Geological Survey of Canada

CURRENT RESEARCH
2001-E6

Conductivity of western Superior Province upper mantle in northwestern Ontario

J.A. Craven, R.D. Kurtz, D.E. Boerner, T. Skulski, J. Spratt, I.J. Ferguson, X. Wu, and R.C. Bailey

Natural Resources Canada
Ressources naturelles Canada
Canada

Available in Canada from the
Geological Survey of Canada Bookstore website at:
http://www.nrcan.gc.ca/gsc/bookstore (Toll-free: 1-888-252-4301)

A copy of this publication is also available for reference by depository libraries across Canada through access to the Depository Services Program's website at http://dsp-psd.pwgsc.gc.ca

Price subject to change without notice

Conductivity of western Superior Province upper mantle in northwestern Ontario

J.A. Craven, R.D. Kurtz, D.E. Boerner, T. Skulski, J. Spratt, I.J. Ferguson[1], X. Wu[1], and R.C. Bailey[2]
Continental Geoscience Division, Ottawa

[1] Department of Geological Sciences
University of Manitoba
233 Wallace Building
Winnipeg, Manitoba R3T 2N2

[2] Department of Physics
University of Toronto
60 St. George Street
Toronto, Ontario M5W 1A7

Craven, J.A., Kurtz, R.D., Boerner, D.E., Skulski, T., Spratt, J., Ferguson, I.J., Wu, X., and Bailey, R.C., 2001: Conductivity of western Superior Province upper mantle in northwestern Ontario; Geological Survey of Canada, Current Research 2001-E6, 10 p.

Abstract

Magnetotelluric (MT) measurements at the Earth's surface are sensitive to charge carriers that may be introduced into an insulating crystalline lithosphere due to active or ancient tectonomagmatic processes operating within the crust and upper mantle. During 1998 and 2000, MT data were acquired within the western Superior LITHOPROBE and NATMAP study area to image conductive lithospheric structures that may be associated with Archean accretionary tectonics. The MT responses observed on either side of the 3 Ga North Caribou terrane are aligned subparallel to ca. 2.7 Ga transpressional zones. An initial 3-D model that reproduces the observed MT data within, and south of the North Caribou terrane locates the conductive structures within the uppermost mantle. We suggest that this upper mantle conductivity aligned subparallel to major zones of transpression, is the residue of partial melting related to syn- to late-Kenoran magmatism and deformation.

Résumé

Les mesures magnétotelluriques faites à la surface de la Terre sont sensibles à la présence de porteurs de charge qui pourraient s'être mis en place dans la lithosphère cristalline isolante à la faveur de processus tectonomagmatiques se déroulant, ou s'étant déroulés, dans l'écorce terrestre et le manteau supérieur. Au cours de 1998 et 2000, des données magnétotelluriques ont été recueillies dans l'ouest de la Province du lac Supérieur, dans la région d'étude de projets des programmes CARTNAT et LITHOPROBE, afin de se représenter graphiquement les structures conductrices de la lithosphère qui sont susceptibles d'être associées à la tectonique accrétionnaire de l'Archéen. Les signaux magnétotelluriques obtenus de part et d'autre du terrain de North Caribou, dont l'origine se situe à 3 Ga, sont alignées presque parallèlement aux zones de transpression remontant à environ 2,7 Ga. Un premier modèle tridimensionnel qui reproduit les données magnétotelluriques observées dans le terrain de North Caribou et au sud de celui-ci, situe les structures conductrices dans la partie sommitale du manteau. Nous émettons l'hypothèse que ces structures conductrices du manteau supérieur, dont l'alignement est presque parallèle aux principales zones de transpression, témoignent de reliquats de la fusion partielle associée à l'activité magmatique et à la déformation qui ont pris place durant l'orogenèse kénoréenne et peu de temps après.

INTRODUCTION

Archean cratons are important economic considerations because, while comprising a relatively small fraction of the exposed crust of the world, they contain a disproportionate amount of the world's mineral wealth. Recently, the Canadian Shield has become a focus for diamond exploration activities as diamonds are thought to be scavenged from thick cratonic roots by ascending kimberlite magmas. With only minor conductivity structures in the upper crust (Boerner et al., 2000), Archean cratons provide an ideal window for deep electromagnetic studies to look into the subcratonic lithosphere. Deep probing electromagnetic techniques such as magnetotellurics (MT) are inexpensive means of investigating the deep conductivity structure of cratons as the oscillations in the Earth's natural magnetic field are sufficiently powerful to penetrate the lithosphere and beyond. The Superior Province lithosphere is thought to preserve features that may be relicts of ancient tectonic processes akin to modern subduction and accretionary processes. The primary goals of our work are to test for links between surficial geology and mantle structure and to provide insight into their causative tectonomagmatic processes.

Data at 38 magnetotelluric regional sites (squares in **Fig. 1**), were acquired in August and September of 2000 by Geosystems Canada under a contract with LITHOPROBE and Public Works and Government Services Canada. An additional three MT sites were collected along an audio-magnetotelluric (AMT) profile across the Fox River Belt to study the utility of MT to image steeply dipping structures beneath the thick overburden. Alongside the contract work, the GSC collected MT data at five sites along the road north of Red Lake. Delivery of contract data occurred mid-December 2000, and the data have been merged with the existing long-period data collected during 1997 and 1998 (circles, Fig. 1) and discussed in Craven et al. (1999). This paper discusses a preliminary 3-D model for upper mantle electrical structure of the LITHOPROBE and NATMAP western Superior transect area. The report also speculates on the nature of the deep conductivity in the upper mantle as the residue of partial melting related to syn- to late-Kenoran magmatism and deformation.

PRELIMINARY DATA ANALYSIS

Electrical strike directions at a period corresponding to a depth of investigation deep within the lithosphere are illustrated as lines at each site in Figure 1 and demonstrate the local preferred 2-D direction of current flow. There is a clear change in the dominantly east-west strike directions south of the North Caribou terrane (NCT, Fig. 1) to an azimuth of about 120° north of the terrane. The implication of the bimodal strike direction population is that the data and lithosphere are, regionally, 3-D. Perhaps the most striking feature of **Figure 1** is the subparallel alignment of the electrical strike directions with the major syn- and post-Kenoran zones of transpression on either side of the North Caribou terrane. The finer strike-direction lines in Figure 1 indicate stations for which the upper mantle can be represented by a weakly defined strike direction and therefore define a region where the lithosphere is predominantly 1-D or layered. This 1-D region closely approximates the area of the North Caribou terrane outlined in Figure 1. Strike directions determined in the southwest portion of the survey area are complex and are discussed in more detail elsewhere (Ferguson et al., in press).

A 3-D regional model has been constructed to quantify the electrical structure in the lithosphere as determined by the MT data. The new model will be three-dimensional as the data have a bimodal strike direction. Three-dimensional models generally consist of more model parameters than data and therefore represent a vastly underdetermined problem. Constraints on the initial forward model were imposed from electrical information pertaining to the Superior Province lithosphere determined from earlier LITHOPROBE transects. The model of Kellett et al. (1992) crosses the Pontiac Subprovince and portions of Superior lithosphere buried beneath the Grenville Orogen. A key feature of the Kellett et al. (1992) model is an anisotropic layer at depths between 29 km and 100 km that is sandwiched between a resistive upper crust and conductive upper mantle. The current model, based on features present in our early regularized 2-D models (Craven et al., 1999) and on models based on the broadband MT coverage from the Abitibi–Grenville transect, is shown in perspective (**Fig. 2**) and plan (**Fig. 3**) views.

The model in Figures 2 and 3 does not include any electrical structure northeast of the 5000 Ω•m wedge, nor features apparent in 2-D models of southeastern Manitoba. The 3-D model provides a coherent framework for future constrained 2-D inversions. The model does incorporate structure required to reproduce the LiMS (Long Period Intelligent Magnetotelluric System) data collected during 1997 and

1998 in the southern and central portion of the transect. In particular, the 3-D model has a long period phase and vertical field response that is in good agreement with the data. The model contains a resistive 5000 Ω•m upper crust to 13 km depth. Resistivities between depths of 13 km and 40 km in the southern portion of the model are 200 Ω•m. To the north, this 200 Ω•m feature is absent. In its stead, the surficial 5000 Ω•m crystalline material appears to continue as a wedge to a depth of 100 km. The spatial extent, especially to the north, of the wedge is, as yet, poorly defined ('?' in **Fig. 3**). The two dominant conductive features in the model, numbered 1 and 2 in **Figure 2**, are a sub-Moho anisotropic region, modelled here as a region of east-trending, alternating 20 Ω•m and 1000 Ω•m material, at depths between 40 km and 100 km and south of the Uchi–North Caribou terrane contact; and a 20 Ω•m conductive layer commencing at 100 km depth.

PRELIMINARY INTERPRETATION

Graphite-based conductors are an attractive explanation for features 1 and 2. Given our understanding of the conductivity of olivine from laboratory studies, features 1 and 2 are too conductive for an olivine-dominant mantle. The observation of 20 Ω•m material within continental upper mantle requires olivine water contents of the order 1000 $H/10^6Si$ (Hirth et al., 2000). Such an amount of water may be tenable at sub-Moho depths if the olivine a-axis is strongly aligned within a region; however, the conductive strike directions observed here are consistently oblique to the teleseismic fast directions (Kay et al., 1999) and the preference of water to partition into hydrous phases and pyroxene by a factor of 10 over olivine make hydrogen less likely to be the dominant upper mantle charge carrier (Constable, 1993). Partial melting commonly enhances the conductivity at depth due to the high mobility of charge carriers within a melt fraction; however, it is unlikely such a shallow partial melt zone exists as heat flow at the surface of the Superior Province is low (Jaupart and Marceschal, 1999). Electrically, graphite behaves as a metal and therefore has a low resistivity. Interconnected graphite has been observed in upper mantle xenoliths (H. Helmsteadt, pers comm., 2001) and is an accessory phase in xenoliths observed worldwide (Pearson et al., 1994).

The conductive layer at 100 km depth may be Superior Province-wide, based on the existence of this layer in both the model of Kellett et al. (1992) and the low apparent resistivities at long periods in both the existing data set (Craven et al., 1999) and in the recent data set acquired by Geosystems Canada. The Kellet et al. (1992) model suggests the anisotropic and deep conductive features are connected electrically and therefore also genetically. Should further modelling reveal topography on the top of this feature at 100 km depth that can be related to geological features or processes, then it may be possible to determine the origin of this layer. The shallow conductive features at approximately 40 km depth are aligned subparallel to the major zones of syn- and post-2.7 Ga transpression within the transect area. Direct examples of the link between the syn- to late tectonic transpression and the electromagnetic response can be demonstrated in at least three areas. For example, in the Stull Lake area of the northwestern Superior Province, the electromagnetic strike direction is closely aligned to the Wolf Bay–Stull–Wumumman and Kenyon (Fig. 1) dextral shear zones (Skulski et al., 2000). Weak 2-D strike directions are subparallel the Favourable Lake shear zone. Electrical strike directions are also demonstrably subparallel the Quetico fault zone. These strike directions are related to electrical conductors in the lithosphere and we suggest the conductors that are aligned with syn- and late tectonic deformation are related to other syn- and late-orogenic processes; perhaps the most pervasive of which is magmatism. Many types of syn- and late-orogenic magmatism occur in the Superior Province. Superior Province magmatic suites evolve from calc-alkaline basalt to sanukitoid and develop into nephelinite syenite and rare carbonatite (Stevenson et al., 1999). Late lamprophyre also occurs at a variety of locations across the Superior Province. The link between transpression and magmatism is perhaps best made through the syntectonic alkali volcanic rocks that are closely aligned with strike-slip faulting in the

Temiskaming-style basins. These pull-apart basins occurred in a variety of locations across the Superior Province between 2705 Ma and 2674 Ma (Thurston and Chivers, 1990; Wyman and Kerrich, 1993), including the Stull Lake area (Skulski et al., 2000). The presence of alkali basalt suggests these faults penetrate to upper mantle depths (Stevenson et al., 1999). Stevenson et al. (1999) also note that a number of the sanukitoid suites (Stern et al., 1989), e.g. Otto Stock, Burchell Lake Pluton, are spatially associated with this style of Archean basin.

A possible link between the EM data and magmatism can be demonstrated with simple melting relationships. **Figure 4** is a plot of the pyrolite melting curves with both C-H fluids present and absent at a depth of 70 km (Green and Falloon, 1998). The solidus is clearly depressed in the case of fluid present melting and, provided the oxygen fugacity is within approximately two log units of the iron-wüstite (IW) buffer, graphite, garnet, and amphibole can be major phases present in the residue. Fugacity values within a few log units of the IW buffer have recently been demonstrated for large regions of the Kapvaal craton (Woodland, 2001) and at a depth range of approximately 80–100 km based on equilibrium pressure and temperature estimates. The residual phases near the IW buffer shown in Figure 4 have notable geophysical properties and are possible sources of spatially correlated geophysical and geochemical anomalies preserved at depths of 50–100 km or more within a cratonic root. In the Superior Province, the graphite in the residue from syn- to post-tectonic partial melting may have been deposited along the (weak) fault zones and may therefore be the source of the link we observe between the EM data and major zones of transpression.

Reduction and geochemical depletion are coupled processes as Fe^{+3} is generally incompatible during partial melting. Magnetotelluric measurements may therefore offer a view of regions where ancient C-H fluid-present partial melting occurred under reducing or depleted conditions. This view can be tested with xenolith information and deep seismic data as the partial melt model predicts that conductivity can be associated with major garnet in the residue. This interpretation also provides a new tool for geoscientists correlating the geochemical stratigraphy with the electrical stratigraphy. The regional conductivity structure coupled with the linkage to geochemical stratigraphy will provide an enhanced 3-D image of the lithosphere. Our goal is an increase in our understanding of the genesis of the Superior Province related to major magmatic and deformational events through better maps of the deep interior of the craton.

FUTURE RESEARCH

Future work within this project will focus on at least three areas: developing and improving the 3-D model for the entire region, including delineating the geometry of the 1-D region and conductors to the north; using the 3-D model as a foundation for detailed 2-D inversion of selected lines and incorporating major features from the 2-D lines into the 3-D model; and applying reduced C-H fluid present partial melting at depth as a potential explanation for syn-, late, and post-tectonic magmatic suites of the Superior Province, such as alkali basalt, Temiskaming style volcanism, sanukitoid, carbonatite, and, perhaps, kimberlites.

ACKNOWLEDGMENTS

We gratefully acknowledge the logistical and financial support of Falconbridge Ltd., Kennecott Canada Exploration, and deBeers Canada Exploration Inc.

REFERENCES

Boerner, D.E., Kurtz, R.D., and Craven J.A.
2000: A summary of electromagnetic studies on the Abitibi-Grenville Transect; Canadian Journal of Earth Sciences, v. 37, p. 427–437.

Constable, S.C.
1993: Conduction by mantle hydrogen; Nature, v. 363, p. 704.

Craven, J.A., Boerner, D.E, Kurtz, R.D., Ferguson, I.J., and Bailey, R.C.
1999: Preliminary results from the 1998 EM survey along the Western Superior Transect; *in* Western Superior Transect Fifth Annual Workshop; LITHOPROBE Report #70, (ed.) R.M. Harrap and H.H. Helmstaedt; LITHOPROBE Secretariat, University of British Columbia, p. 23–25.

Ferguson, I.J., Craven, J.A., Wu, X., Norton, M., and Wennberg, G.
in press: Review and two-dimensional modelling of magnetotelluric data from Manitoba and Western Ontario on the LITHOPROBE Western Superior Transect; *in* Western Superior Transect Annual Workshop; LITHOPROBE Report, (ed.) R.M. Harrap and H.H. Helmstaedt; LITHOPROBE Secretariat, University of British Columbia.

Green, D.H. and Falloon, T.J.
1998: Pyrolite: A Ringwood concept and its current expression; *in* The Earth's Mantle: Composition, Structure, and Evolution, (ed.) I. Jackson; Cambridge University Press, Cambridge, United Kingdom, p. 311–380.

Hirth, G., Evans, R.L., and Chave, A.D.
2000: Comparison of continental and oceanic mantle electrical conductivity: is the Archean lithosphere dry?; Geochemistry Geophysics Geosystems, v. 1, paper number 2000GC000048 (electronic journal).

Jaupart, C. and Mareschal, J.C.
1999: The thermal structure and thickness of continental roots; Lithos, v. 48, p. 93–114.

Kay, I., Sol, S., Kendall, J.M., Thomson, C., White, D., Asudeh, I., Roberts, B., and Francis, D.
1999: Shear wave splitting observations in the Archean Craton of western Superior; Geophysical Research Letters, v. 26, p. 2669–2672.

Kellett, R.L., Mareschal, M., and Kurtz, R.D.
1992: A model of lower crustal electrical anisotropy for the Pontiac subprovince of the Canadian Shield; Geophysical Journal International, v. 111, p. 141–150.

Pearson, D.G., Boyd, F.R., Haggerty, S.E., Pasteris, J.D., Field, S.W., Nixon, P.H., and Pokhilenko, N.P.
1994: The characterisation and origin of graphite in cratonic lithospheric mantle: a petrological carbon isotope and Raman spectroscopic study; Contributions to Mineralogy and Petrology, v. 115, p. 449–466.

Skulski, T., Corkery, M.T., Stone, D., Whalen, J.B., and Stern, R.A.
2000: Geological and geochronological investigations in the Stull Lake-Edmund Lake greenstone belt and granitoid rocks of the northwestern Superior Province; *in* Report of Activities 2000, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 117–128.

Stern, R.A., Hanson, G.N., and Shirey, S.B.
1989: Petrogenesis of mantle-derived, LILE-enriched Archean monzodiorites and trachyandesites (sanukitoids) in southwestern Superior Province; Canadian Journal of Earth Sciences, v. 26, p. 1688–1712.

Stevenson, R., Henry, P., and Graiépy, C.
1999: Assimilation-fractional crystallization origin of Archean sanukitoid suites: Western Superior Province, Canada; Precambrian Research, v. 96, p. 83–99.

Thurston, P.C. and Chivers, K.M.
1990: Secular variation in greenstone sequence development emphasizing Superior Province, Canada; Precambrian Research, v. 21, p. 21–58.

Woodland, A.
2001: Ferric-ferrous iron in mantle minerals from South African and Lesotho xenoliths: changing oxygen fugacity with depth; *in* European Union of Geosciences; EUG 11, Strasbourg, France, Conference Abstracts, Cambridge Publications, Cambridge, United Kingdom, p. 416.

Wyman, D. and Kerrich, R.
1993: Archean shoshonitic lamprophyres of the Abitibi Subprovince, Canada: Petrogenesis, age and tectonic setting; Journal of Petrology, v. 34, p. 1067–1109.

Geological Survey of Canada Project 870046

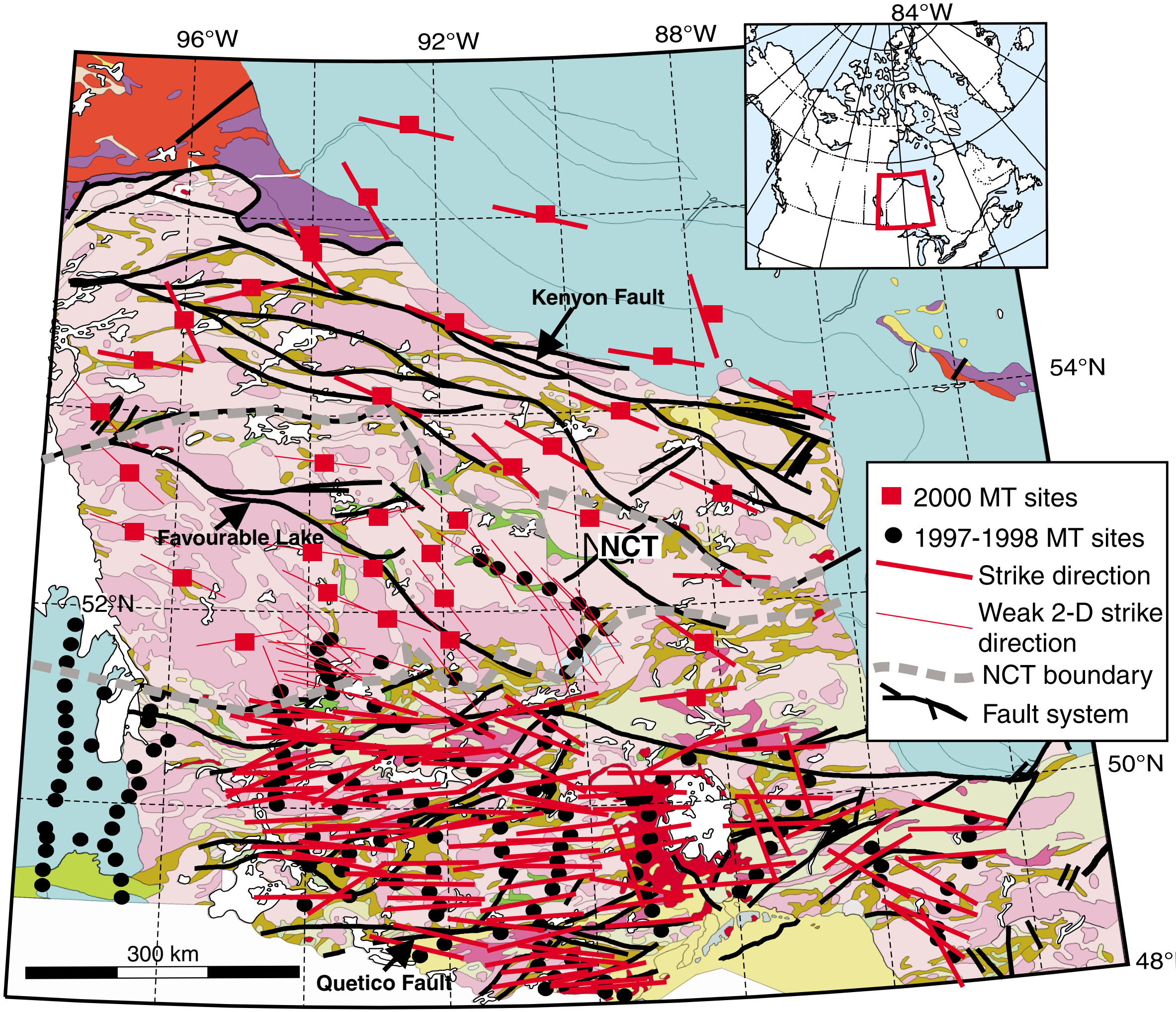

Figure 1. Site locations and 2-D strike directions. A weakly 2-D or approximately 1-D region falls withing the boundaries of the North Caribou terrane (NCT).

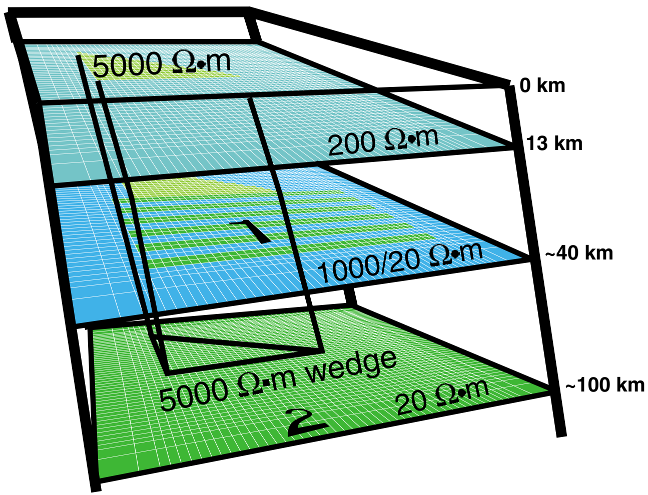

Figure 2. Three-dimensional forward model, perspective view. Features 1 and 2 from the text are identified.

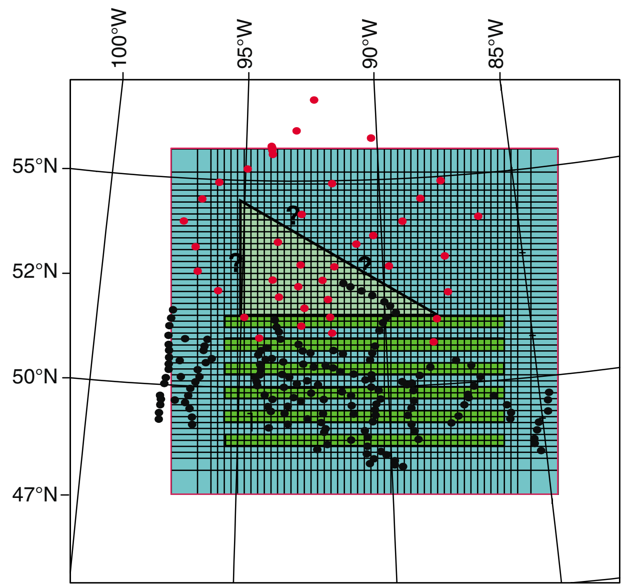

Figure 3. Plan view of the 3-D model at 40 km depth. The top of the anisotropic region (number 1, Fig. 2) is evident. Also shown is the wedge of resistive material located to the north of the anisotropic region.

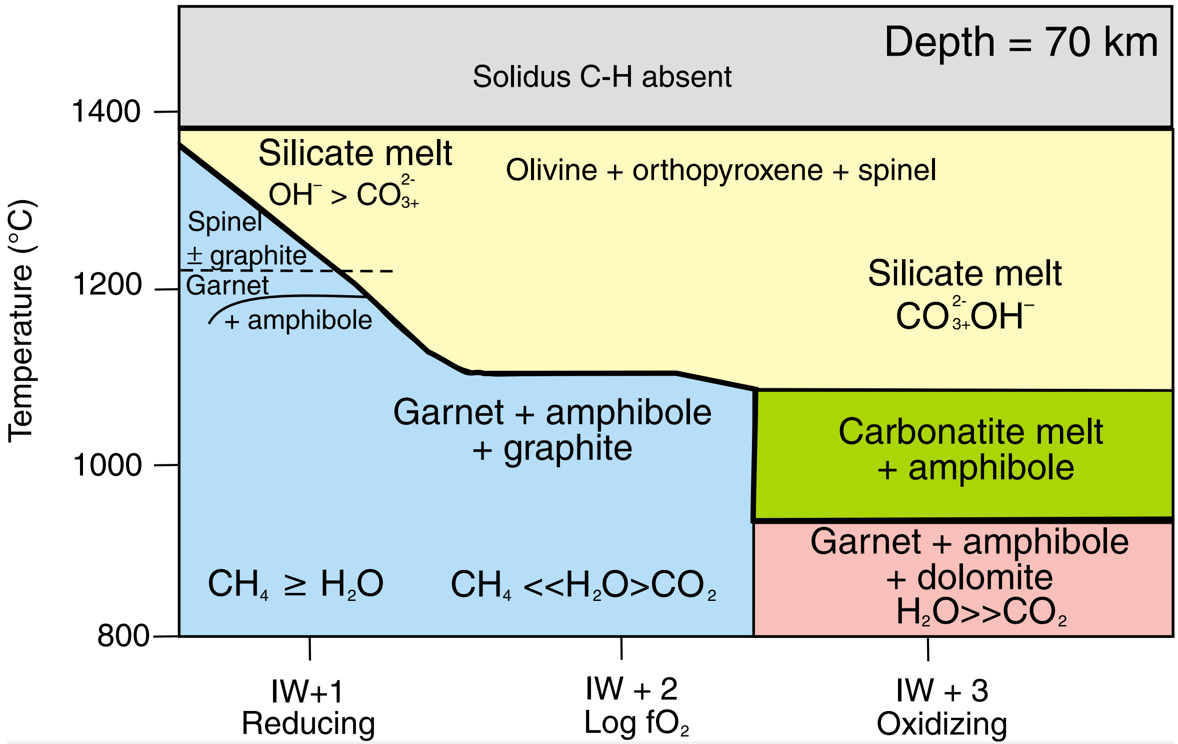

Figure 4. Fluid-absent and fluid-present melting of pyrolite at 70 km depth. Solidus lines are shown with thick black lines (*after* Green and Falloon, 1998).