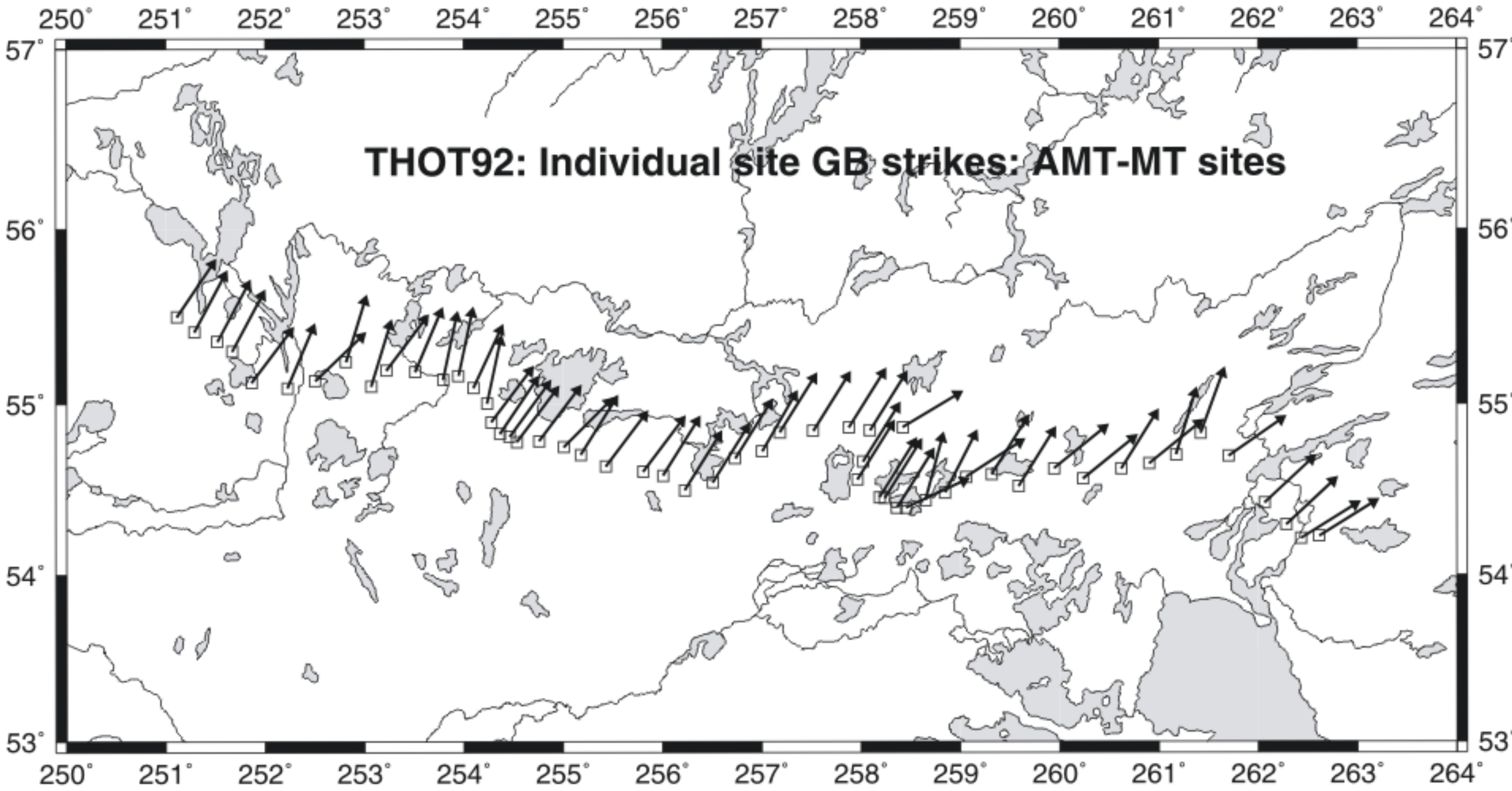
2) A deep crustal conductor CLC beneath the putative Sask craton

EMinar series 2 MTNet

1992 MT site locations in western THO

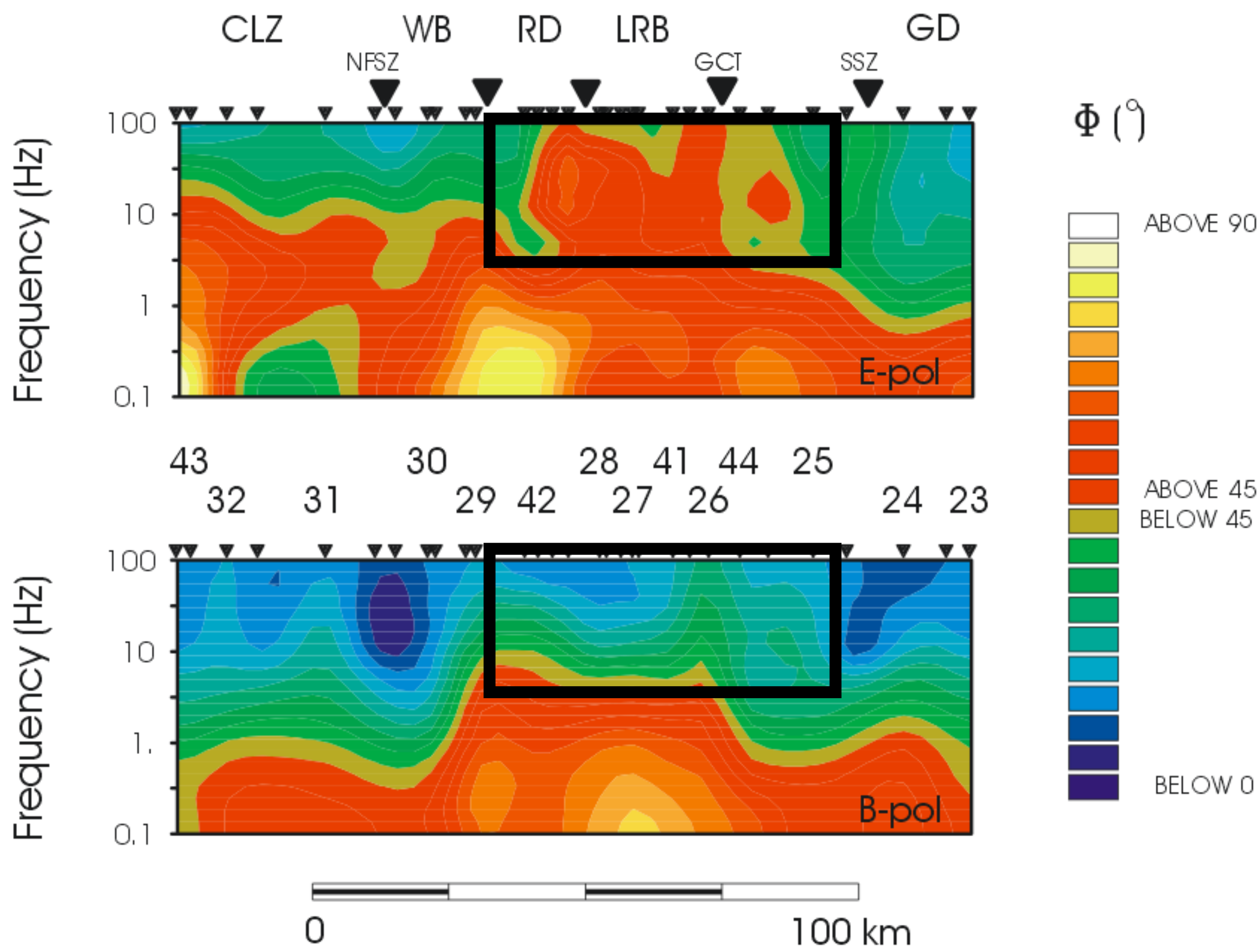


Geoelectric strike very uniform across the whole internides of the orogen
Changes close to the THO-Sup boundary



MTNet

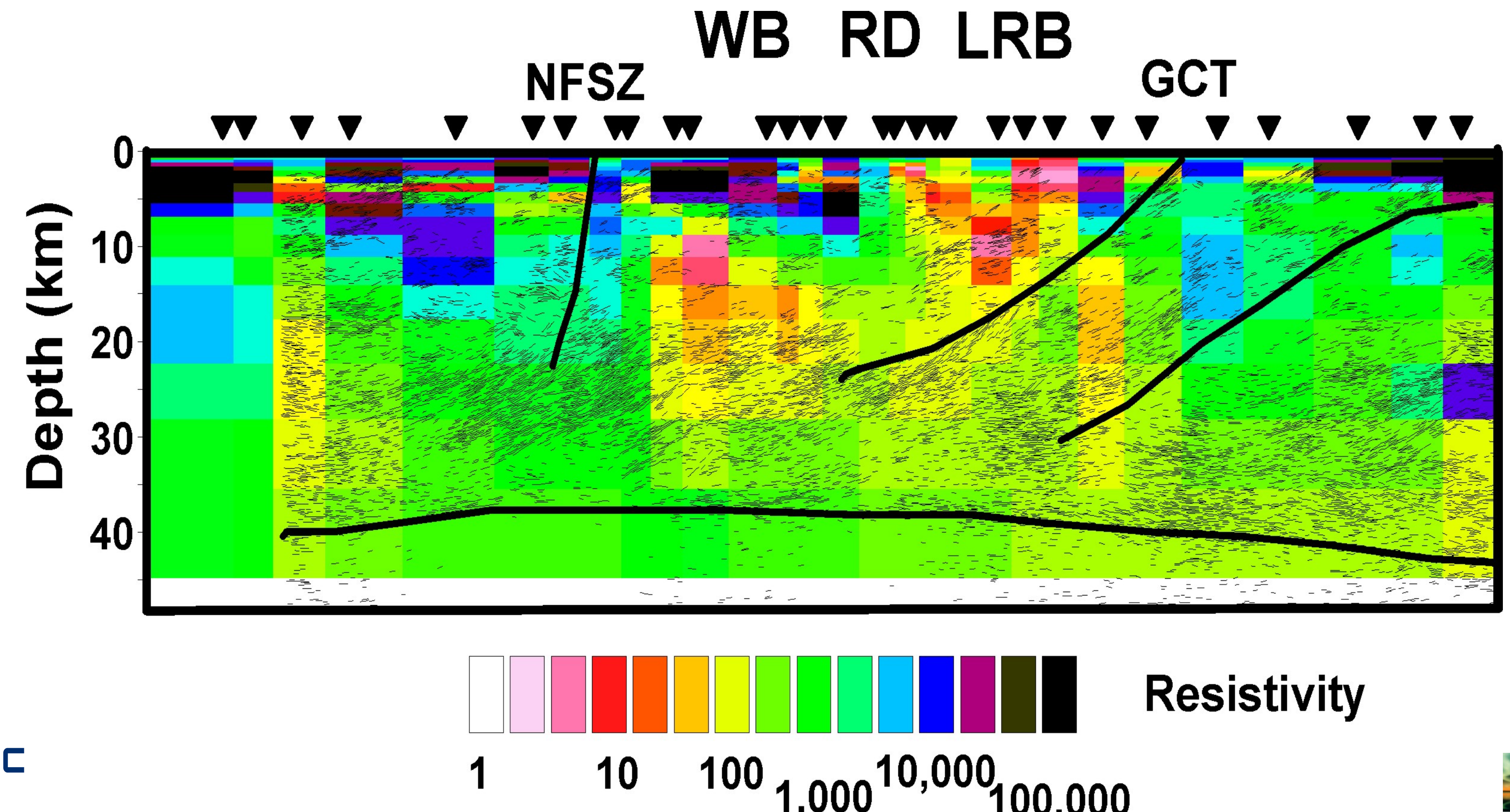
Anomalous phase responses: No TM at high freqs



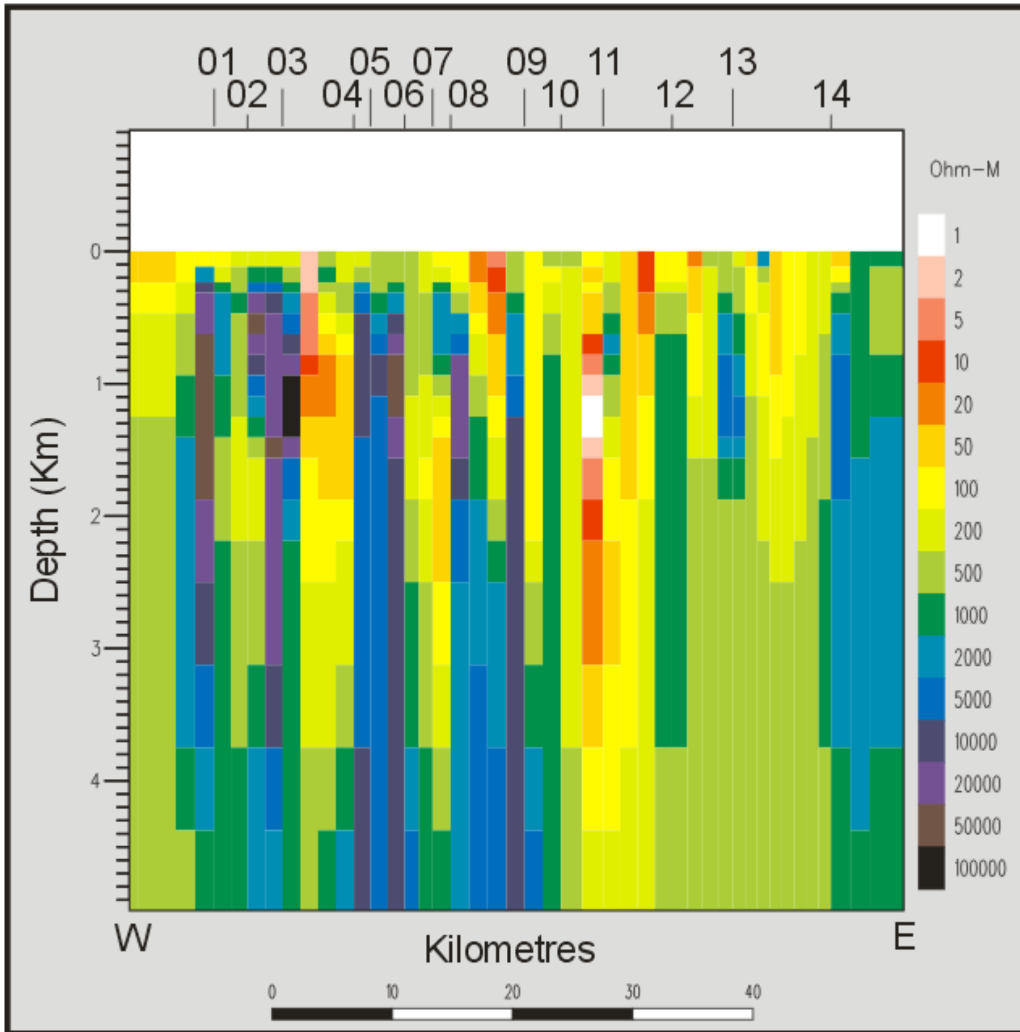
COMPLETE M SOLUTION

Minar series 2 MTNet

2-D inversion of North American Central Plains (NACP) conductivity anomaly within the Trans-Hudson Orogen (THO)



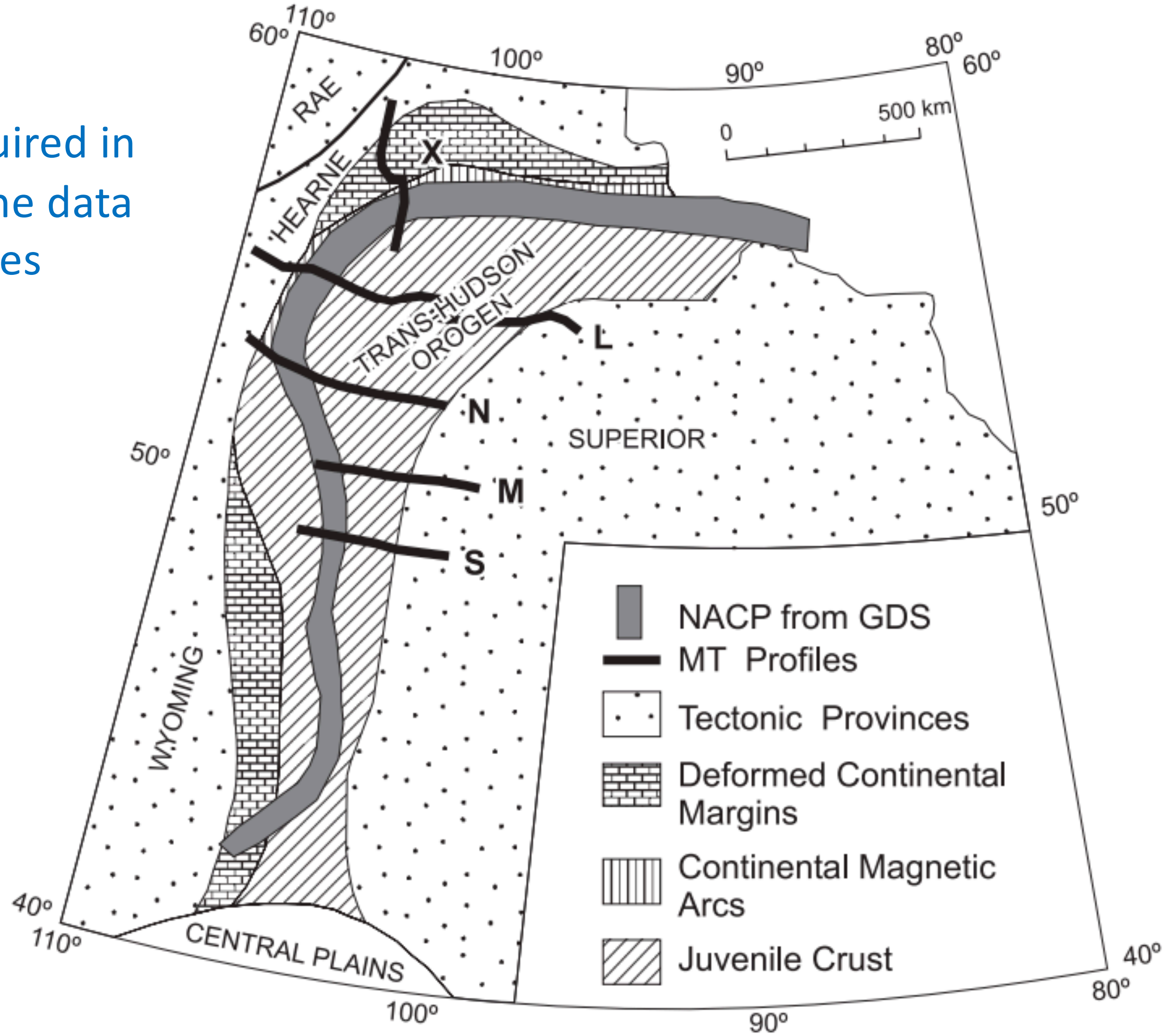
High frequencies show sub-vertical structures



COMPLETE MT SOLUTIONS

Profile X

MT data along Profile X were acquired in 1994 as part of Lithoprobe, and the data were published by Garcia and Jones (2005)



Electromagnetic image of the Trans-Hudson orogen — THO94 transect[1, 2]

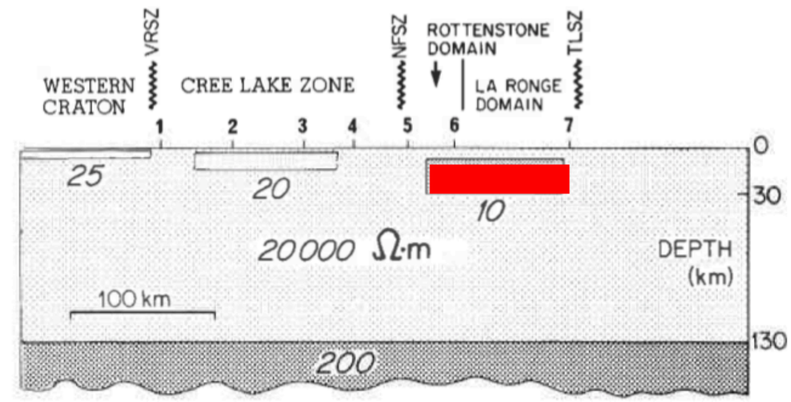
Xavier Garcia and Alan G. Jones

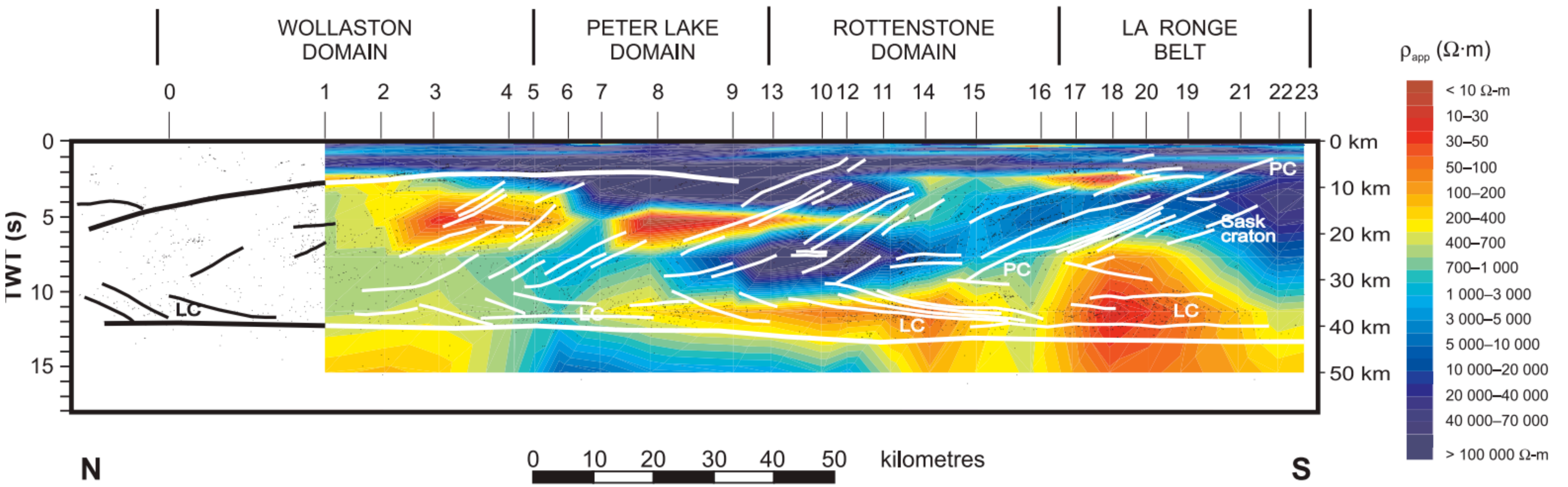
Can. J. Earth Sci. **42**: 479–493 (2005)) N S

Profile X

2D inversion model shows very strong conductor associated with the La Ronge Belt that we can associate with the NACP

This looks exactly like the Handa and Camfield model





Extension of NACP to the east

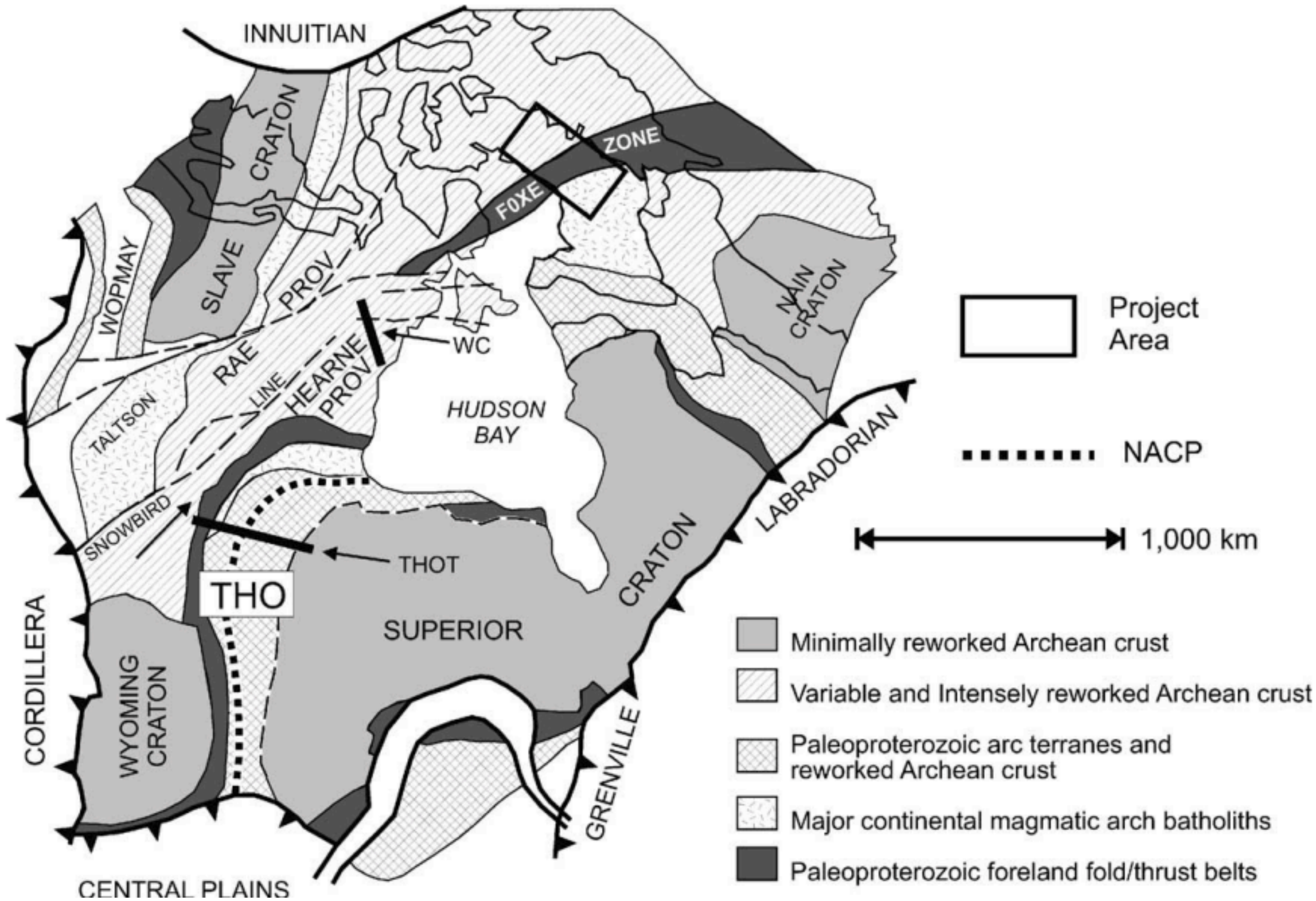
Geologically, the THO is projected to extend eastwards across Hudson Bay to Baffin Island where it is named the Fox River Zone

MT project conducted in 2002 & 2003 on Baffin Is.

Central Baffin electromagnetic experiment (CBEX): Mapping the North American Central Plains (NACP) conductivity anomaly in the Canadian arctic

Shane Evans[a,1], Alan G. Jones[b,*], Jessica Spratt[c,2], John Katsube[d]

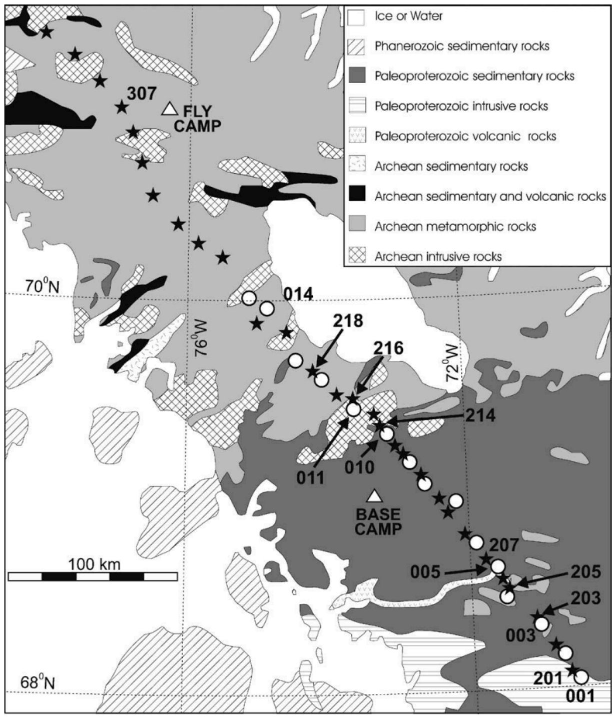
Physics of the Earth and Planetary Interiors 150 (2005) 107–122

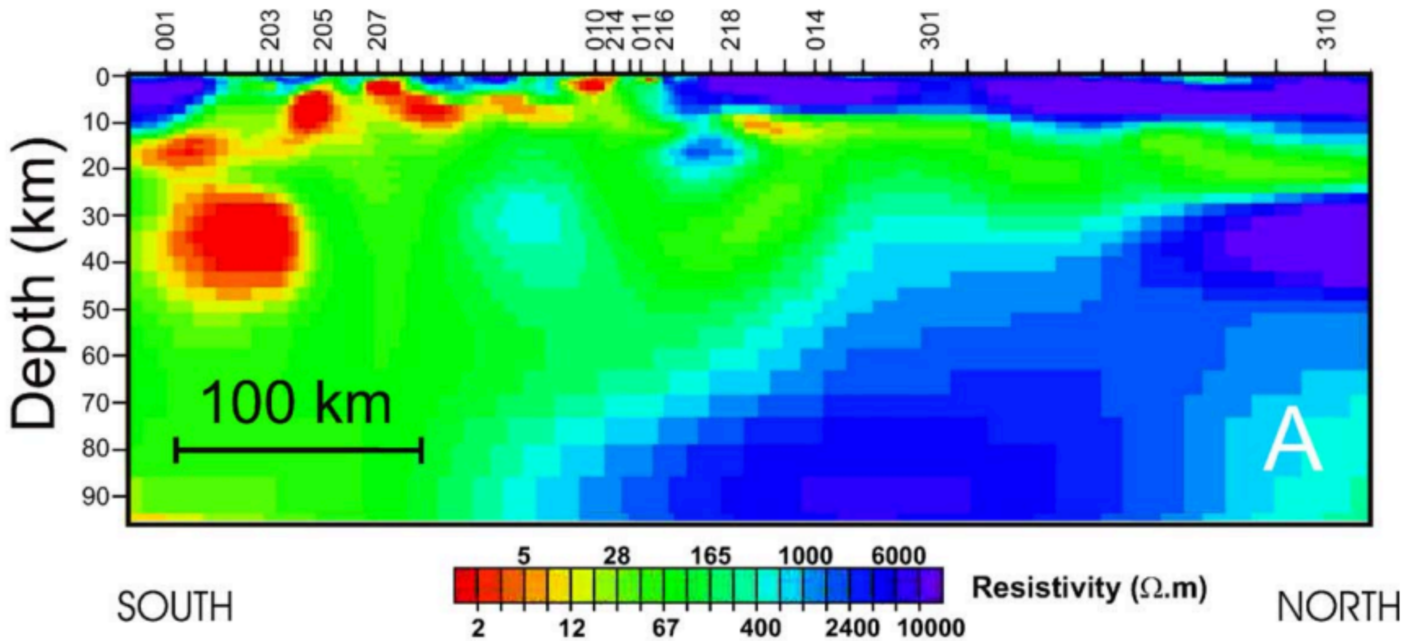


COMPLETE MT SOLUTIONS

EMinar series 2 MTNet

Extension of NACP to the east





Model of the MT data shows exactly the same characteristics as in other locations along the NACP/THO. Discrete disconnected conductors

Extension of NACP even further to the east

The Pan-Scandamerican orogenic belt connects the THO and the Svecofennian orogenies through Baffin Is. and the Nagssugtoqidian belt of Greenland (modified from Condie, 1990)

This would make the NACP anomaly the largest in the world by far!

Continuity of orogenic processes along strike has led – not surprisingly – to similitude of conductivity structures along strike.

Tectonophysics, 219 (1993) 29–45
Elsevier Science Publishers B.V., Amsterdam
29

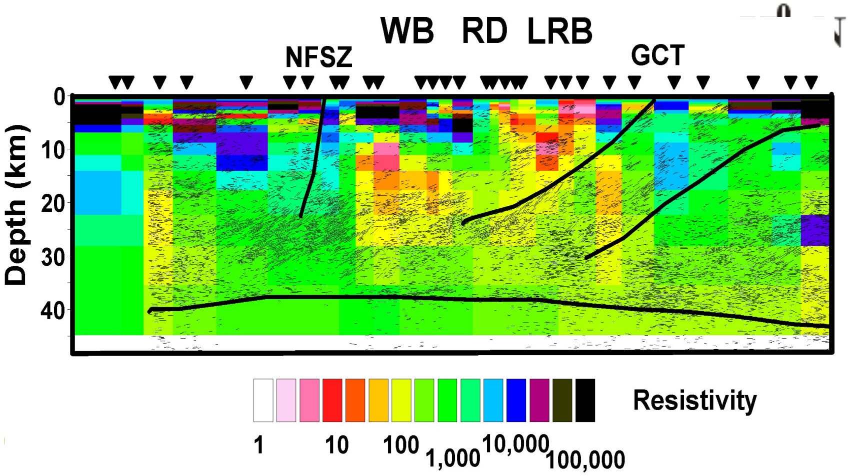
Electromagnetic images of modern and ancient subduction zones

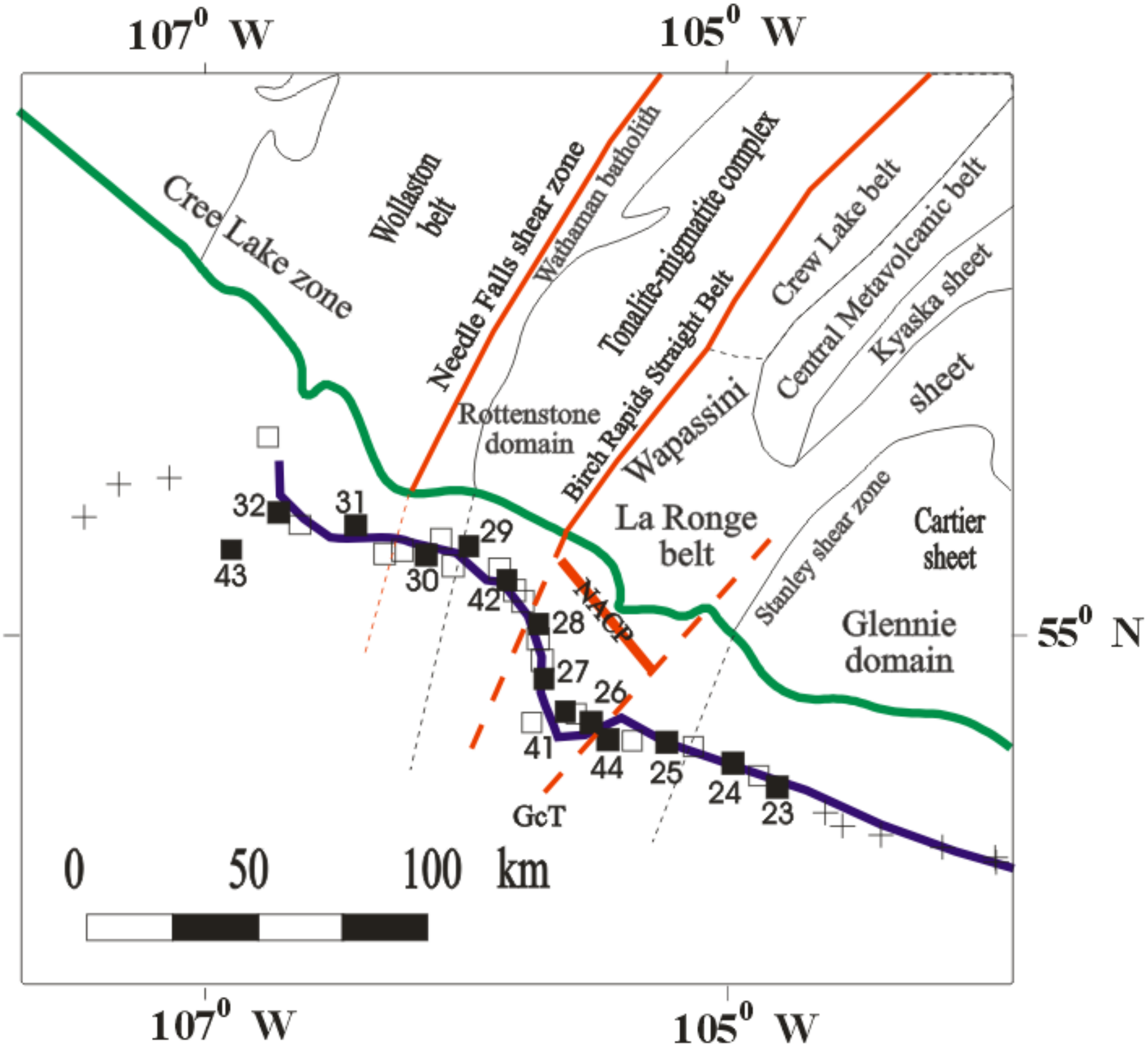
Alan G. Jones

COMPLETE MT SOLUTIONS

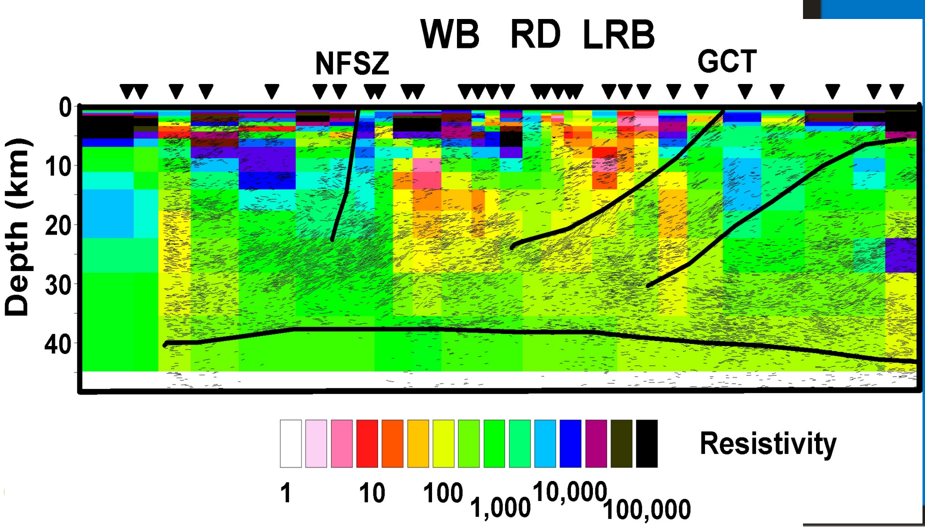
Spatial relationship of NACP with exposed terranes within the THO

NACP correlates with the La Ronge belt (as noted previously by Gupta et al.)



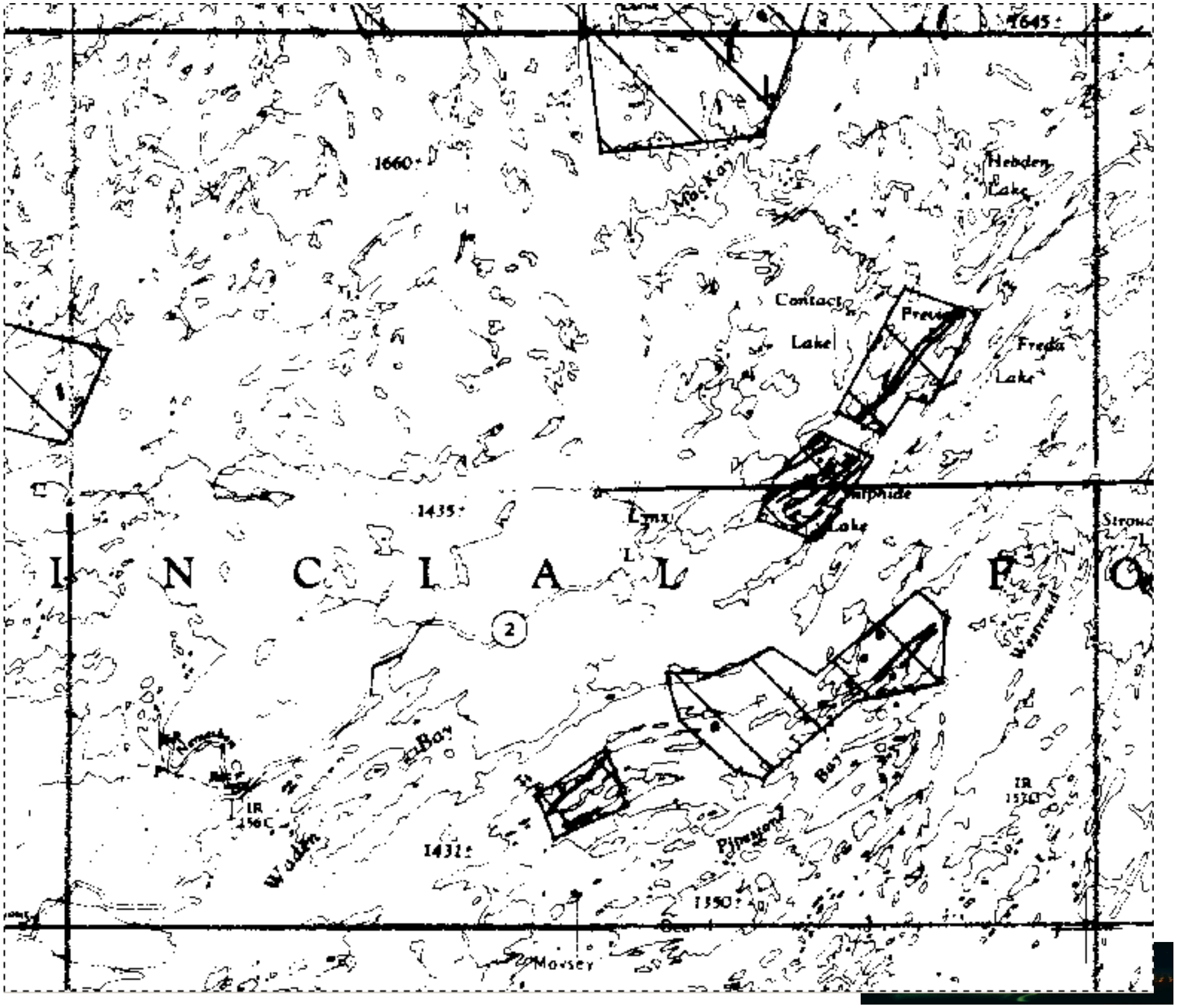


Detail of 1992 MT site locations and rock sampling locality in western THO



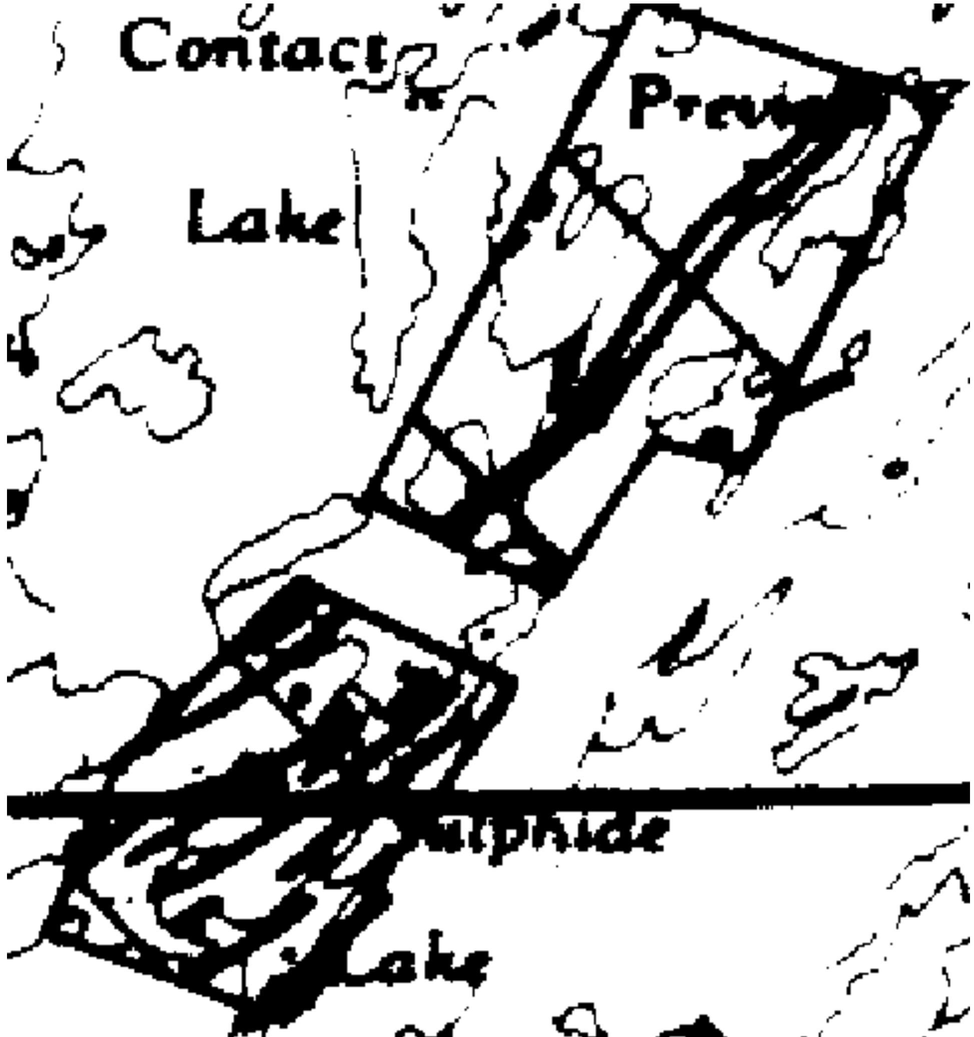
Detail from compilation of airborne EM data flown in the 1970s

Linear isolated conductors identified

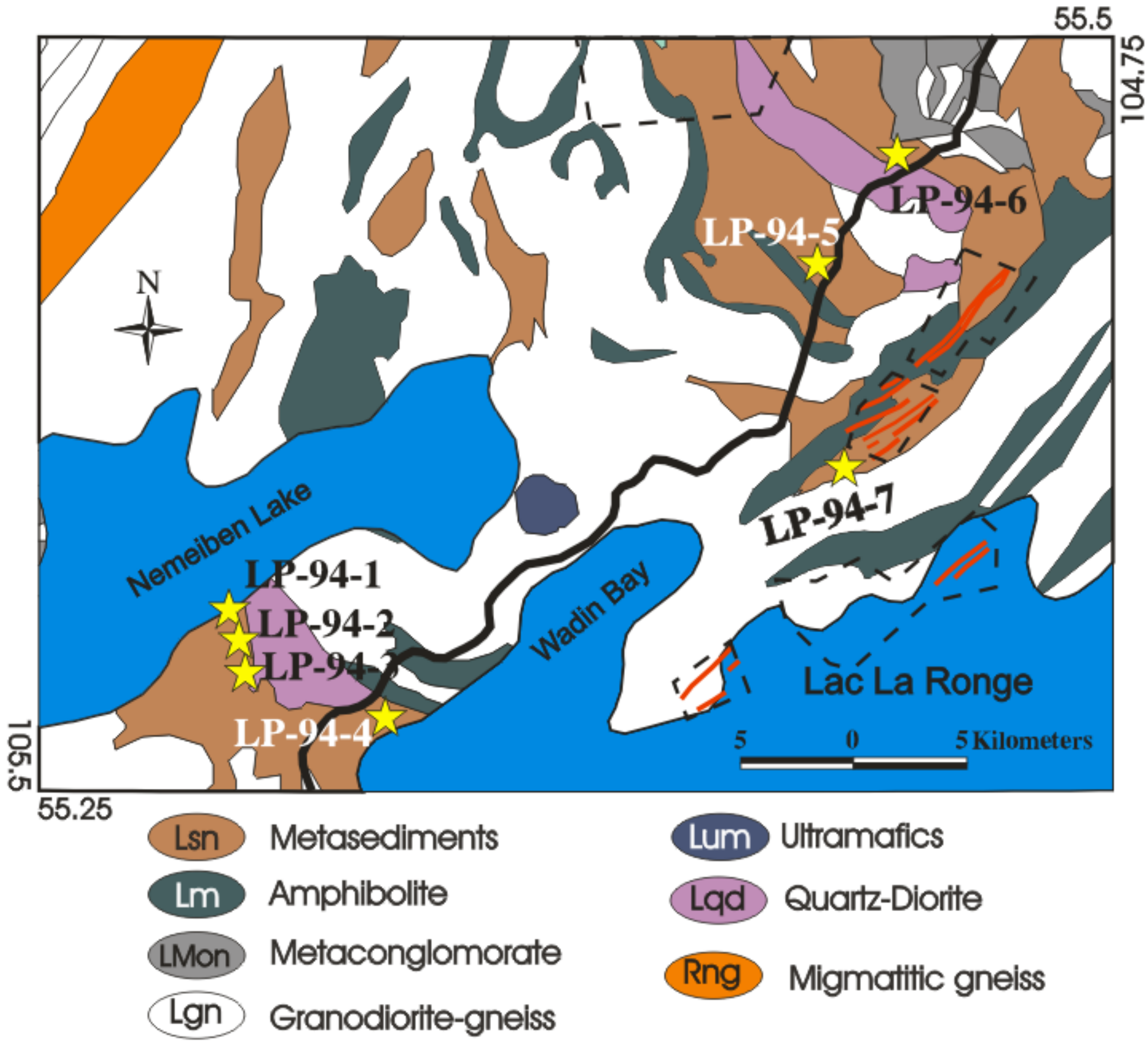


COMPLETE MT SOLUTIONS

Close up of AEM map in region of Sulphide Lake



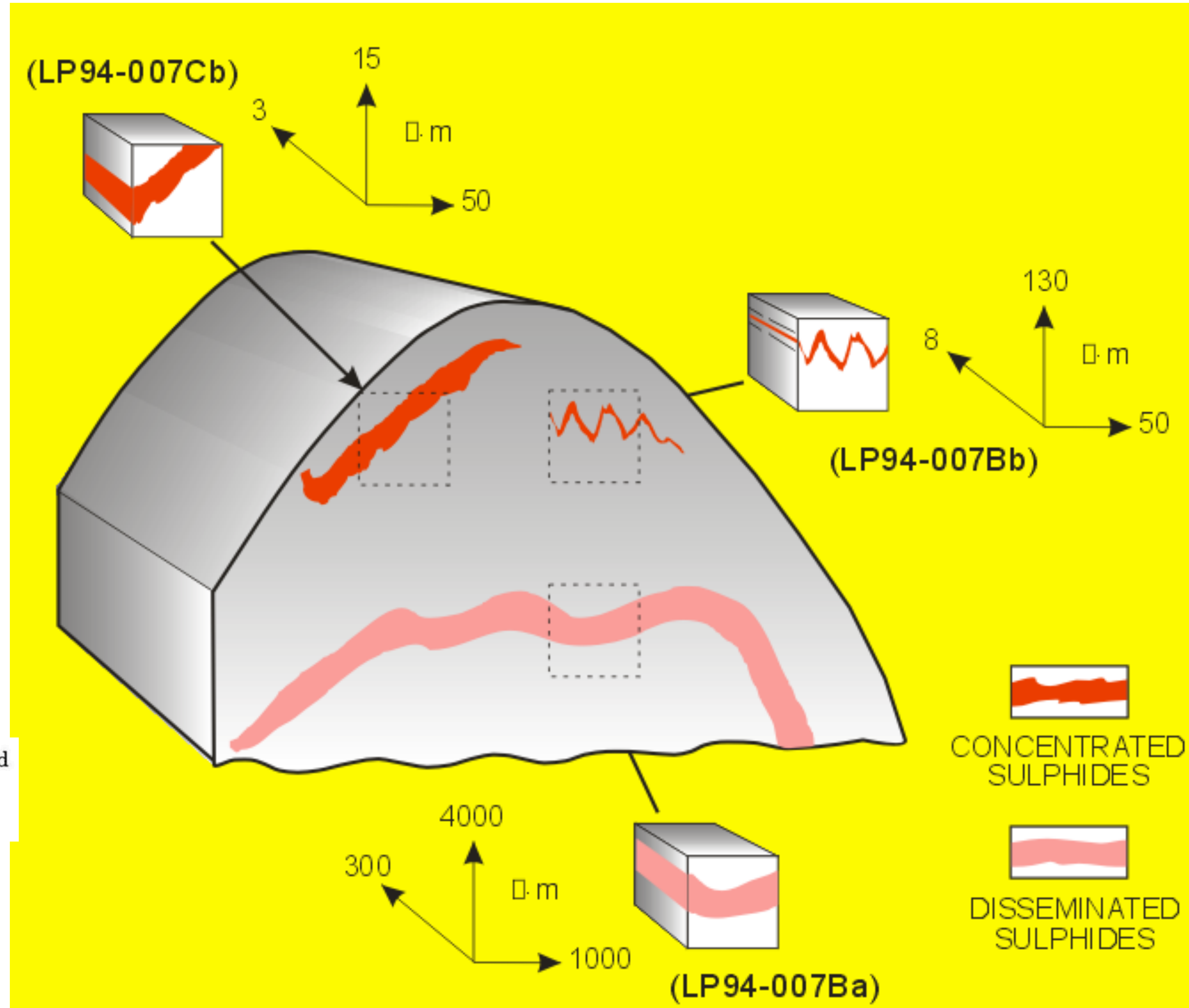
Rock sampling location map plus AEM anomalies from 1970s compilation



COMPLETE MT SOLUTIONS

Cartoon sketch of rock sample from SW of Sulphide Lake on continuation of AEM anomalies

Sulphides migrated to fold hinges and are connected along strike but not connected across strike



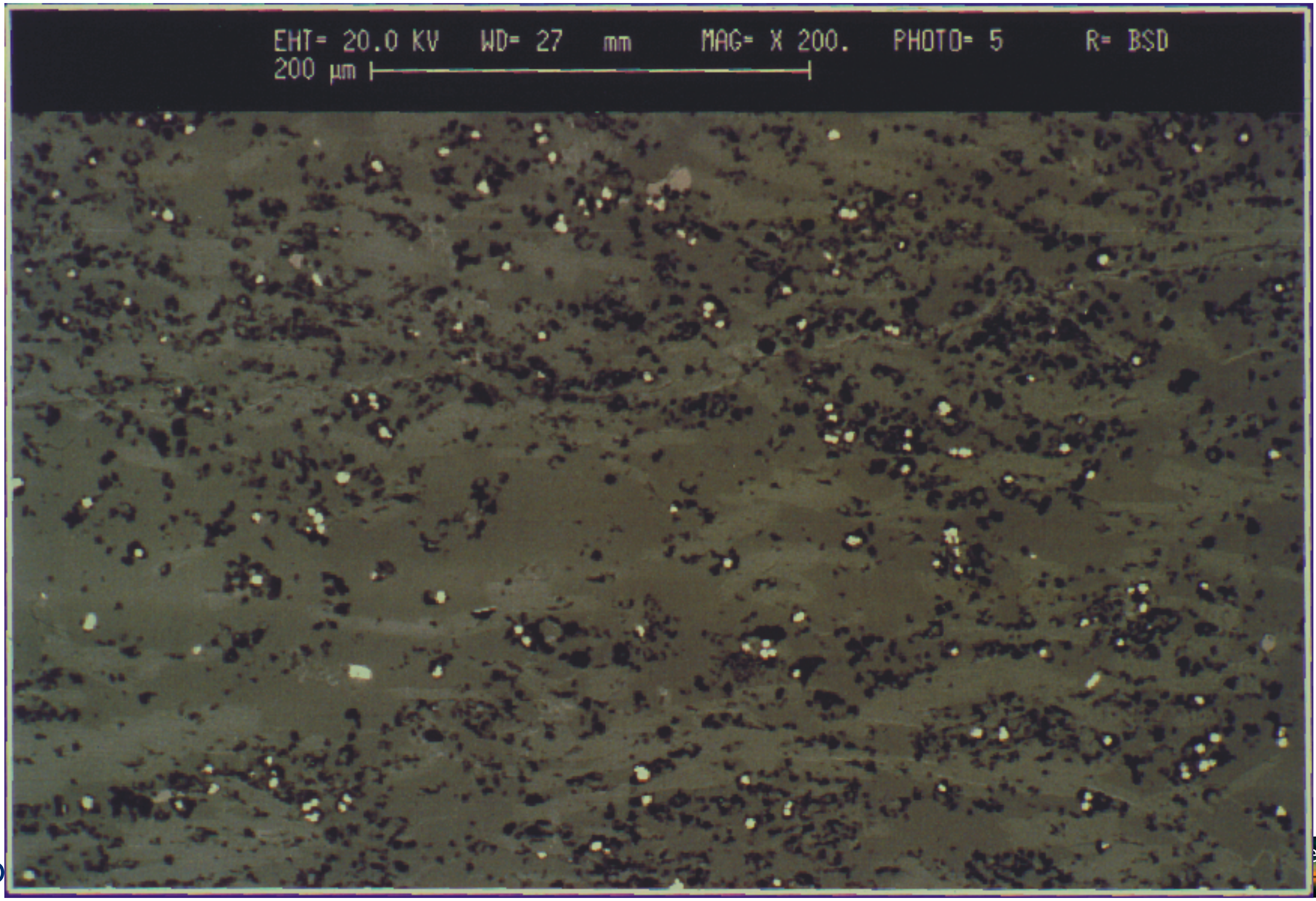
The Longest Conductivity Anomaly in the World Explained: Sulphides in Fold Hinges Causing Very High Electrical Anisotropy

Alan G. Jones[1], T. J. Katsube[2], and Pamela Schwann[3]

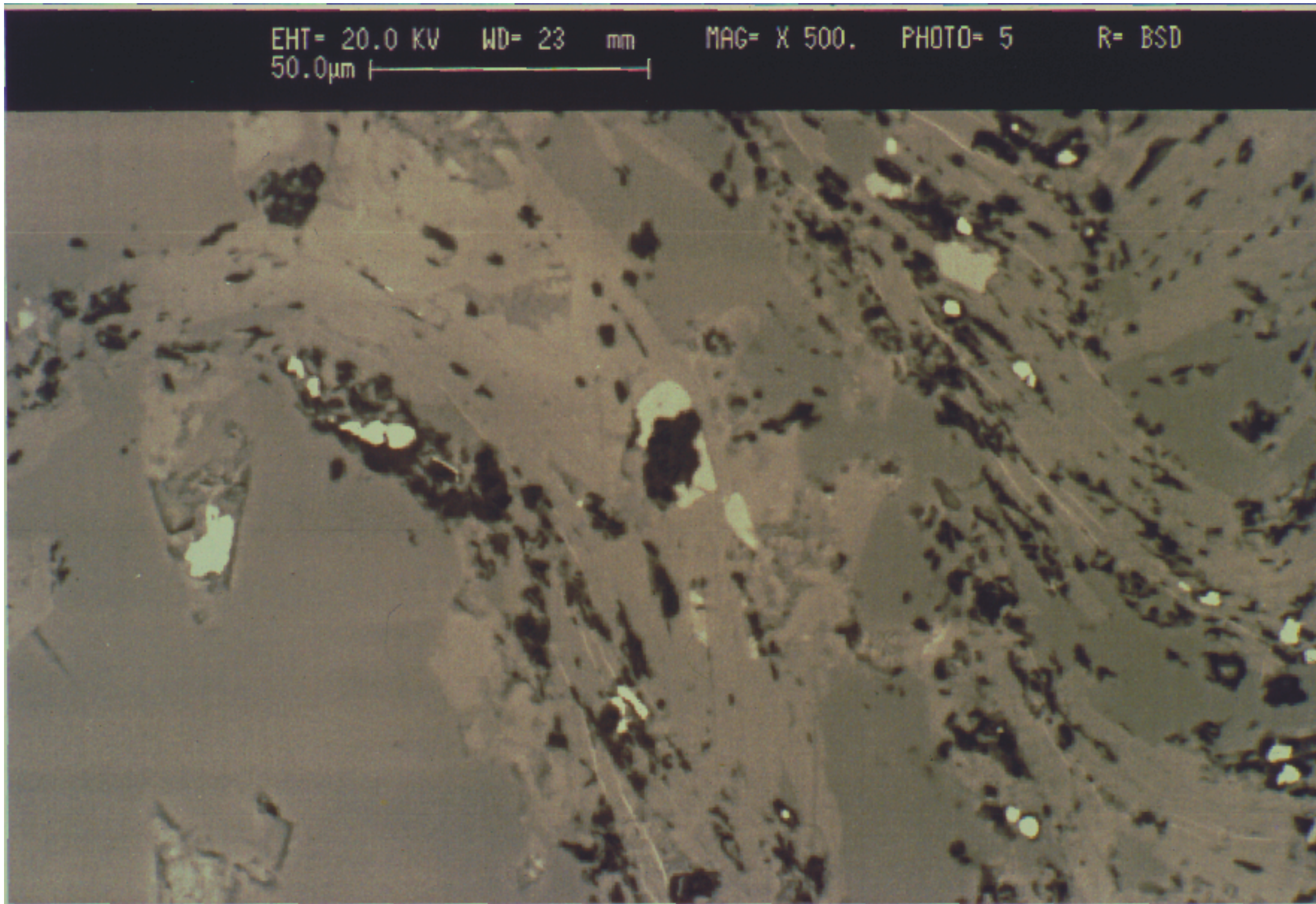
J. Geomag. Geoelectr., **49**, 1619–1629, 1997

COMPLETE MT SOLUTIONS

SEM scan of sample across strike – pyrite grains not connected



SEM scan of sample along strike – pyrite grains disconnected but pyrite (+FeO) stringers evident

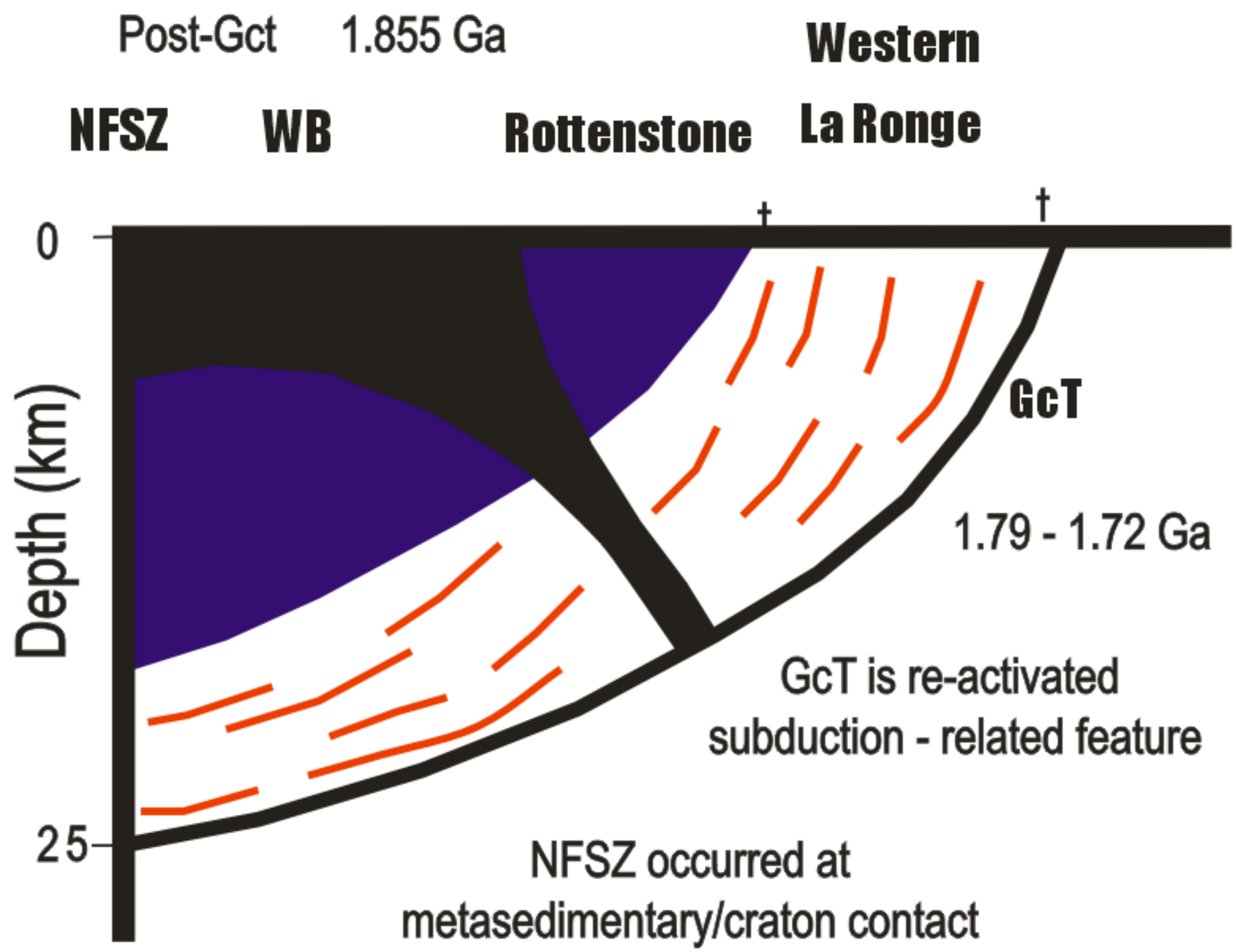


Electrical anisotropy at the individual, subsample and sample scale

Table 1: Maximum anisotropy values for rock samples
("individual" are measured, others are derived)

Subsample	ρ_{min} $\Omega\cdot$m	ρ_{interm} $\Omega\cdot$m	ρ_{max} $\Omega\cdot$m	maximum anisotropy: individual	maximum anisotropy: subsample	maximum anisotropy: sample
007Aa	19	33	290	15		
007Ab	23	52	320	14	1000	
007Ac	0.3	0.5	1	3		12800
007Ba	330	980	3840	12	490	
007Bb	7.8	48	130	17		
007Ca	8.3	50	79	10	25	
007Cb	3.1	15	54	17		

Cartoon of interpretation: Implications for tectonic history

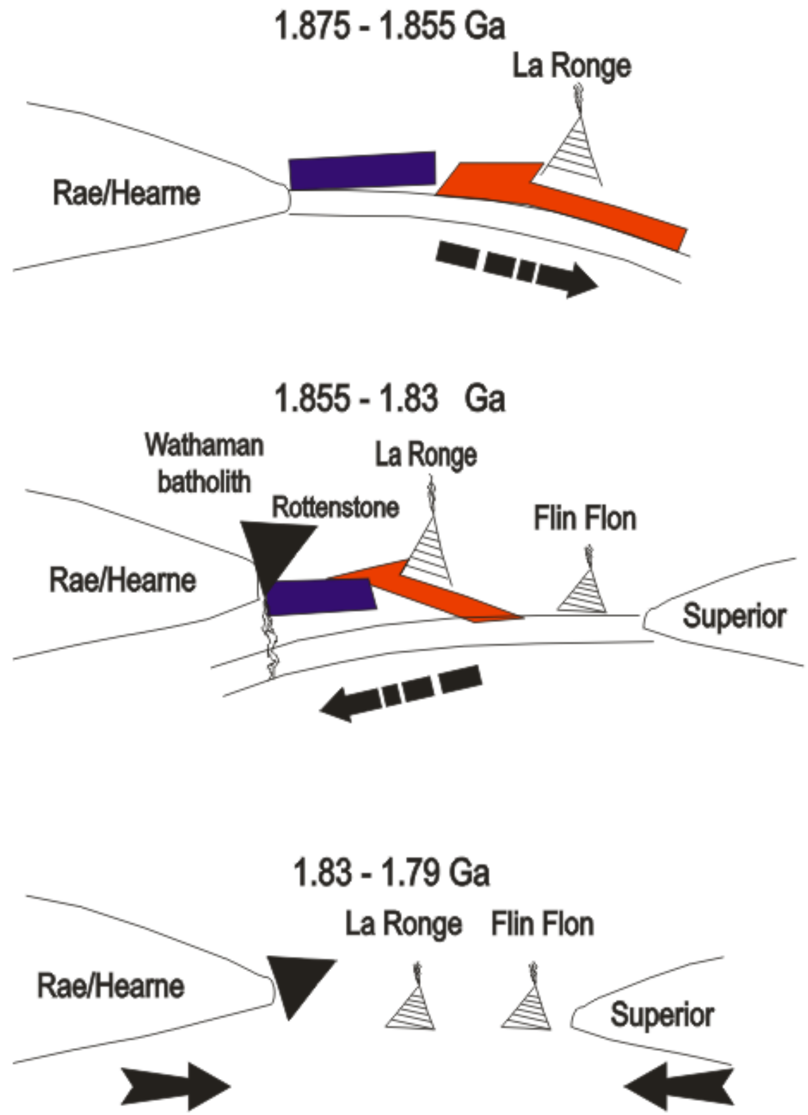


Model suggested from geological mapping

Initial E-directed subduction

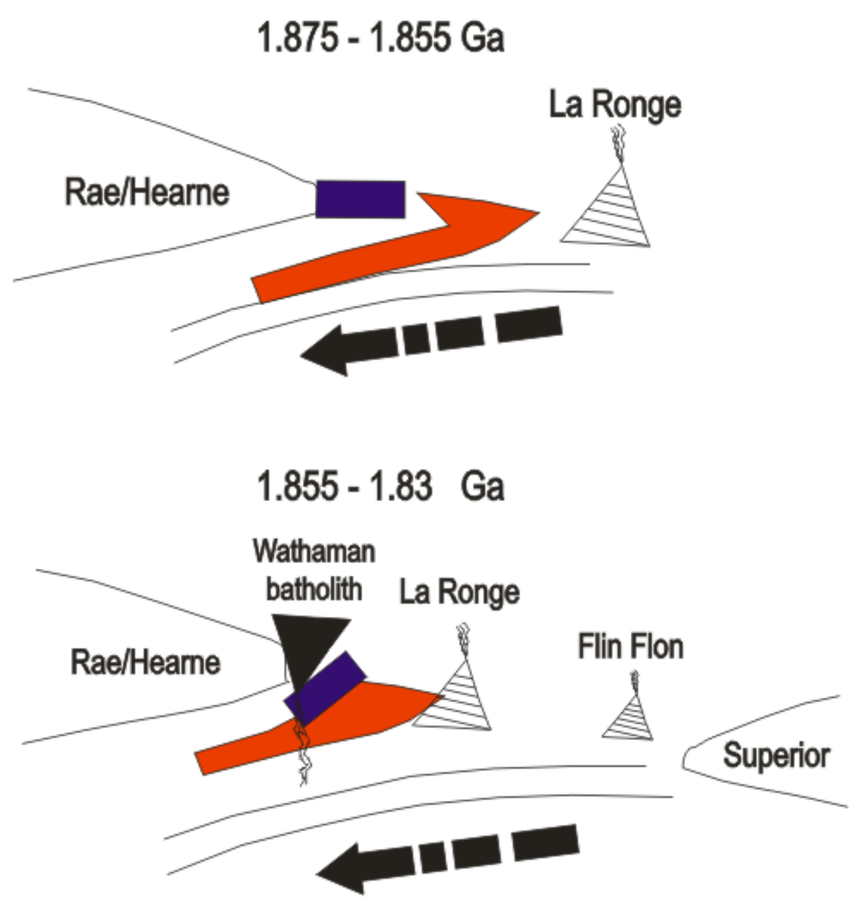
Subduction polarity flip

Then W-directed subduction



Model suggested from geometry of La Ronge metasediments

W-directed subduction during whole time to get La Ronge metasediments below BRSP and below Wathaman batholith



NACP from North Dakota to northern Saskatchewan (Jones et al., 2005)

Electromagnetic images of the Trans-Hudson orogen: the North American Central Plains anomaly revealed[1, 2]

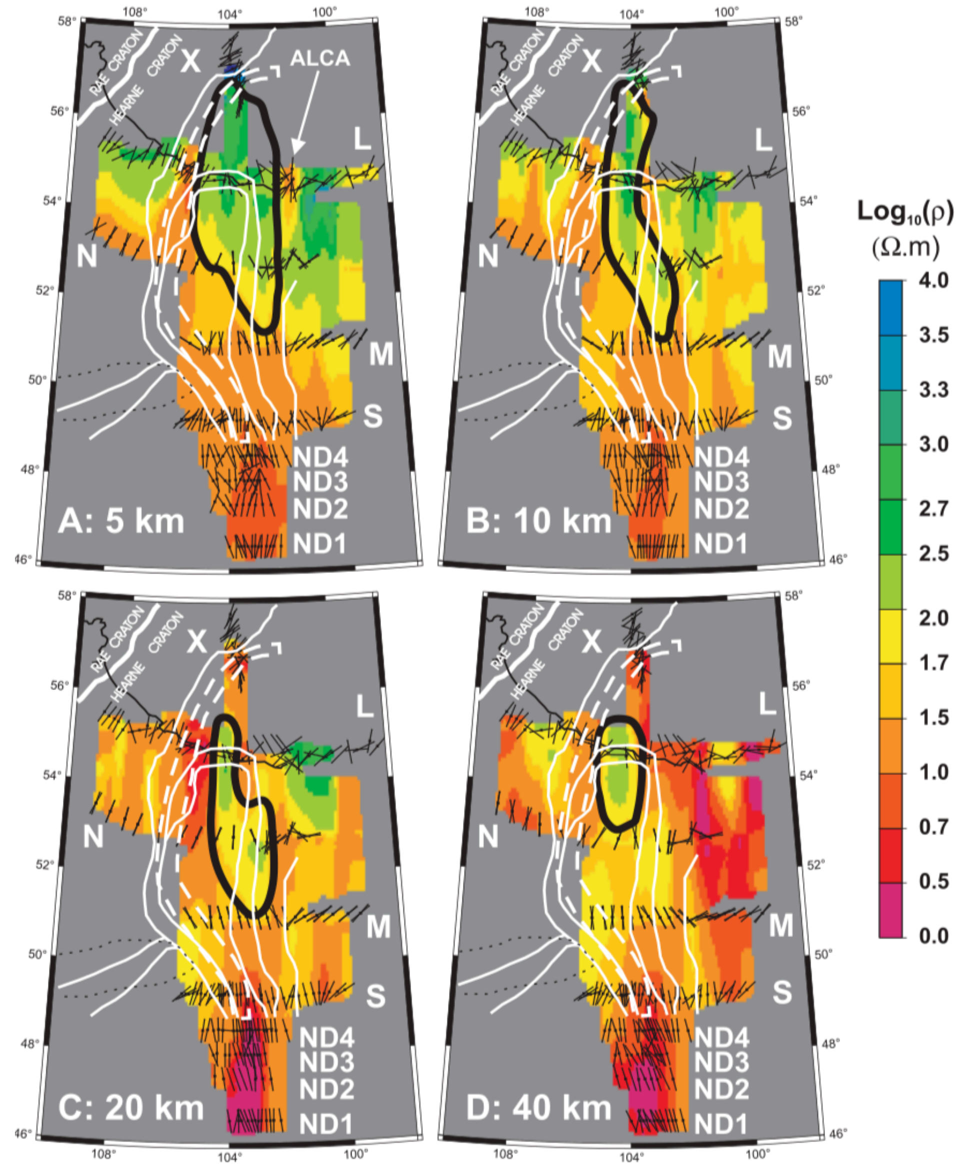
Alan G. Jones, Juanjo Ledo, and Ian J. Ferguson

Can. J. Earth Sci. **42**: 457–478 (2005)

Minimum resistivity at various crustal depths

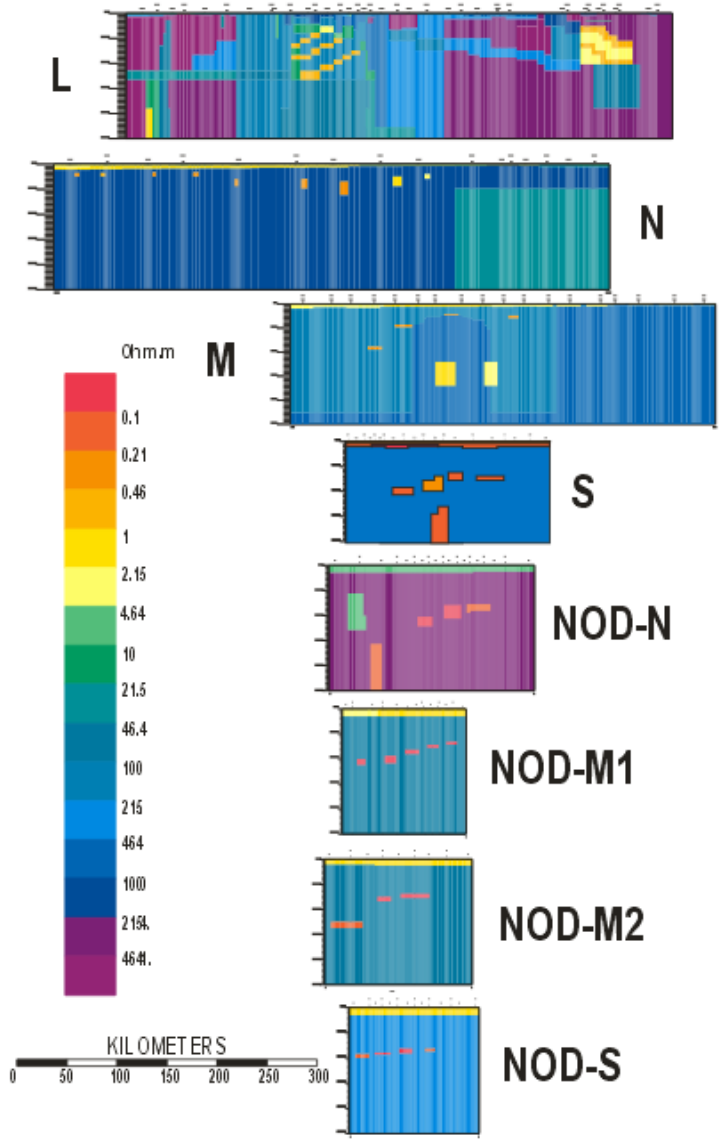
NACP path shows by dashed white lines

Excellent mapping of the “Sask craton” (black lines)



COMPLETE MT SOLUTIONS

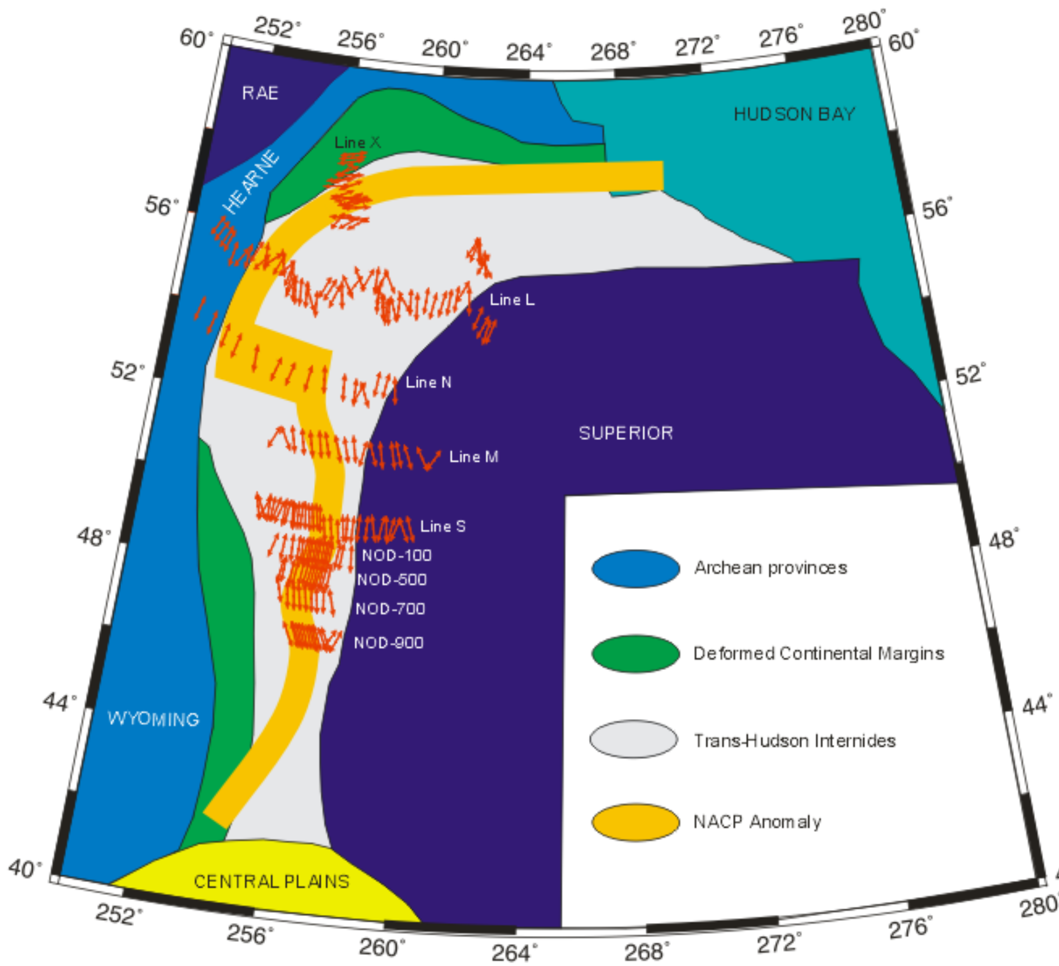
2-D models of NACP from North Dakota to northern Saskatchewan



COMPLETE MT SOLUTIONS

r series 2 MTNet

Known extent of NACP

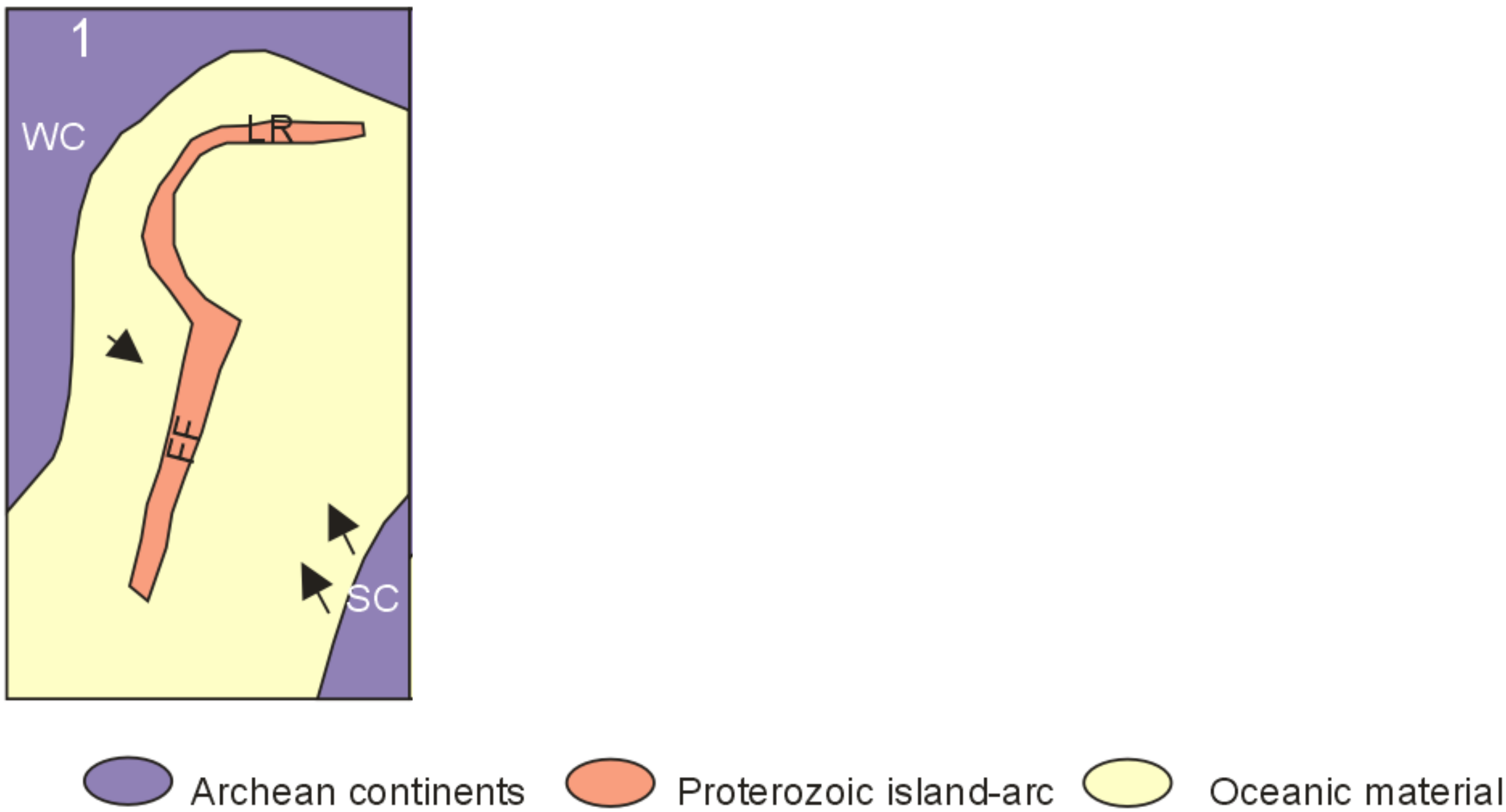


COMPLETE MT SOLUTIONS

ar series 2 MTNet

Evolutionary model to explain NACP

1) Deposition of the metasediments and syn-genetic sulphides between La Ronge arc and the Wyoming/Hearne craton

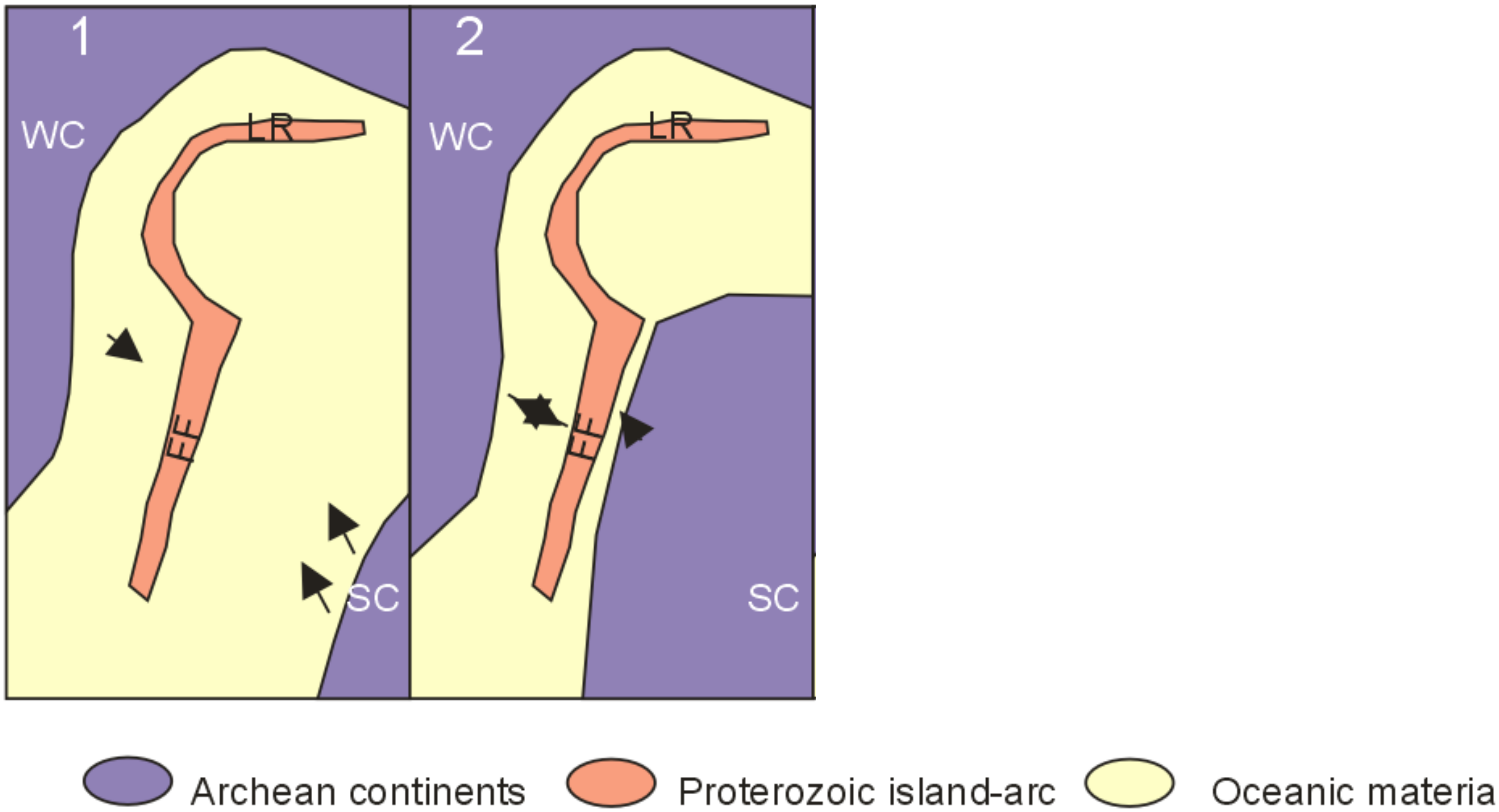


COMF SOI

MTNet

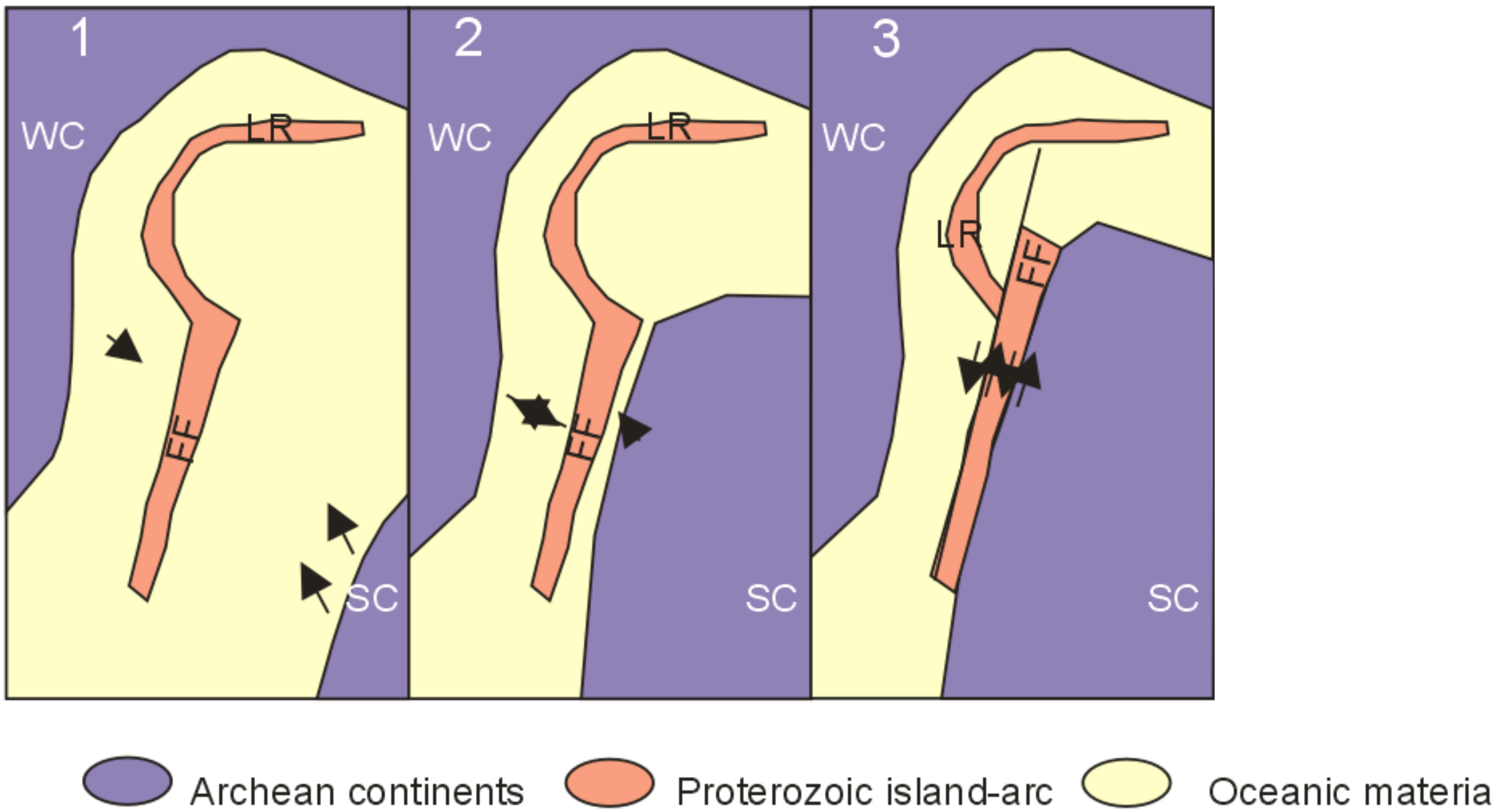
Evolutionary model to explain NACP

2) Compression and folding of the metasediments, posterior migration of the sulphides from high stress regions to lower stress regions (fold hinges) and formation of the NACP conductivity anomaly. This two episodes occurred before the collision of the Superior craton with the island-arc system.



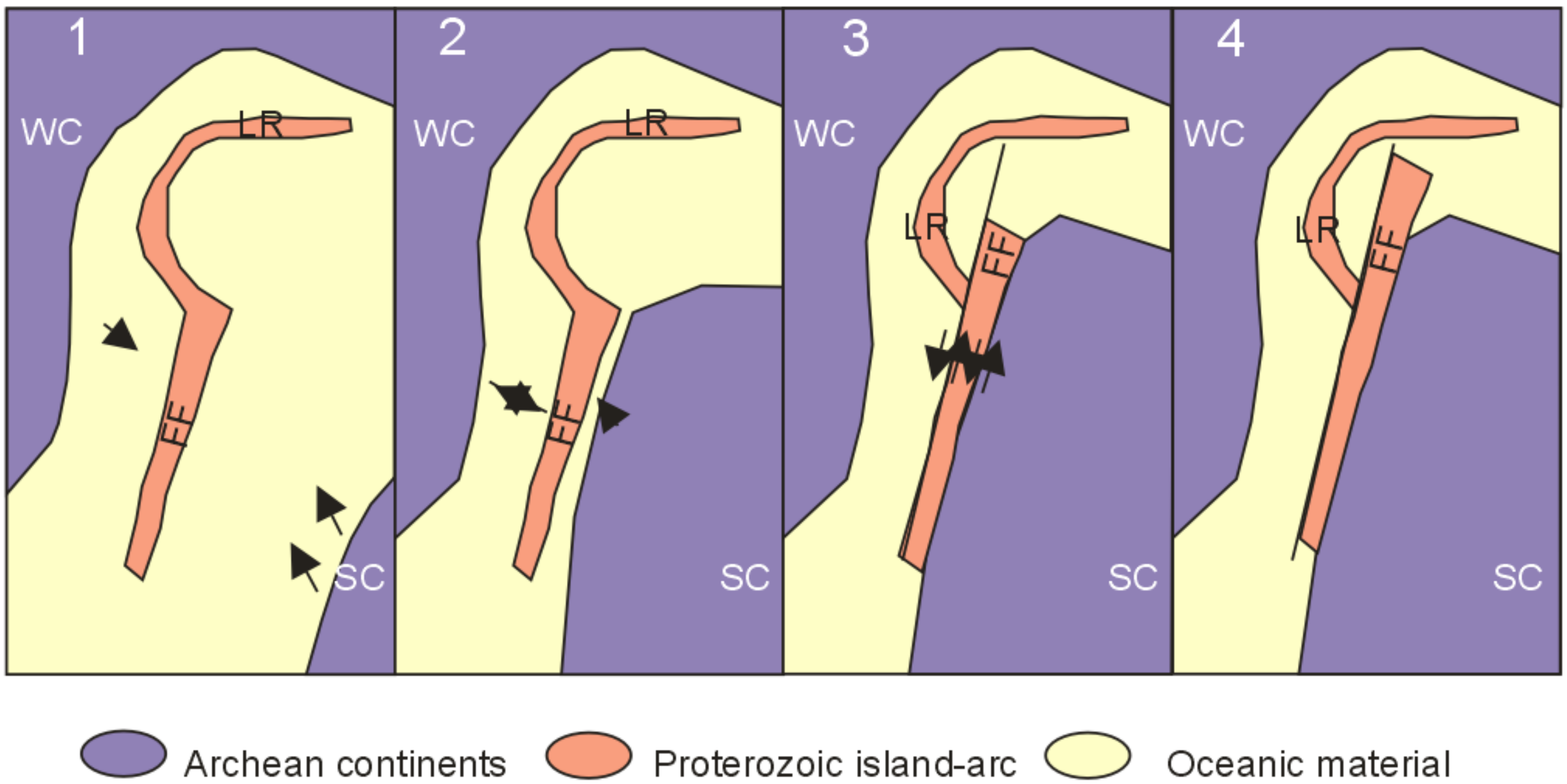
Evolutionary model to explain NACP

3) Sinistral faulting along the Tabbernor fault zone, and as consequence the break up of the NACP anomaly

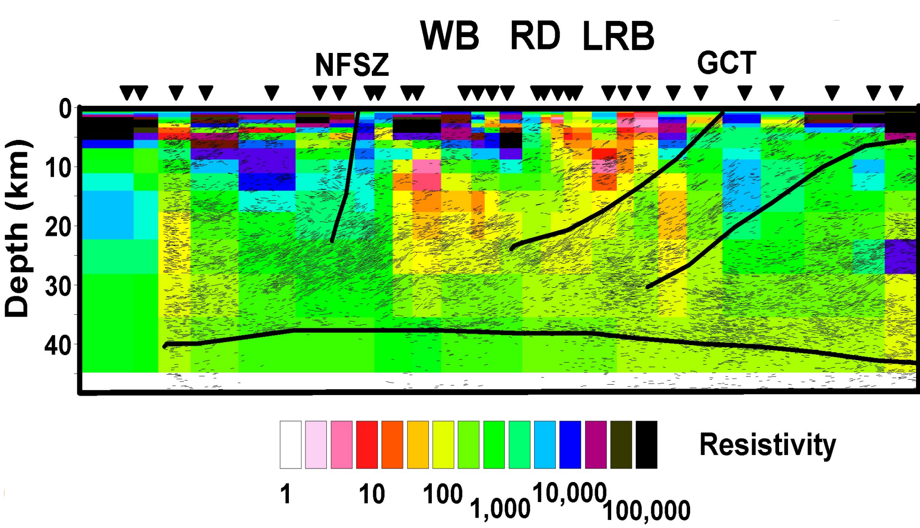


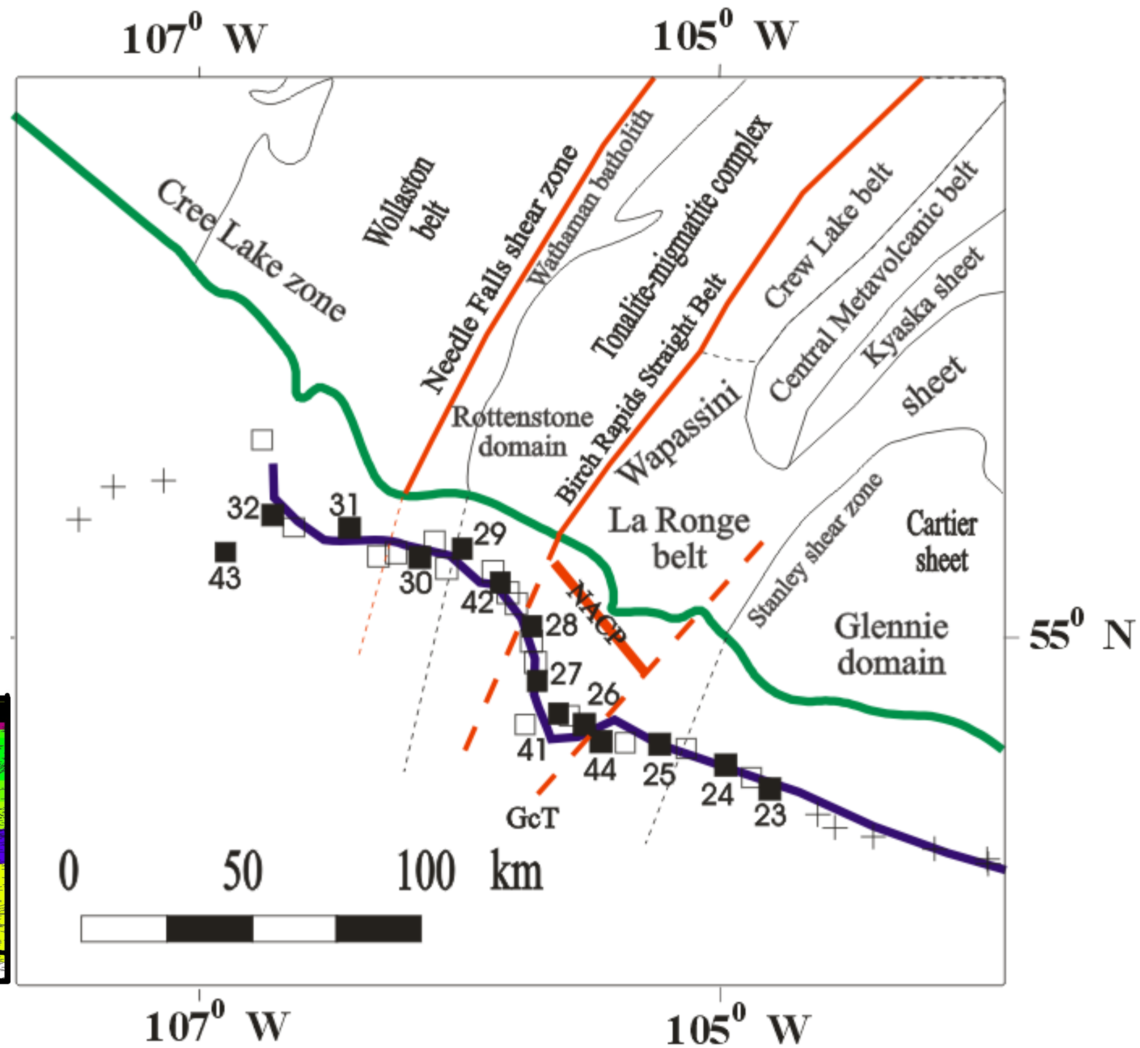
Evolutionary model to explain NACP

4) End of the orogeny.



2-D inversion of MT data from the NACP just on the edge of the sedimentary Williston basin shows the spatial affinity of the anomaly with the La Ronge Belt (LRB), an historic gold district





Mineralized occurances within the La Ronge belt shown by yellow (Au, 7-22), blue (Cu-Zn, 3-7) and green (Cu-Ni-PGE, 8-12) dots.

No major world-class deposits, and most closed, but recent renewed interest in the La Ronge belt

Gold

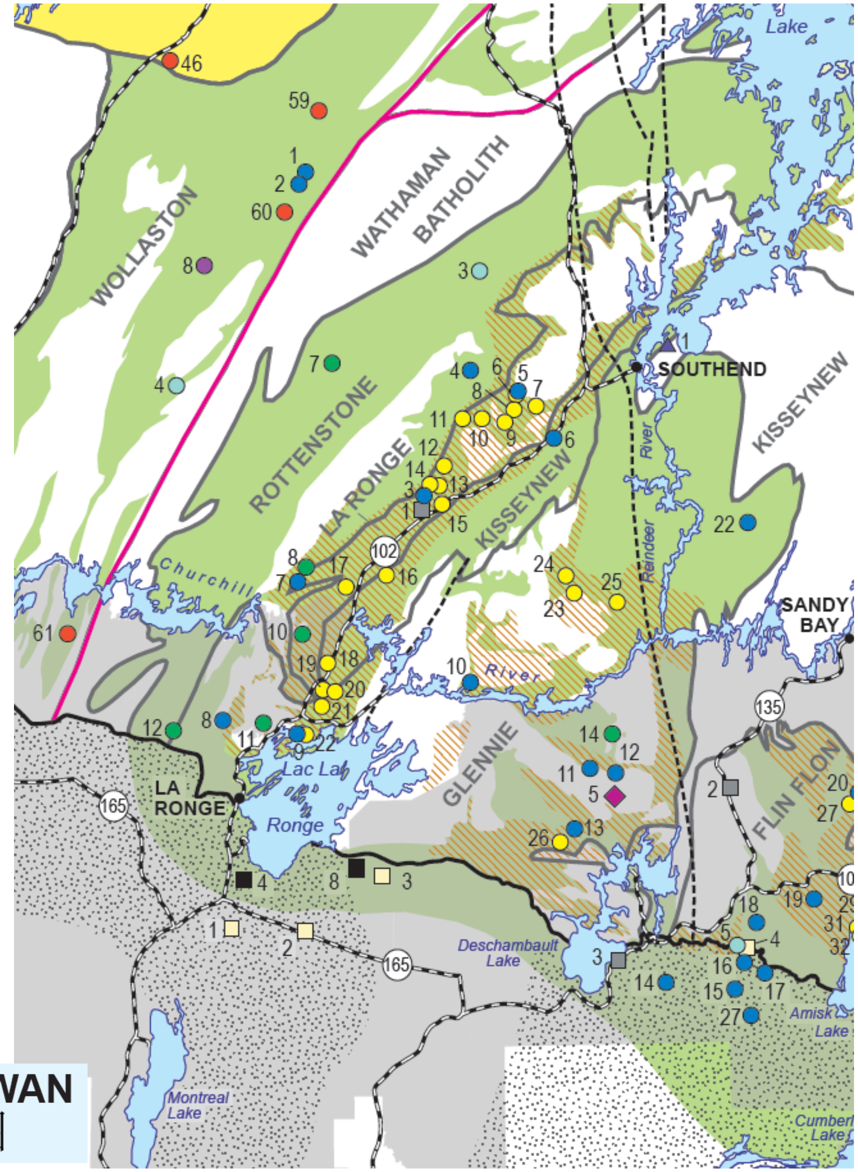
7. Golden Heart deposit
8. EP and Komis mines (closed)
9. Corner Lake deposit
10. Tower East and Memorial deposits
11. Birch Crossing deposits
12. Jojay deposit
13. Star Lake mine (closed)
14. Jolu and Decade mines (closed)
15. Jasper mine (closed)
16. Greywacke deposit
17. Roy Lloyd mine - Bingo deposit (suspended)
18. North Lake deposit
19. Contact Lake mine (closed)
20. Preview North and South, PAP A, B and C and PAP/Preview SW deposits
21. Sulphide Lake deposits
22. Anglo-Rouyn tailings

Cu-Zn

3. Frog Lake prospect
4. Reef Lake prospect
5. Discovery Lake prospect
6. Brabant-McKenzie deposit
7. Borys (Watts) Lake deposit

Cu-Ni-PGE

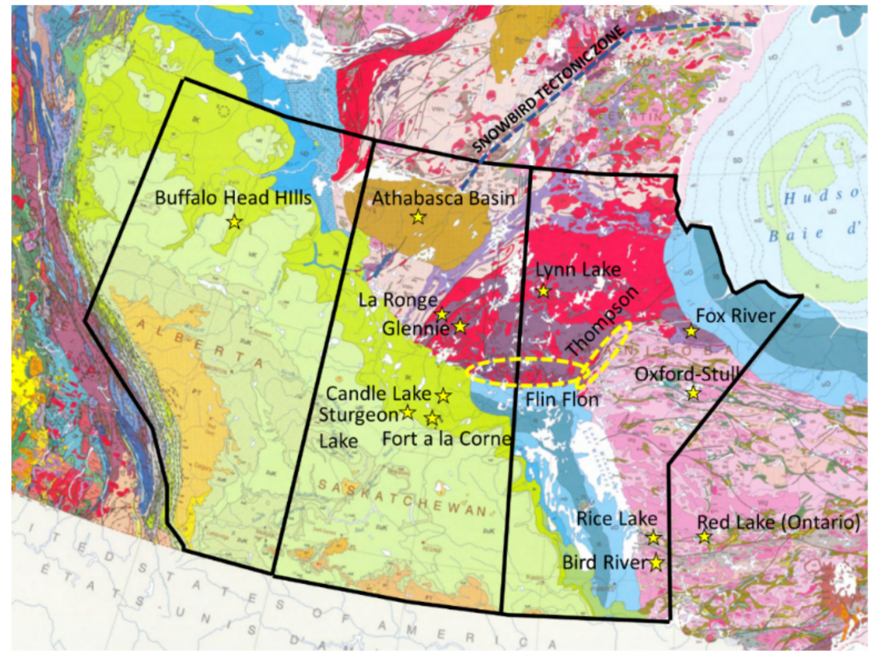
8. Gochager Lake deposit
9. West Bear (Co-Ni) deposit
10. Triangle Lake deposit
11. Dunlop (International Ni) deposit
12. Howard (Little Clam) Lake deposit



RESOURCE MAP OF SASKATCHEWAN
2019萨斯喀彻温省资源分布图

COMPLETE MT SOLUTIONS

“Many riches underlie Canadian Prairies”



Geology and metal districts of the Canadian Prairies. Credit: The Geological Survey of Canada, modified by The Northern Miner.

Canada finally waking up to the wealth beneath cover…

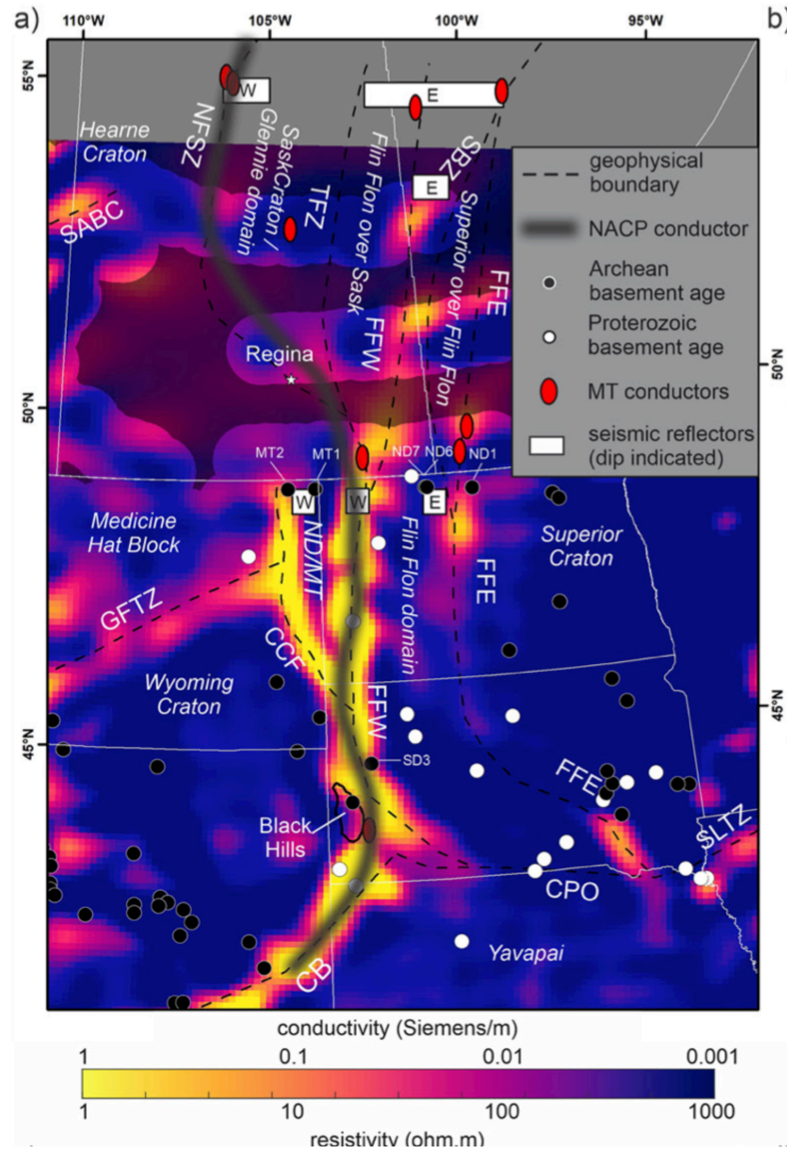
NACP tracks the extension of the La Ronge gold district beneath the Prairies.

Recent story to the South

USarray data combined with NOD and Lithoprobe data were inverted in 3D by Bedrosian and Finn (2021)

NACP at 30 km well imaged in the USA, but poorly imaged in Canada

Others focus on what they call sTHO – southern Trans-Hudson Orogen



When Wyoming Became Superior: Oblique Convergence Along the Southern Trans-Hudson Orogen

Paul A. Bedrosian[1] and Carol A. Finn[1]

Geophys Res. Lett.: 10.1029/2021GL092970

Tectonic history

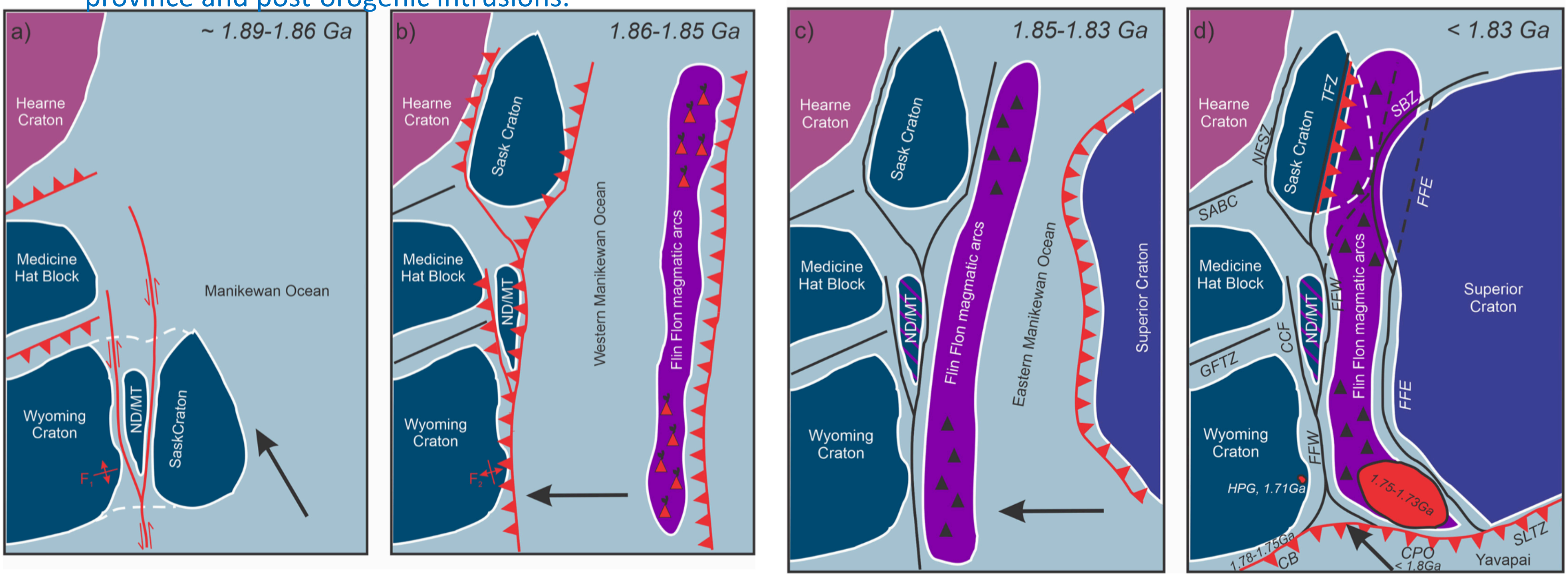
Proposed time evolution of the southern Trans-Hudson orogen—active tectonic elements in red, relic in black.

(a) Oblique convergence with northward translation of fragments of the Wyoming craton.

(b) Subduction of the western Manikewan Ocean beneath the composite Archean margin and approach of FF arc(s).

(c) Closure of the eastern Manikewan Ocean via subduction beneath the Superior craton margin.

(d) Deformation between the Sask and Superior cratons during terminal closure; subsequent accretion of the Yavapai province and post-orogenic intrusions.



The new story – anisotropy!!!

More and more MT work and lab studies showing strong anisotropic behaviour of rocks at the grain scale

Modelling the data assuming 2D anisotropy axes align with strike axis, so the 3x3 anisotropy resistivity matrix is only diagonal.
TE mode only involves RhoXX
TM mode involves RhoYY and RhoZZ

$$\frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} + i\omega\mu\sigma_{xx}E_x = 0$$

Note: MT primarily a toroidal current system so is weakly sensitive to RhoZZ, which is given by horizontal gradient of Hx

$$\frac{\partial}{\partial y}\left(\rho_{zz}\frac{\partial H_x}{\partial y}\right) + \frac{\partial}{\partial z}\left(\rho_{yy}\frac{\partial H_x}{\partial z}\right) + i\omega\mu H_x = 0,$$

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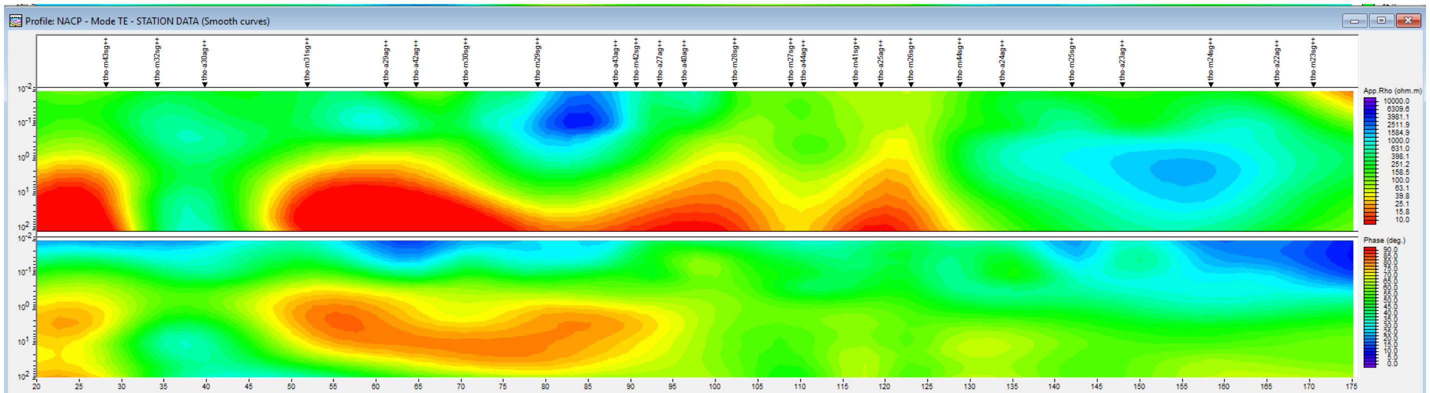
The new story – anisotropy!!!

NACP-THOT TE mode RhoA and Pha data shows presence strong conductors, whereas TM mode data doesn't – just the same as COPROD data

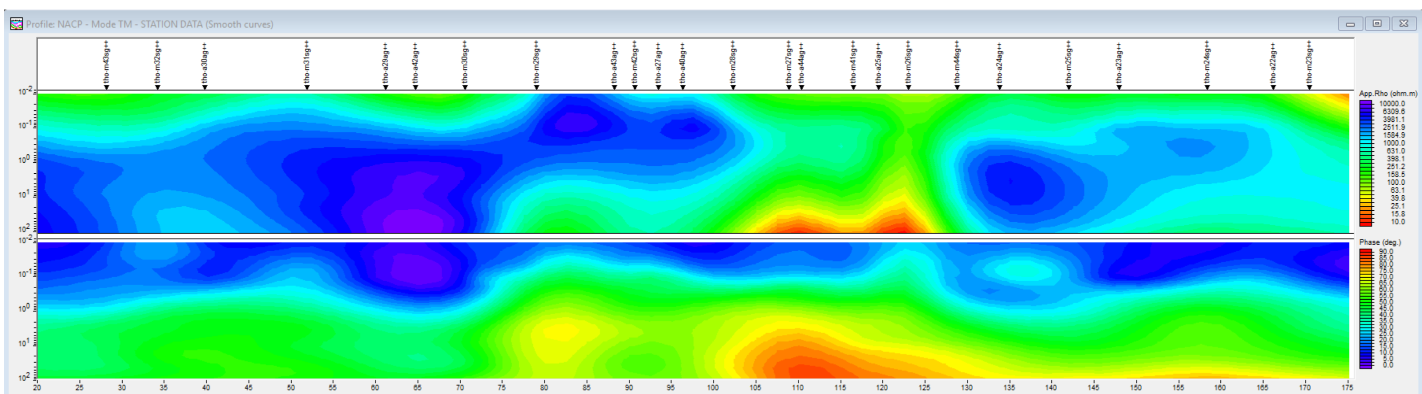
TE Rho

TE Pha



TM Rho

TM Pha

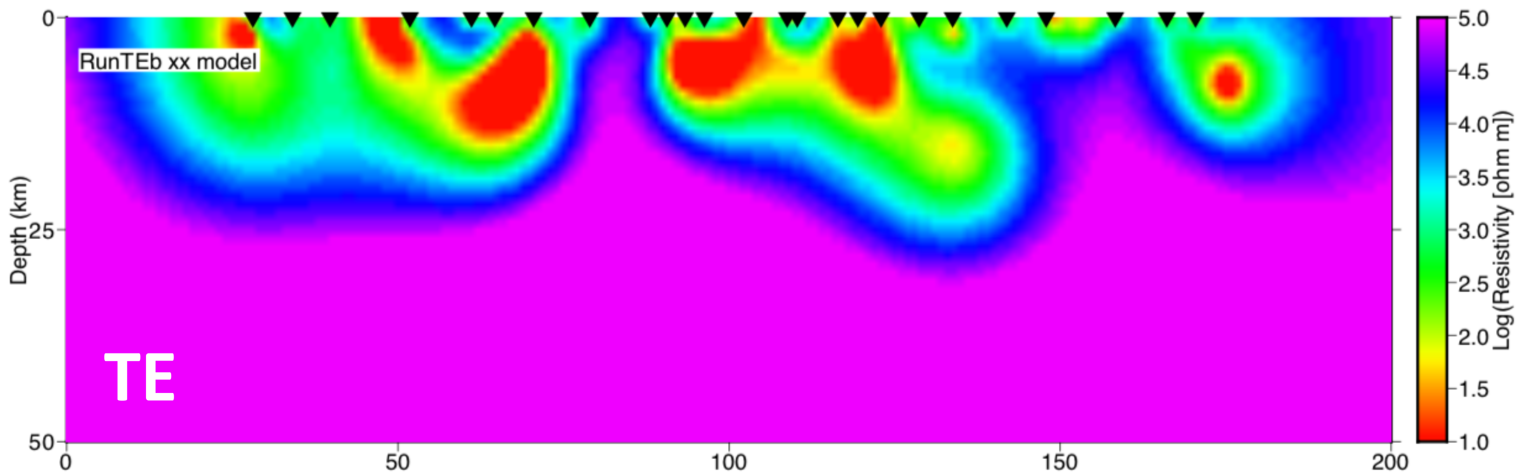


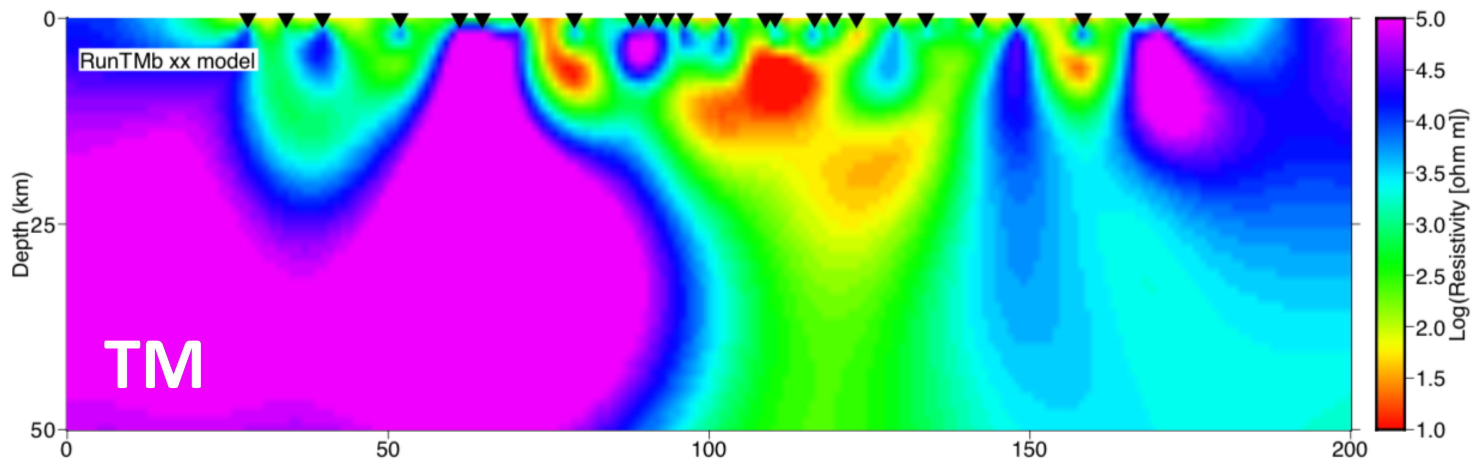
Independent inversions - models

Independent inversions of TE (top) and TM (bottom) data look like they are from a different Earth !

TE nRMS = 2.06
TM nRMS = 2.76

Efloors: 7% in Rho
2º in Pha





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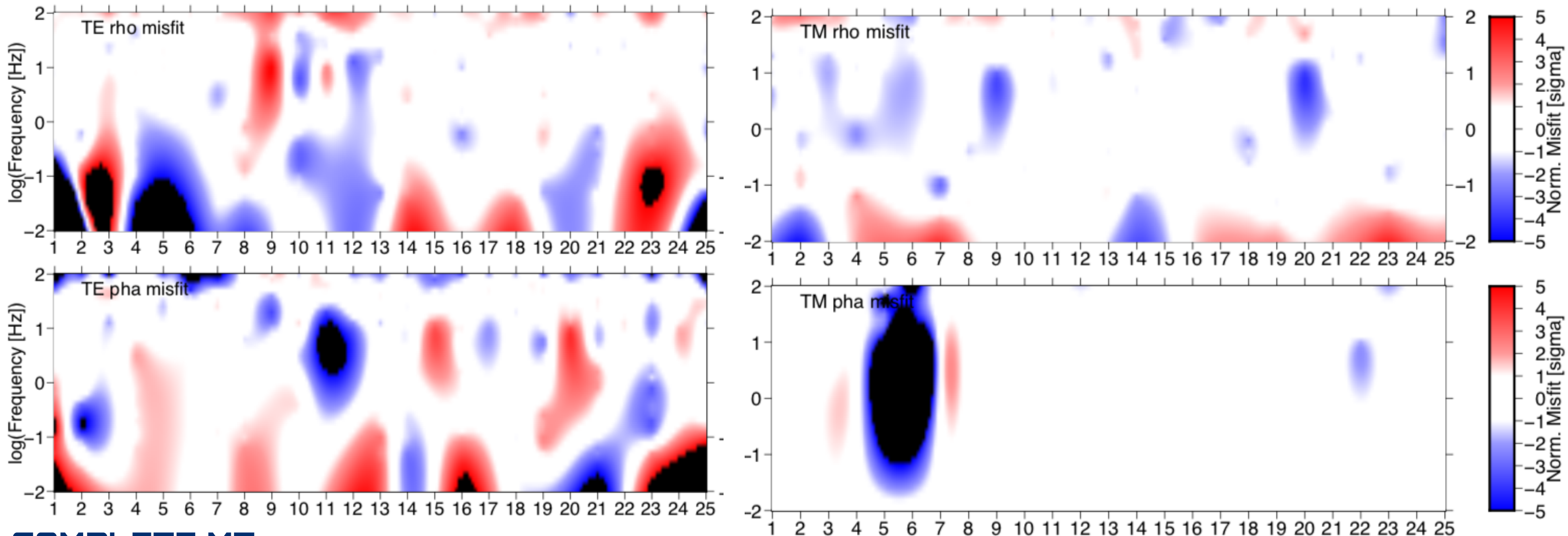
Independent inversions - misfits

Apart from Site 6 PhaTM misfit, all of the others are reasonable

TE nRMS = 2.06 TM nRMS = 2.76



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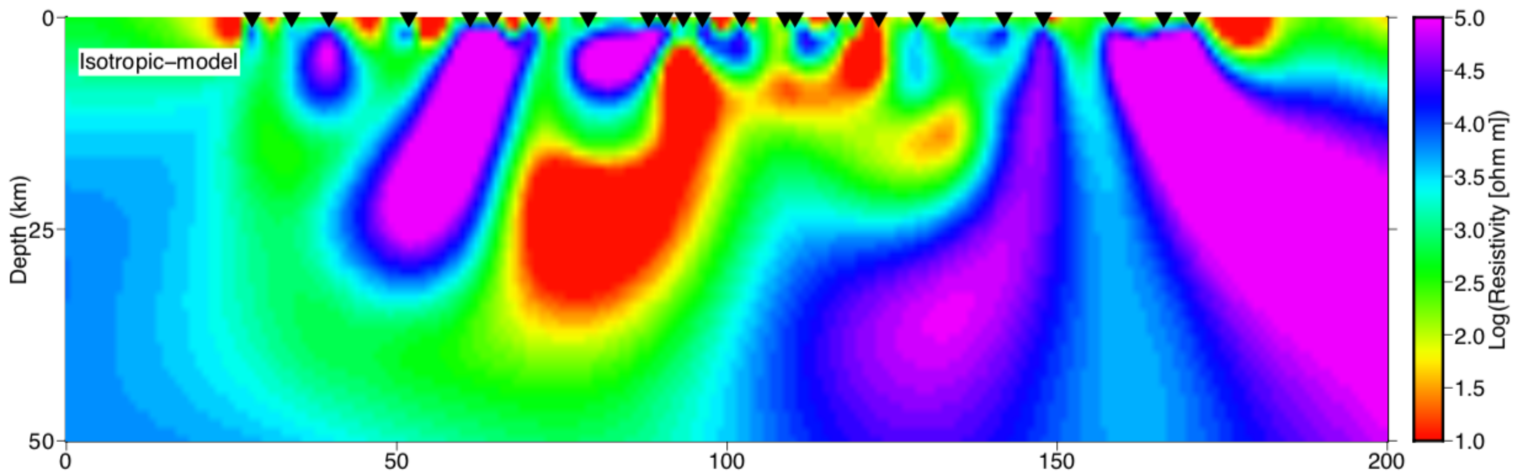
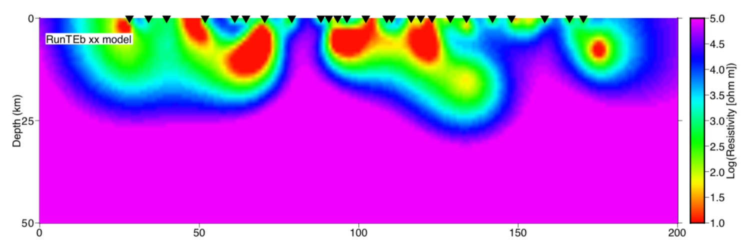
Joint TE+TM isotropic inversion - model

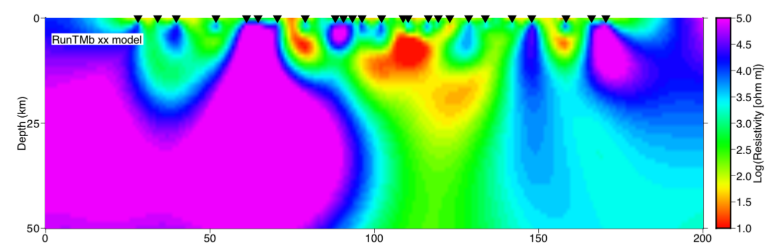
Joint inversion* of TE and TM data together looks like a mix of the prior independent inversions !



nRMS = 2.76

Efloors: 7% in Rho
2º in Pha

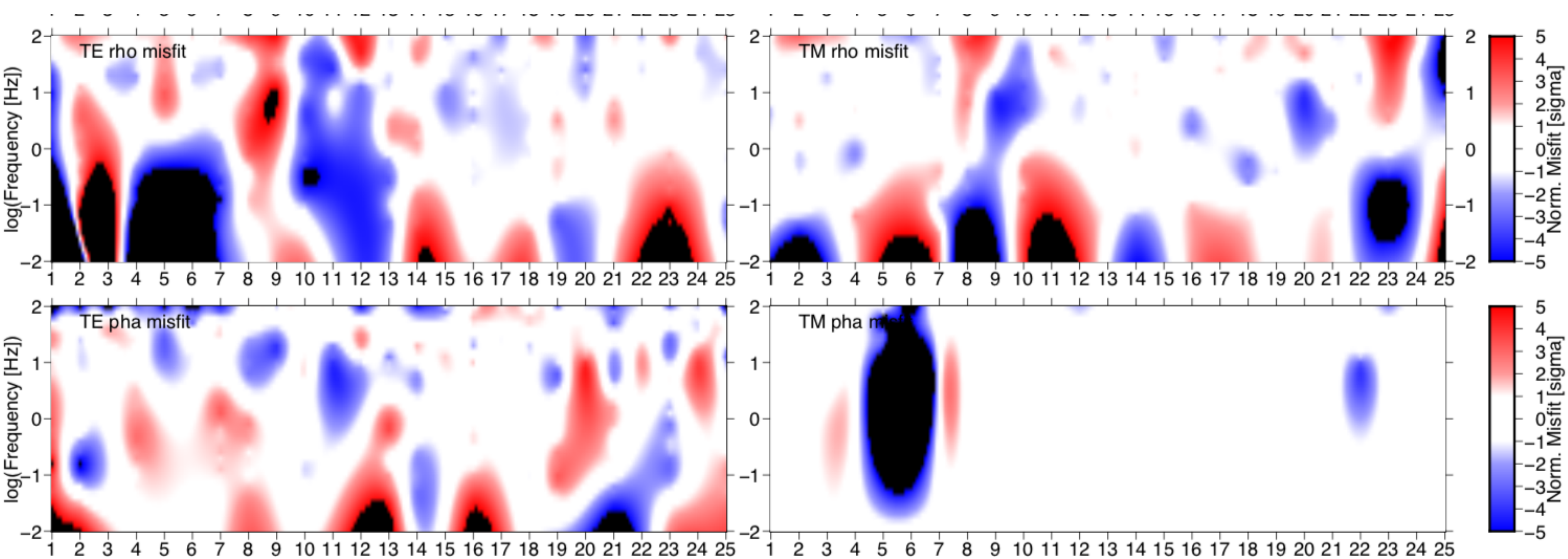




Inverting TE & TM together is a true Joint Inversion, as they “see” the Earth differently
– TE sees current concentrations flowing within conductors along strike
– TM sees charges on boundaries caused by deflections of currents flowing parallel to the profile

Joint TE+TM isotropic inversion - misfits

Very strong misfits for RhoTE, RhoTM and PhaTE. The only data that are well fit are the PhaTM data



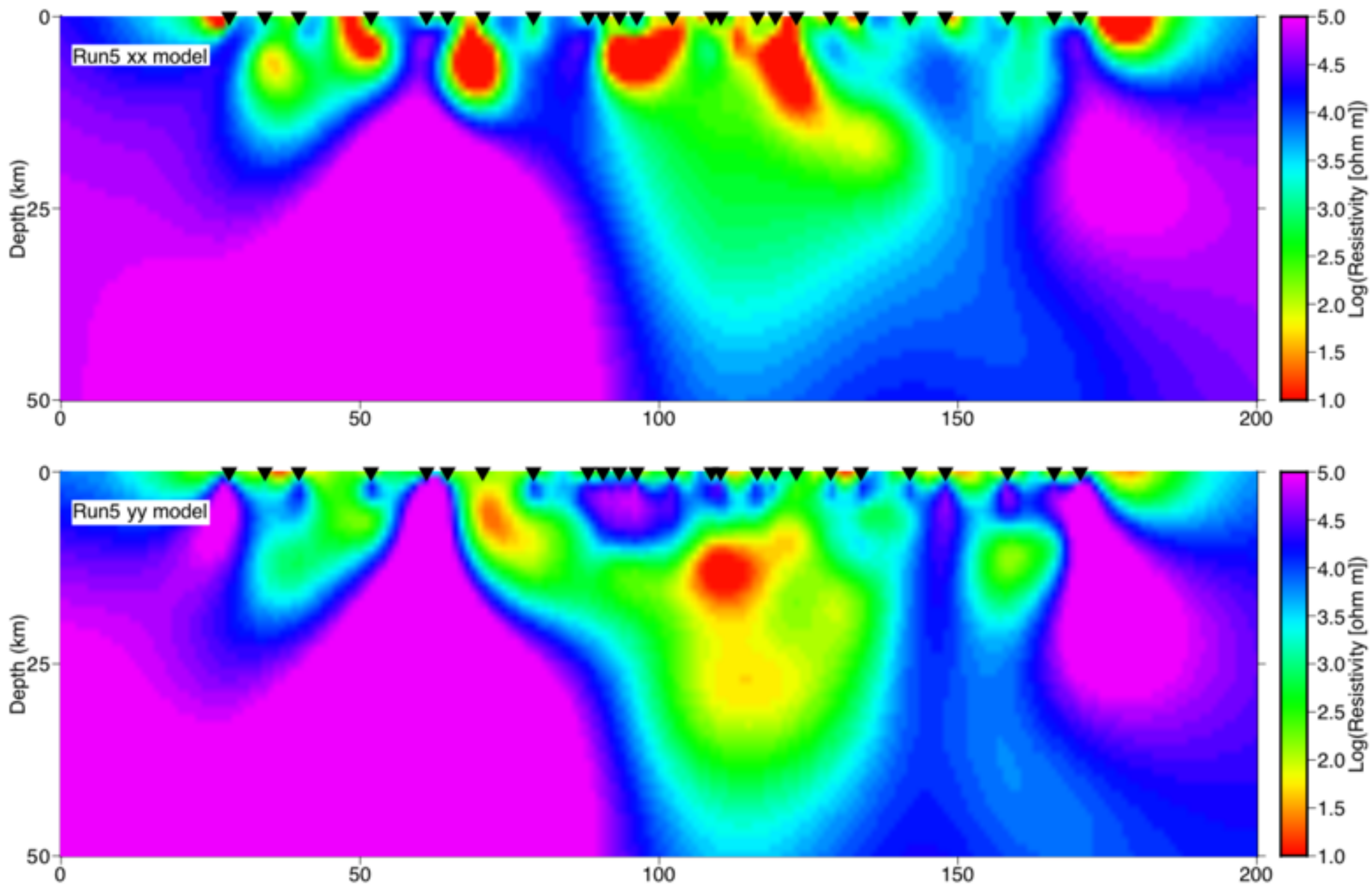
Joint TE+TM anisotropic inversion - models

Choice of tau_{anis} is critical !
(You are basically trading off between independent inversions and isotropic inversion as you change tau_{anis})

nRMS = 1.54 !!!

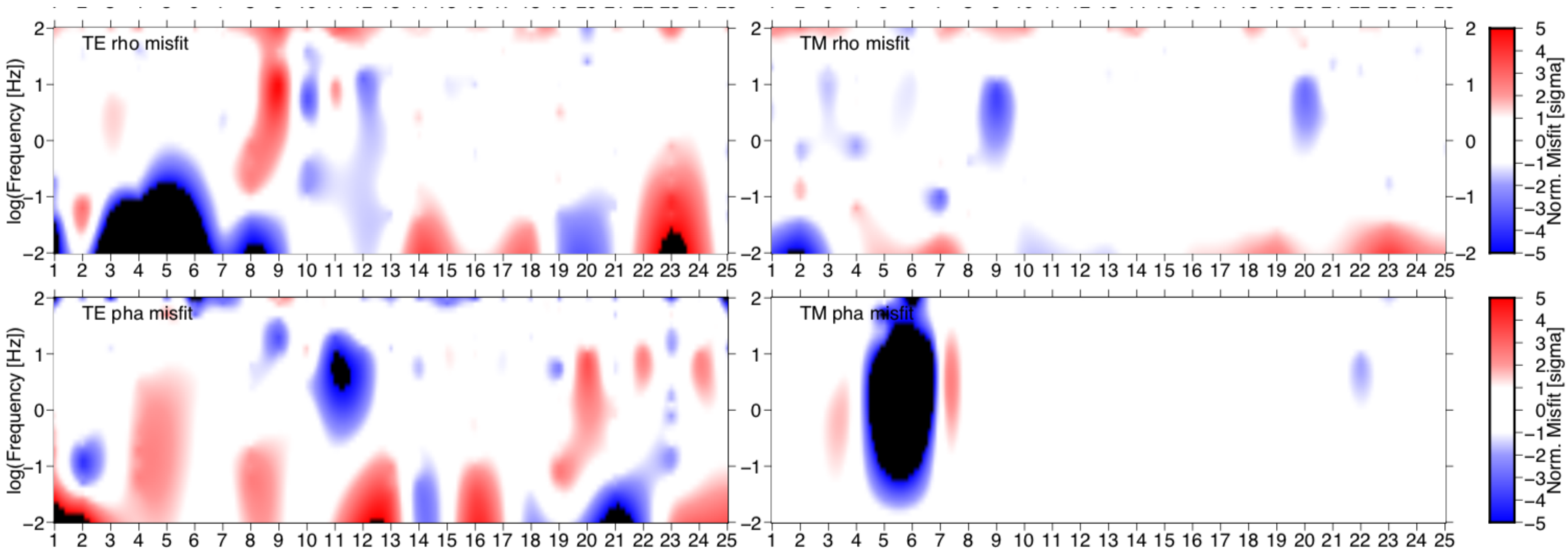
Efloors: 7% in Rho
2º in Pha

Anomalies identified that are consistent with observations in the exposed rocks



Joint TE+TM anisotropic inversion - misfits

Apart from long period TE RhoA, and the odd Site 6 PhaTM, fits are all excellent



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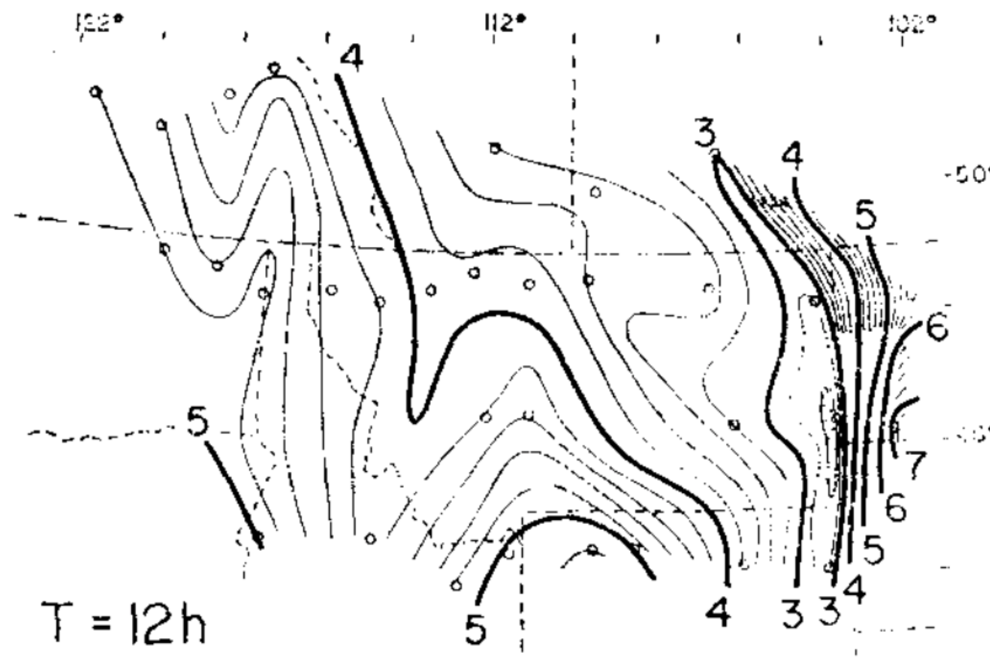
Conclusions to the crustal story

- NACP intimately associated with THO
- NACP lies in west or north of internides
- NACP has significant along-strike response but virtually no across-strike response
- NACP likely due to highly anisotropic conductors – likely en echelon imbricated metasediments
- Where exposed, NACP is associated with sulphides – pyrite grains in fold hinges – with connectivity from pyrite (+FeO) stringers
  - Another interpretation (Bedrosian and Finn, 2021) is in terms of graphite – either metamorphic or from mantle C-O-H fluids
- Along-strike continuity and similarity of NACP suggests continental-scale of orogenic processes

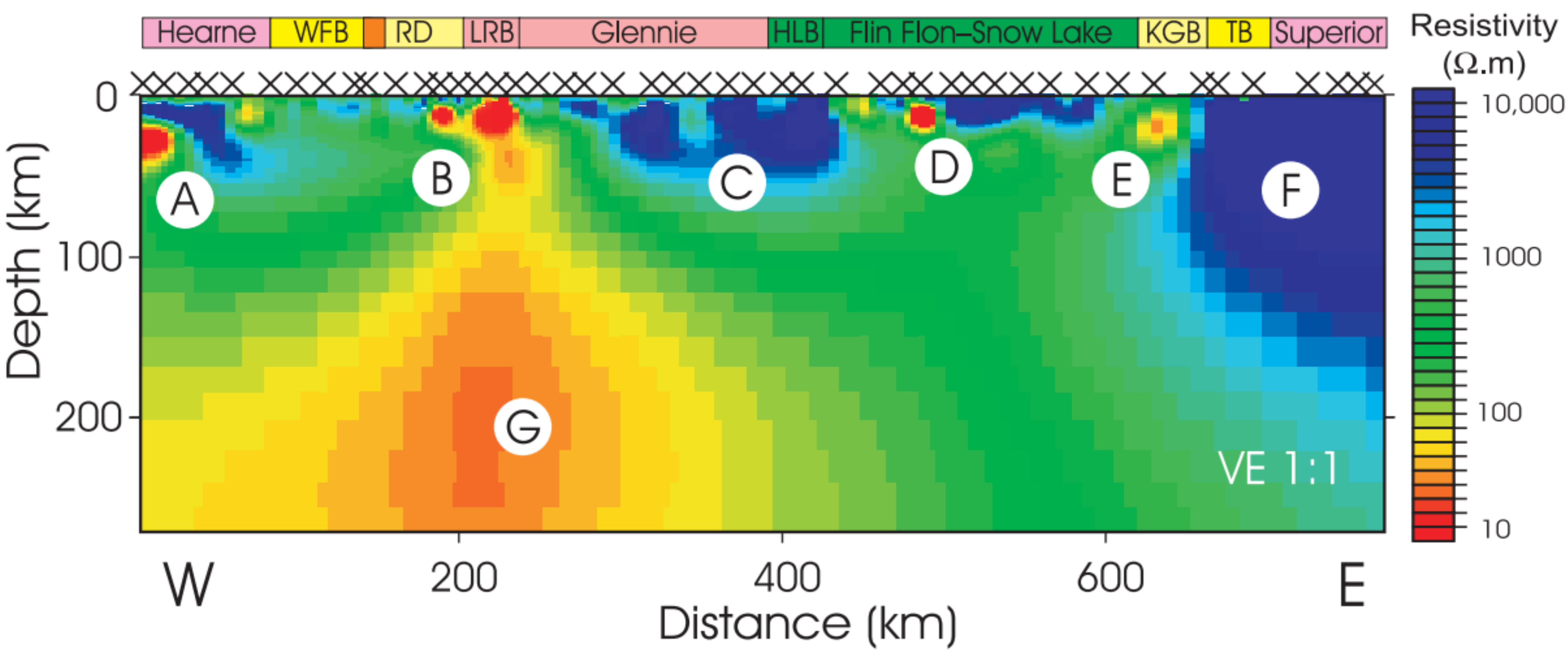
BUT!!!!!

The crustal conductor mapped from the Dakotas to northern Saskatchewan does not explain the very, long period GDS responses!

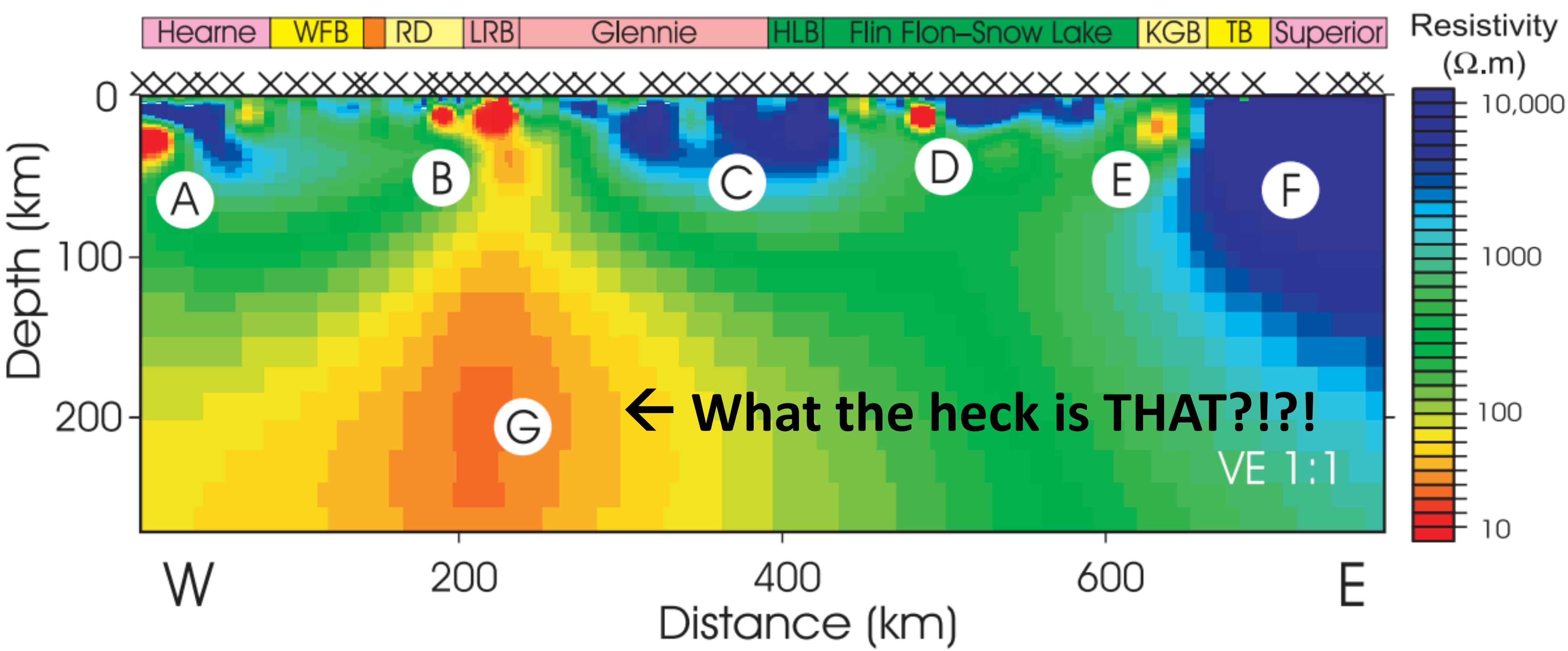
Very high tipper responses out to many hours (over 12h)



Lithospheric-scale model for Profile L shows mid-lithosphere conductor “G” with its top at approx. 80-100 km directly beneath the La Ronge Belt

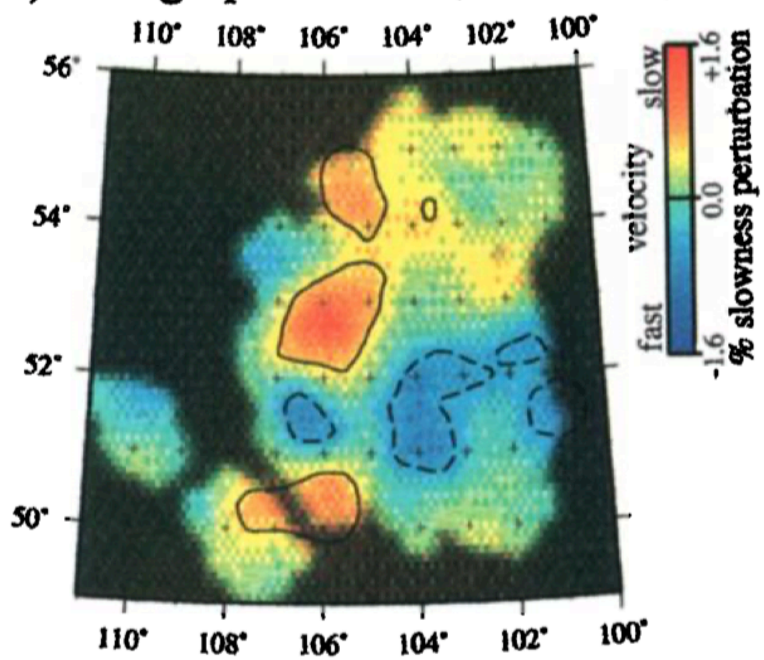


Lithospheric-scale model for Profile L shows mid-lithosphere conductor “G” with its top at approx. 80-100 km directly beneath the La Ronge Belt

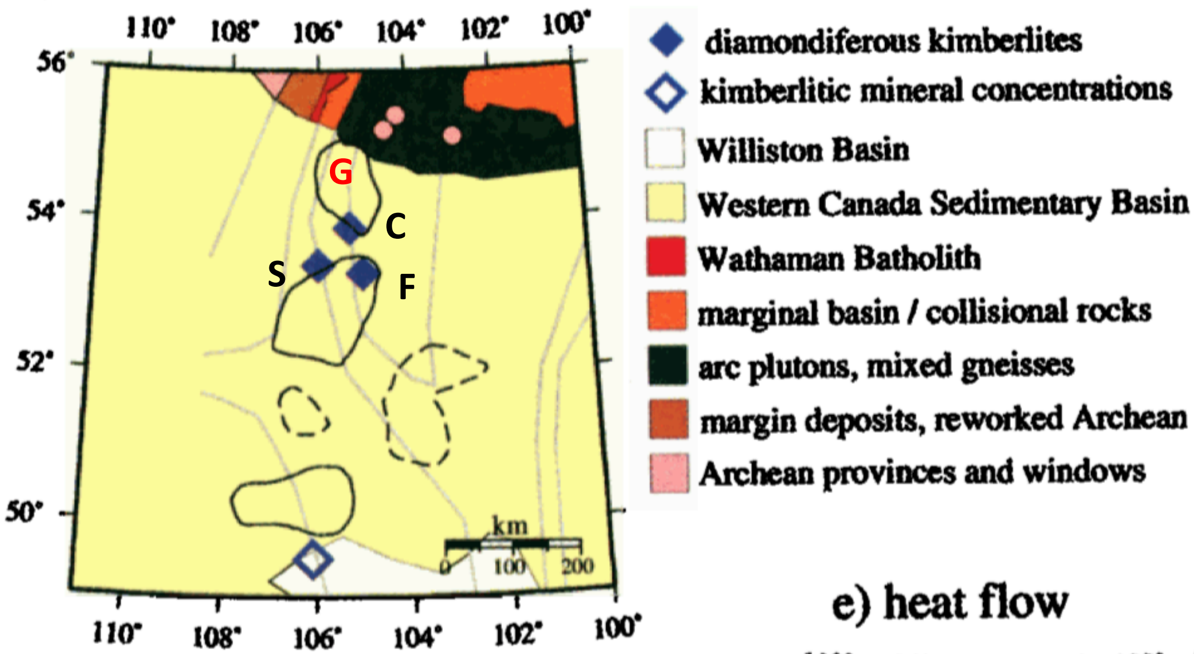


Kimberlites and Seismic Tomography of northern Saskatchewan

a) tomographic result (100km depth)



b) surface tectonics (with inferred boundaries)



e) heat flow

110° 108° 106° 104° 102° 100

Lithospheric mantle structure beneath the Trans-Hudson Orogen and the origin of diamondiferous kimberlites

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Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada

Zoltan Hajnal
Department of Geological Sciences, University of Saskatchewan, Saskatoon, Canada

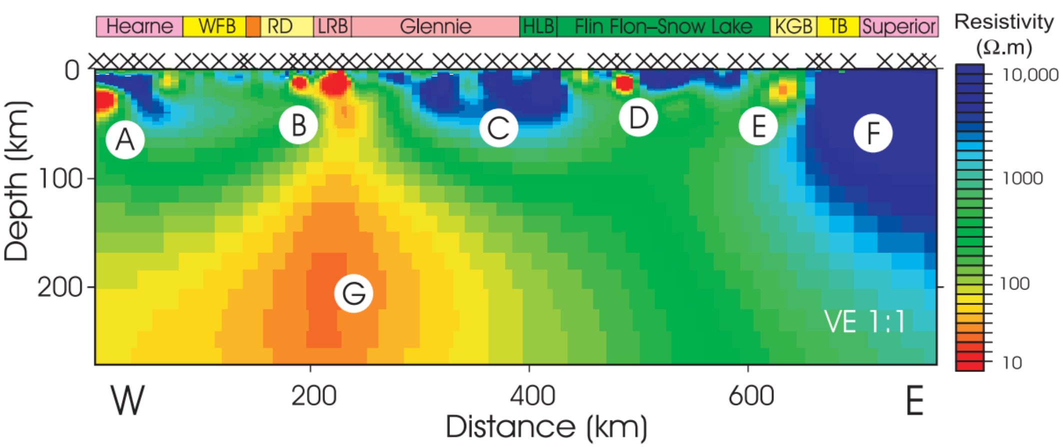
John C. VanDecar
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

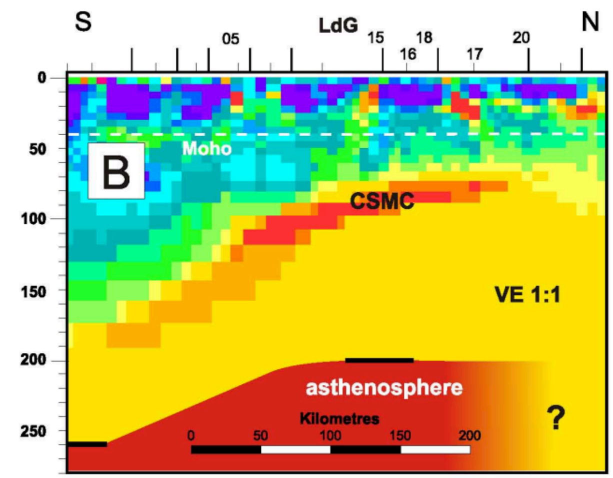
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. B5, PAGES 10,103–10,114, MAY 10, 1998

Along strike from the “G” conductor is one of the world’s largest kimberlite fields, Fort à la Corne (F), plus two others, Sturgeon Lake (S) and Candle Lake (C).
Directly where we note conductor ”G” is a low-velocity zone (1.6% slower)

Mantle conductor G

- Lies directly beneath the crustal expression of the NACP
- Correlates with a low velocity zone
- Along strike from major kimberlite fields
- Correlative in in all three aspects with the mid-lithosphere conductor found in the Slave Craton – Central Slave Mantle Conductor (CSMC)
- Looks very like the “fingers of God” images from Australia
    - Pathways for mantle fluids into the crust?
    - But this mantle fluids interpretation is a very different interpretation that my tectonic/metamorphic one





Conclusions to the mantle story

- NACP has a deep lithospheric mantle expression that spatially correlates with the surface expression of the internides of the THO
- Process that occurred 1.85 Ga yr ago has left a geophysical marker (high conductivity, low velocity) in the lithospheric mantle that can be imaged today using long period MT
- Alternatively, the anomalies are recent (Fort-a-la-Corne 104-95 Ma) – kimberlitic magmas left residue from C-O-H fluids during ascent
- This is an excellent example of the “Mineral System mapping paradigm”

- The story is not over!!! We still need to understand conductivity anomaly formation in the crust and in the lithospheric mantle

Acknowledgements

I wish to acknowledge the many colleagues who have been with me on this journey to understand the NACP and its relationship to the THO

Those include in MT:
Juanjo Ledo (all), Ian Ferguson (L, X), Jim Craven (M, N), Xavier Garcia (X), Shane Evans (Baffin), John Booker (NOD)

I also acknowledge the giants on whose shoulders I have stood:
General: Rosemary Hutton
NACP: Ian Gough, Adrian Camfield