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On a Type Classification of Lower Crustal Layers Under Precambrian Regions

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Abstract. Various parameters pertinent to the lower crustal layer under Precambrian regions are listed for locations where seismic, and geomagnetic or geoelectric, studies have been undertaken. The parameters define three distinct types of lower crustal layer with certain dominant characteristics: Type I – "Normal" – typical continental seismic parameters and a high electrical resistivity (10^3–10^4 Ωm); Type II – "Intermediate" – high compressional wave velocity (either fixed V_p=7.0 km s^{-1} or transitional V_p= 6.7→7.3 km s^{-1}) and a moderate resistivity (100–300 Ωm); Type III – "Low" – a low shear wave velocity layer (LV_sL), high Poisson's ratio (> 0.30) and low electrical resistivity (10–50 Ωm). Possible conditions and rock types, existing at the P–T environment of the lower crust and which could account for the observations, are suggested. The zoning of Canada into types implies that Type II layers are shield "edge" effects, and that inability to observe what is regarded as the final stage of development of a shield region under certain shields may be due to their being too small.

Key words: Precambrian regions – Crustal structure – Electromagnetic induction studies – Seismic studies

Introduction

Various seismic and electrical studies over Precambrian regions of the world have been able in the past to detail some of the parameters of the lower crustal layers, e.g., compressional wave velocity (V_p), shear wave velocity (V_s), density (ρ), Poisson's ratio (σ) from multi-method seismic studies, and electrical resistivity (R – the normal symbol for electrical resistivity ρ is not used to avoid confusion with density) from geoelectric and geomagnetic methods. However, confusion is often apparent in the literature as to why certain features are found in some parts of the world, but not in others. This confusion is perhaps highlighted by Kovtun (1976) who states, with reference to geomagnetic studies, that "at present, we have almost no results on which a study of the 'normal' distribution of conductivity vs depth in Precambrian shields could be based"

It is with these points in mind, that the author has attempted a broad classification of lower crustal Precambrian layers into three types. In the following section, each of these types will be described in turn and examples of their locations will be specified. The locations and their corresponding data sets, both seismic and geoelectric, were chosen for the following reasons:

(i) all come from stable regions of low seismicity and heat flow,
(ii) the data sets have all been thoroughly scrutinized by the groups involved, and
(iii) the information is readily available.

Finally, possible candidates for the rocks at lower crustal depths causing the various observed responses are suggested.

Classification

Type I – "Normal"

The prime example of a Type I lower crustal layer is that observed in the centre of the Canadian shield. Seismic models presented by Wickens and Buchbinder (1980), based on surface waves (Wickens 1971) and refraction information (Mereu and Hunter 1969), Hall and Hajnal (1973), and Green et al. (1980), representative of middle and northern Manitoba, are illustrated in Fig. 1 a, and their estimated parameters for the lower crustal layer are detailed in Table 1. The model of Wickens and Buchbinder (1980) was shown by them to be consistent with the S-wave residuals observed in the central shield region.

A transient electromagnetic sounding investigation undertaken by Jacobson (1969; reported in Keller 1971) in Manitoba inferred that there must exist a layer of uniform resistivity, of $R \simeq 2{,}000$ Ωm, to depths greater than 20 km, whilst magnetotelluric (MT) investigations by three groups in Alberta (Srivastava and Jacobs 1964; Vozoff and Ellis 1966; Reddy and Rankin 1971) all infer resistivities for this layer of 10^3–10^4 Ωm.

It appears that the Ukrainian shield also falls into this Type I category. Models P2 and P3 of Jentsch (1979) display a lower crustal layer with V_p=6.2–6.4 km s^{-1} (the very thin transitional layer between 32.5–33.4 km depth, of velocity increase from 6.8 to 7.6 km s^{-1} can be ignored for this comparison), and the data from the majority of magnetotelluric stations recorded by Tkachev (1973; reported in Kovtun 1976) display apparent resistivities of greater than 10^3 Ωm over the period range 1–10^3 s. Such values require a highly resistive crust, i.e., resistivity greater than about 4,000 Ωm.

The heat flow observed on the Canadian shield is, on average, 39 mW m^{-2} (Rao and Jessop 1975), i.e., 0.93 HFU, whilst on the Ukranian shield values of 25–35 mW m^{-2} (Kutas et al. 1979), i.e., 0.60–0.84 HFU, are reported.

Type II – "Intermediate"

The three main examples of a Type II lower crust are to be found in northern Scotland, eastern Canada, and northern Sweden. No heat flow estimates are available for northern Scotland (Bloomer

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Table 1. Lower crustal parameters as inferred by the investigations reported in the text

Type	Code	Area	Parameters V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})	σ	R (Ωm)	Reference
I	W	Central Canadian shield	6.6	3.8		0.252[a]		Wickens and Buchbinder (1980)
	G		6.55					Green et al. (1980)
	HA		6.85	4.0		0.241[a]		Hall and Hajnal (1973)
	JA	Manitoba					2,000	Jacobson (1969)
	SR	Alberta					940	Srivastava and Jacobs (1964)
	R	Alberta					3,500	Reddy and Rankin (1971)
	VO	Alberta					10,000	Vozoff and Ellis (1966)
	JE	Ukrainian shield	6.4					Jentsch (1979)
	T						>4,000	Tkachev (1973)
II	BA	Northern Scotland	7.0					Bamford et al. (1978)
	A			4.04[a]		0.249		Assumpção and Bamford (1978)
	H						100–300	Hutton et al. (1980, 1981)
	O	Southern Superior Province	7.0–7.2					O'Brien (1968)
	ST						50–1,500	Sternberg (1979)
	B1	Eastern Superior Province	6.7→7.1					Berry and Fuchs (1973)
	HA	Southwestern Superior Province	7.1 ±0.04					Hall and Hajnal (1973)
	G	Southern Churchill Province	7.1, 7.2					Green et al. (1980)
	B2	Northern Grenville Province	6.7→7.5					Berry and Fuchs (1973)
	KU	Grenville Province					200	Kurtz and Garland (1976)
	D	Superior Province					270	Duncan et al. (1980)
	JO	Southeastern Grenville Province	7.14	4.11	3.11	0.25		Jordan and Frazer (1975)
		Northern Sweden	6.75→7.15					Hirschleber et al. (1975)
			~7					Lund (1970)
	J						140–450	Jones (1981)
		Southern Norway	7.17					Massé and Alexander (1974)
III	BL	Southeastern Africa	6.8	3.75–3.85	2.95	0.28[a]		Block et al. (1969)
	V						10–50	van Zijl (1977)
	B						50	Blohm et al. (1977)
	JO	Southeastern Grenville Province	>6.8	3.4	3.11	>0.30		Jordan and Frazer (1975)
	C						10–30	Connerney et al. (1980), Connerney and Kuckes (1980)

[a] denotes a calculated value assuming perfect elasticity on the rock

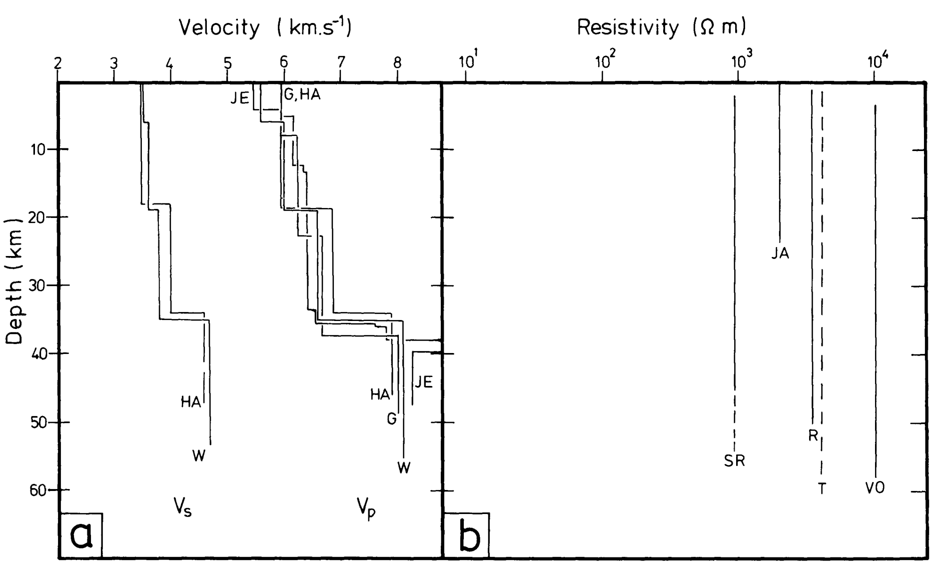

Fig. 1. a Seismic profiles as determined by several investigations over Type I lower crustal layers (for key see Table 1). **b** Resistivity profiles for the same locations as in **a**, dashed lines denote minimum values

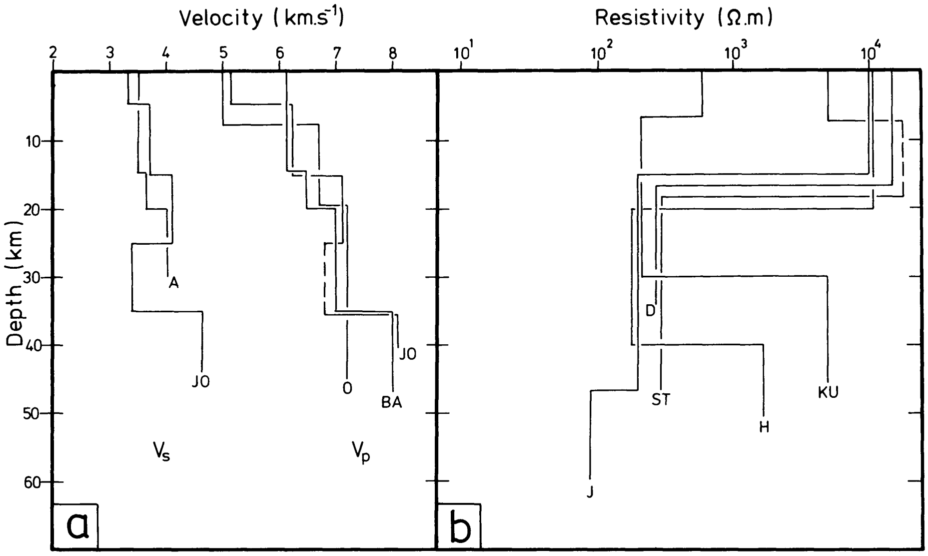

Fig. 2. a, b as Fig. 1 but for investigations over Type II lower crustal layers

et al. 1979), but in eastern Canada values of 40–50 mW m^{-2} (1.0–1.25 HFU) are most commonly observed (Lachenbruch and Sass 1977), and in northern Sweden 38–47 mW m^{-2} (0.91–1.12 HFU) are reported (Eriksson and Malmquist 1979).

In northern Scotland there exists between the Highland Boundary Fault and the Great Glen Fault a lower crustal layer with $V_p = 7.0$ km s^{-1} (Bamford et al. 1978) and $\sigma = 0.249$ (Assumpção and Bamford 1978), giving a calculated $V_s = 4.04$ km s^{-1}, which corresponds with a layer of electrical resistivity $R = 100$–300 Ωm (Hutton et al. 1980, 1981). The original seismic interpretation of this layer was of a velocity gradient layer from 6.7 to 7.3 km s^{-1} (Bamford et al. 1976), but such a layer was later found not to be consistent with ray-tracing and a uniform layer of 7.0 km s^{-1} was found to be most effective (Bamford et al. 1978).

In eastern Canada, various seismic and geomagnetic studies have been carried out. In southern Superior Privince, O'Brien (1968) reported a zone with $V_p = 7.0$–7.2 km s^{-1} at a depth of 19.5 km for stations on the north eastern side of Lake Superior, whilst Berry and Fuchs (1973; reproduced in Berry and Mair 1977) interpret their data as inferring a velocity gradient layer with $V_p = 6.7 \rightarrow 7.5$ km s^{-1} between 27–40 km depth. This layer correlates with a geoelectric layer of 270 Ωm, the top of which deepens from 19 km in the south-west to 29 km in the north-east, defined by Duncan et al. (1980) for the region around Timmins, and with a layer of $R = 50$–$1{,}500$ Ωm for Wisconsin found by Sternberg (1979).

In Grenville Province, Berry and Fuchs (1973) find another velocity gradient layer with $V_p = 6.7 \rightarrow 7.1$ km s^{-1} between 22–40 km, whilst Jordan and Frazer (1975) report a layer between 15–25 km with $V_p = 7.14$ km s^{-1} and $V_s = 4.11$ km s^{-1}. The 2-dimensional geoelectric model for eastern Canada presented by Kurtz and Garland (1976) has a uniform crust under Grenville Province of $R = 200$ Ωm.

In northern Sweden, the best fitting gradient model to the "Blue Road" seismic data includes a layer with V_p increasing from 6.5 km s^{-1} at 20 km depth to $V_p = 7.15$ km s^{-1} at 42 km depth (Hirschleber et al. 1975). Values of around 7 km s^{-1} for the bottom crustal layer were confirmed in a more sophisticated analysis of the data by Lund (1979). Monte-Carlo inversion (Jones and Hutton 1979) of the geomagnetic response function observed at Kiruna (Jones 1980), with the constraints that i) the top layer have a resistance of 10^4 Ωm (Westerlund 1972) and ii) that the second interface be at 46 km, to correspond with the latest values of Moho depth (Bungum et al. 1980), yielded a lower crustal layer of $R = 140$–450 Ωm (Jones 1981).

Type III – "Low"

The two examples for a Type III lower crustal layer are from the Adirondacks, New York State, and the southeastern African shield region.

In the Adirondacks, a joint controlled-source and horizontal spatial gradient (HSG) investigation by Connerney et al. (1980) and Connerney and Kuckes (1980) determined a zone of low electrical resistivity (L*R*L – low resistivity layer) of $R = 10$–30 Ωm at a depth of 25–34 km. This is exactly the depth at which Jordan and Frazer (1975) interpret a shear wave low velocity layer (LV_sL) from S_p phases for stations mostly situated close to Ottawa. The studies of Jordan and Frazer inferred that the layer must have a *minimum* Poisson's ratio of $\sigma = 0.30$, hence the value of the compressional wave velocity for the layer $V_p = 6.80$ km s^{-1} is to be regarded as a minimum. Thus, the existence of a compresssional wave low velocity layer (LV_pL) is not proven, but the existence of an LV_sL has been confirmed by Wickens and Buchbinder (1980).

Two geoelectric studies on southern African cratons inferred L*R*Ls. These were on the Kaapvaal craton (van Zijl 1977) and the Zimbabwe (formerly Rhodesian) craton (Blohm et al. 1977). Data from the Limpopo mobile belt also were explained in terms of an L*R*L, but heat flow estimates on mobile belts have been observed to be anomalously high when compared with cratonic terrains (Carte and van Rooyen 1969) hence the model is not included here. Bloch et al. (1969), in an analysis of surface waves observed by an array of seismometers centered on Johannesburg, infer from their data the existence of two LV_sLs, one at 12 km and the other at 24 km (Fig. 3a). The depth of the deeper LV_sL corresponds exactly to the depth of the L*R*L as interpreted by Blohm et al. (1977), and the L*R*L under the Limpopo mobile belt (van Zijl 1977). It may be significant that the model of Bloch et al. (1969) does not display an LV_pL.

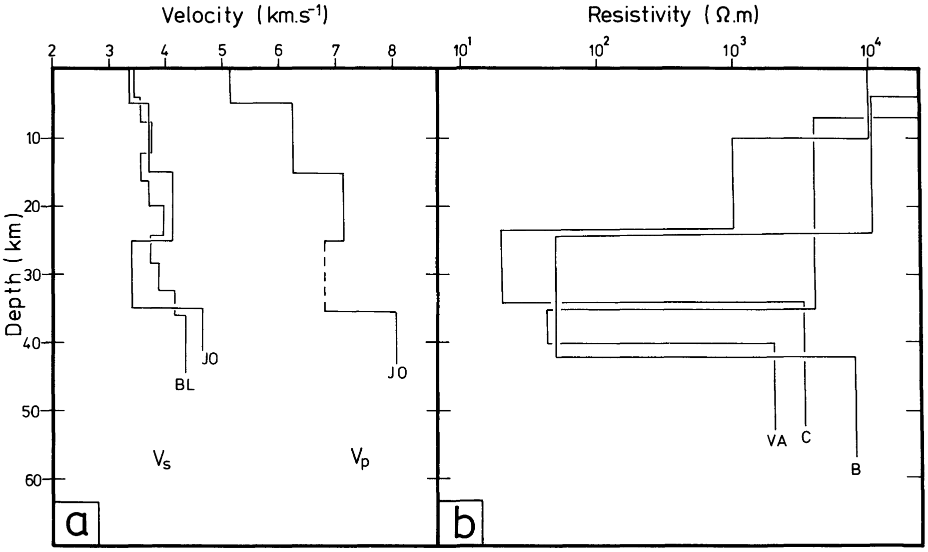

Fig. 3. a, b as Fig. 1 but for investigations over Type III lower crustal layers

Discussion

The notable characteristics of the three types classified are:

a) Type I – Normal

- typical continental V_p, V_s and σ values
- highly resistive, i.e., greater than 10^3 Ωm.

b) Type II – Intermediate

- V_p of around 7.0 km s^{-1}, either fixed (northern Scotland) or transitional from 6.7→7.2 km s^{-1} (eastern Canada, northern Sweden)
- typical σ values of around 0.25
- moderately resistive, $R = 100$–300 Ωm.

c) Type III – Low

- low shear wave velocity layer (LV_sL), possibly without a corresponding low compressional wave velocity (no LV_pL)
- high Poisson's ratio, of $\sigma > 0.30$
- highly conductive, with $R = 10$–50 Ωm.

The association of LV_pL layers with LRL layers in more tectonic regions has been known since the early 1970's (see, for example, Landisman et al. 1971), even though the existence of both was initially in question (Healy 1971; Porath 1971). Many theories have been proposed to explain these layers, the two most often mentioned being the rôle of water of dehydration escaping into pore spaces (Hyndman and Hyndman 1968), or of hydrated rocks under typical P–T conditions in the lower crust (Landisman et al. 1971; Jordan and Frazer 1975). For Precambrian regions, the former of these is however considered untenable (see later).

At Moho depths under the centre of the Canadian shield (~35 km, Wickens and Buchbinder 1980), the temperature is believed to be in the range 400°–500° C (Rao and Jessop 1975), preferably towards the upper end of this limit (475° C as given by Eq. (5) of Hall 1977), with a pressure of around 10 kbar (9.5 kbar, Eq. (7), Hall 1977). At such P–T and anhydrous conditions, eclogite is the stable mineral assemblage for basalt of quartz tholeiite composition, rather than garnet granulite (Ringwood 1975, p. 25, Figs. 1–6). However, the inferred compressional wave velocities for eclogite under these P–T conditions, of $V_p = 7.8$–8.6 km s^{-1} (Press 1966, Table 9–2; Manghnani et al. 1974; Christensen 1979), require the presence of large amounts of minerals of relatively low V_p, e.g., quartz and alkali feldspars (Ringwood 1975, p. 39). This implies a dioritic rock in the granulite-eclogite facies as a suitable candidate, e.g., quartz diorite, $V_p = 6.71$ km s^{-1}, $V_s = 3.8$ km s^{-1} (Press 1966, Tables 9–2 and 9–3), $\rho = 2.68$–2.96 g cm^{-3} (Daly et al. 1966, Table 4.1). Measurements of electrical conductivity on alkali basalts at 500° C indicate values in the range $R = 10^3$–10^4 Ωm (Bondarenko and Galdin 1972; reported in Haak 1980) whilst Volarovich and Parkhomenko (1976) specify a range of $R = 10^4$–10^5 Ωm for granodiorites, quartz diorites and diorites at this temperature.

The compressional wave velocity for the Type II layer, $V_p = 6.8 \rightarrow 7.2$ km s^{-1}, can be explained by either a garnet granulite in an anhydrous crust, as suggested by Manghnani et al. (1974) and Ringwood (1975, p. 39), or by amphibolites in a hydrous crust (Ringwood 1975, p. 41). Measurements of Poisson's ratio at 10 kbar by Manghnani et al. (1974) on their garnet granulite samples give a mean of $\bar{\sigma} = 0.282 \pm 0.017$ (one standard deviation), which is too large compared with field observations (northern Scotland, $\sigma = 0.249 \pm 0.020$, Assumpção and Bamford 1978; eastern Canada, $\sigma = 0.25$, Jordan and Frazer 1975). Also, the electrical resistivity of the majority of dry rocks expected to be found at lower-crustal depths under Precambrian regions is never below 10^3 Ωm for temperatures less than 500° C (Brace 1971, Fig. 3; Haak 1980), with the notable exception of a Wisconsin gabbro with $R = 650$ Ωm at $T = 500$° C (Housley and Oliver 1977). The effects of increasing the pressure to 10 kbar at this temperature were shown by Volarovich and Parkhomenko (1976) to have little effect on the electrical conductivity, i.e., less than one third an order of magnitude. However, Ringwood (1975, pp. 35–47) believes that gabbro is not stable at the P–T conditions of the lower crust. Seismic evidence appears to confirm this suggestion because although gabbros display compressional wave velocities of the correct order when at 10 kbar ($V_p \sim 7.2$ km s^{-1}, Press 1966, Table 9–2), the effects of temperature will reduce this to $V_p \sim 6.8$ km s^{-1} (Press 1966, Fig. 9–7; Christensen 1979). Also, gabbros do not show sufficiently large shear wave velocities, e.g., $V_s = 3.84$ km s^{-1} (Press 1966, Table 9–4). Thus, having apparently disqualified all suitable rocks that might exist in an anhydrous lower crust, it is necessary to conclude that hydrous conditions prevail

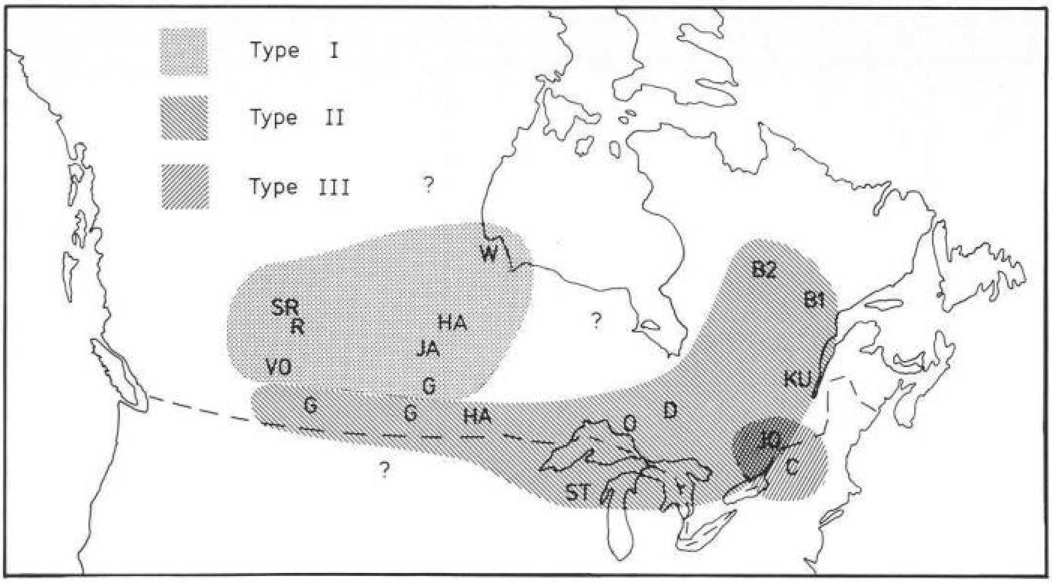

Fig. 4. Sketch map of Canada illustrating the zones of lower crustal layers, letters refer to investigations as reported in the text (see Table 1)

in Type II lower crustal layers. Amphibolites, as suggested by Ringwood (1975, p. 41) as the probable rock at the P–T conditions of a hydrous lower crust, display the correct order of seismic velocities (V_p=7.18–7.22 km s^{-1}, Christensen 1965; V_s= 4.03 km s^{-1}, Christensen 1966) but it is probably necessary to infer a slightly seismically faster epidote amphibolite (V_p=7.67–7.75 km s^{-1}, Christensen 1965) due to the reduction in velocities at temperatures of around 400–500° C (Christensen 1979). Unfortunately, not many measurements of the electrical resistivity of amphibolites at these P–T conditions have been made, but the data of Volarovich and Parkhomenko (1976) illustrate that certain amphibolites display the required resistivity of a few hundreds of Ωm at 500° C.

For the Type III lower crustal layer, Jordan and Frazer (1975), van Zijl (1977), and Connerney et al. (1980) all independently suggested the effects of serpentinisation to explain their data. Jordan and Frazer (1975) observe that a serpentinised peridotite has the high Poisson's ratio required, and van Zijl (1977) and Connerney et al. (1980) both remark that serpentinised rocks display the appropriately low resistivities, of 10–50 Ωm, provided that the water of hydration does not escape (Zablocki 1964; see van Zijl 1977).

An interpretation of the high conductivities observed in Type III crusts in terms of electrolytic conduction is considered untenable by Connerney et al. (1980) because investigations by Richter and Simmons (1977) on Precambrian igneous rocks showed that the majority of the original cracks were healed or sealed by secondary minerals. However, the somewhat speculative models presented by Dewey (1969a) and Ringwood (1975, p. 298–304) for the development of a Benioff zone require, as a passive initial state, a thick accumulation of sediments, the prime example of which is the non-volcanic margin of the spreading Atlantic Ocean (Drake et al. 1959). Assuming that the east coast of North America represents such an initial state, and considering that there is much support in the Appalachians for a progressive migration of deformation and metamorphism towards the stable continental foreland (Dewey 1969b), it is not inconceivable that the lower foreland crust be fractured and fissured. If so, then electrolytic conduction effects would become significant, which would explain the results of Connerney et al. (1980) for the Adirondacks, and also those of Edwards and Greenhouse (1975), of a highly conducting lower crustal layer, R=2 Ωm, underlying the southern Appalachians.

An eigenparameter investigation by Edwards et al. (1980) of the model presented by Blohm et al. (1977) revealed that the resistivity and depth of the lower crustal conducting layer are not independently estimated when geoelectric sounding data are inverted. The resolvable eigenparameter pertinent to this layer is the layer's depth-integrated conductivity, i.e., thickness-conductivity product. Hence it may be possible that the data of van Zijl (1977) and Blohm et al. (1977) are also consistent with a slightly less conducting but thicker zone of Type II class. A similar possibility cannot be suggested for the conducting zone delineated by Connerney and Kuckes (1980) and Connerney et al. (1980) as their controlled-source electromagnetic induction experiment inferred a resistivity in the range R=12.5–25 Ωm for this layer. The conductance of this layer was defined by Horizontal Spatial Gradient (HSG) data as being approximately 400 S (Connerney and Kuckes 1980), hence inferring a thickness of 5–10 km. This estimate is fully consistent with the 10 km thick LV_sL delineated by Jordan and Frazer (1975).

There is evidence from Jordan and Frazer (1975) that a Type III crustal layer underlies a Type II layer. The data from Berry and Fuchs (1972) and Kurtz and Garland (1976) imply that the Type III layer pinches out to the north, leaving solely a Type II layer, and the work of Connerney et al. (1980) suggests the opposite is true on going further southeast, i.e., that the Type II layer pinches out and a Type III layer exists alone. For the Canadian shield, a sketch map is shown in Fig. 4 illustrating the lower crustal layers as classified in this paper. The illustration includes the recent results of Green et al. (1980) with a layer of V_p=7.1–7.2 km s^{-1} underlying southeastern Churchill Province at a depth of 36–45 km and those of Hall and Hajnal (1973) of a layer with V_p=7.1±0.04 km s^{-1}, observed south of Lake Winnipeg.

It is apparent from Fig. 4 that a Type II lower crustal layer is an "edge" phenomenon of the Canadian shield, where "edge" means not the actual physical boundary of the shield, but a wide zone encompassing the central core of the shield. This may be evidence of a general feature of shield regions in that their centres

Table 2. Classification system with values of the parameters inferred for the lower crustal layer and conditions and possible candidates for the rock responsible

Classification		Parameters					Conditions and possible rock types
		V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})	σ	R (Ωm)	
Type I	"Normal"	6.6	3.8		0.25	10^3–10^4	Anhydrous: Quartz Diorite
Type II	"Intermediate"	6.8→7.3	4.1	3.11	0.25	100–300	Hydrous: Amphibolite
Type III	"Low"	6.8	3.4–3.7	3.11	>0.30	10–50	Hydrous: Serpentinite

have evolved into what is regarded as the final stage of development of a continental plate (see, for example, Hyndman and Hyndman 1968) whilst their edges develop much more slowly due to their tectonic juxtaposition to other environments. This is in agreement with the classification that the "edge" of the Fennoscandian shield, as inferred not only in northern Sweden (see above) but also by Massé and Alexander's (1974) reinterpretation of Sellevoll and Warrick's (1971) data revealing a lower crustal layer of between 21.8–42.2 km depth with $V_p = 7.17 \pm 0.05$ km s^{-1} for southern Norway, displays a Type II lower crustal layer. Such an interpretation of the information described by Fig. 4 leads naturally to the suggestion that there may be a size criterion involved, in that if a shield is below a certain size, it may never evolve into the final stage, hence explaining the southeast African data.

It is possible that a different explanation is required for the existence of the Type II lower crustal layer observed in northern Scotland, as the temperature at the depth of the transition from high to intermediate resistivities could be of the order of 500° C (Hutton et al. 1980), leading to a hotter Moho boundary than herein discussed. However, the tectonic equivalence of northern Scotland and the Grenville Province of eastern Canada, i.e., both zones belonged to the same continent before the closure of the Early Paleozoic Iapetus Ocean, has been noted by many authors (see, for example, Phillips et al. 1976; Jones and Hutton 1979; Keen and Hyndman 1979; Williams 1979) and hence it is not too surprising that they should display the same type of lower crustal layer.

Conclusions

From this comparison of seismic and electric investigations over various Precambrian regions of the world, it appears that the data may be classified into three distinct groupings with regard to their information content concerning the lower crustal layer. The descriptive parameters of each of these three types are listed in Table 2, together with possible conditions and rock types that display the required characteristics in the *P–T* environments involved.

The zoning of the Canadian shield region implies that the Type I layer should be expected in the centre of large shields, surrounded by a Type II layer. This suggests that there may be some size criterion, in that if a shield is too small it does not fully develop to a Type I crust, which may be regarded as the end stage of a development process (Hyndman and Hyndman 1968).

The Type III lower crustal layer requires a more complete explanation, especially in terms of the high values of conductivity associated with it. The two observations reported here may be local effects, in that both have radically differing explanations (possible fracturing due to the passive initial state of Benioff zone development in eastern North America?), or may be global effects, e.g., that the layer is another edge effect of a shield region.

It must be remarked that it is not expected that all Precambrian lower crustal layers fall into one of the three general categories detailed in Table 2. One seemingly notable exception to this classification is the East European Platform. Seismic models of this platform include a lower crustal layer with $V_p = 6.8$–7.2 km s^{-1} (Bozhko and Starovoit 1969; Kosminskaya and Pavlenkova 1979; Pavlenkova 1979; Patton 1980), hence defining it as Type II. However, magnetotelluric data (Kovtun and Chicherina 1969), particularly the "generalised curve" for the region (Vanyan et al. 1977), imply a highly resistive crust, i.e., a Type I lower crustal layer. This latter result is, in the opinion of the author, not totally conclusive as it is based solely on apparent resistivity information, whereas the magnetotelluric phase is far more discriminating between Types I, II, and III.

Finally, this study has shown the decided advantages of undertaking cooperative seismic and geomagnetic or geoelectric measurements in the same area. Independent interpretations of the data recorded may differ wildly, hence either, or both, may be wildly wrong. This may be particularly true for seismic data from shield regions because, as noted by Pavlenkova (1979), compressional wave velocities of between 6.6–7.7 km s^{-1} are not usually observed in the first arrivals, hence implying that seismically Type II layers are difficult to delineate. A good example of this is Massé and Alexander's (1974) reinterpretation of Sellevoll and Warrick's (1971) data from southern Norway. The initial model had a lower crustal layer of $V_p = 6.51$ km s^{-1} (Sellevoll and Warrick 1971), whereas a more sophisticated analysis gave a value of $V_p = 7.17$ km s^{-1} (Massé and Alexander 1974). Joint interpretation of dual data sets, in the manner described in this work, is likely to reduce drastically the number of possible likely candidates for the lower crustal layer.

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References

Assumpção, M., Bamford, D.: LISPB – V. Studies of crustal shear waves. Geophys. J.R. Astron. Soc. **54**, 61–74, 1978

Bamford, D., Faber, S., Jacob, B., Kaminski, W., Nunn, K., Prodehl, C., Fuchs, K., King, R., Willmore, P.: A lithospheric profile in Britain – I. Preliminary results. Geophys. J.R. Astron. Soc. **44**, 145–160, 1976

Bamford, D., Nunn, K., Prodehl, C., Jacob, B.: LISPB – IV. Crustal structure of Northern Britain. Geophys. J.R. Astron. Soc. **54**, 43–60, 1978

Berry, M.J., Fuchs, K.: Crustal structure of the Superior and Grenville provinces of the northeastern Canadian shield. Bull. Seismol. Soc. Am. **63**, 1393–1432, 1973

Berry, M.J., Mair, J.A.: The nature of the Earth's crust in Canada. In: The Earth's Crust: Its nature and physical properties, Geophys.

Monogr. Ser. Vol. 20, J.G. Heacock, ed.: pp. 319–348. Washington DC: Am. Geophys. Union 1977
Bloch, S., Hales, A.L., Landisman, M.: Velocities in the crust and upper mantle of southern Africa from multi-mode surface wave dispersion. Bull. Seismol. Soc. Am. **59**, 1599–1629, 1969
Blohm, E.K., Worzyk, P., Scriba, H.: Geoelectrical Deep Soundings in southern Africa using the Cabora Bassa power line. J. Geophys. **43**, 665–679, 1977
Bloomer, J.R., Richardson, S.W., Oxburgh, E.R.: Heat flow in Britain: an assessment of the values and their reliability. In: Terrestrial Heat Flow in Europe, Inter-Union Comm. Geodyn. Sci. Rep. No. 58, V. Cermák and L. Rybach, eds.: pp. 293–300. Berlin: Springer 1979
Bondarenko, A.T., Galdin, N.Y.: On the physiomechanical and electrical properties of basalts at high pressures and temperatures. Izv. Akad. Nauk. SSSR, Earth Physics **5**, 28–40, 1972
Bozhko, G.N., Starovoit, O.E.: Phase velocities of Rayleigh waves on the Russian platform. In: Proceedings of the Eight Assembly of the European Seismological Commission, E. Bisztricsany, ed.: pp. 339–343. Budapest, Hungary: Akad. Kiadó 1969
Brace, W.F.: Resistivity of Saturated Crustal Rocks to 40 km based on laboratory studies. In: The Structure and Physical Properties of the Earth's Crust, Geophys. Monogr. Ser. Vol. 14, J.G. Heacock, ed.: pp. 243–255. Washington, D.C.: Am. Geophys. Union 1971
Bungum, H., Pirhonen, S.E., Husebye, E.S.: Crustal thickness in Fennoscandia. Geophys. J.R. Astron. Soc. **63**, 759–774, 1980
Carte, A.E., Rooyen, A.I.M. van: Further measurements of heat flow in South Africa. Upper Mantle Project. Geol. Soc. S. Afr. Spec. Publ. **2**, 445–448, 1969
Christensen, N.I.: Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars. J. Geophys. Res. **70**, 6147–6154, 1965
Christensen, N.I.: Shear wave velocities in metamorphic rocks at pressures to 10 kilobars. J. Geophys. Res. **71**, 3549–3556, 1966
Christensen, N.I.: Compressional wave velocities in rocks at high temperatures and pressures, critical thermal gradients and crustal low-velocity zones. J. Geophys. Res. **84**, 6849–6857, 1979
Connerney, J.E.P., Kuckes, A.F.: Gradient analysis of geomagnetic fluctuations in the Adirondacks. J. Geophys. Res. **85**, 2615–2624, 1980
Connerney, J.E.P., Nekut, A., Kuckes, A.F.: Deep crustal electrical conductivity in the Adirondacks. J. Geophys. Res. **85**, 2603–2614, 1980
Daly, R.A., Manger, G.E., Clark, S.P.: Density of rocks. In: Handbook of Physical Constants, S.P. Clark, ed.: pp. 19–26. New York: Geol. Soc. Am. Inc. 1966
Dewey, J.F.: Continental margins: a model for conversion of Atlantic type to Andean type. Earth Planet. Sci. Lett. 189–197, 1969a
Dewey, J.F.: Evolution of the Appalachian/Caledonian orogen. Nature **222**, 124–219, 1969b
Drake, C.L., Ewing, M., Sutton, G.H.: Continental margins and geosynclines: The east coast of North America, north of Cape Hatteras. In: Physics and Chemistry of the Earth, Vol. 2, L.H. Ahrens, F.Press, K. Rankama and S.K. Runcorn, eds.: pp. 110–198. London: Pergamon Press 1959
Duncan, P.M., Hwang, A., Edwards, R.N., Bailey, R.C., Garland, G.D.: The development and applications of a wide band electromagnetic sounding system using a pseudo-noise source. Geophysics **45**, 1276–1296, 1980
Edwards, R.N., Bailey, R.C., Garland, G.D.: Crustal and upper mantle electrical conductivity studies with natural and artificial sources. In: The Continental Crust and Its Mineral Deposits, Spec. Pap. No. 20, D.W. Strangway, ed.: pp. 255–271. Geol. Assoc. Can. 1980
Edwards, R.N., Greenhouse, J.P.: Geomagnetic variations in the eastern United States: evidence for a highly conducting lower crust. Science **188**, 726–728, 1975
Eriksson, K.G., Malmquist, D.: A review of the Past and Present Investigations of Heat Flow in Sweden. In: Terrestrial Heat Flow in Europe, Inter-Union Comm. Geodyn. Sci. Rep No. 58, V. Cermák and L. Rybach, eds.: pp. 267–277. Berlin: Springer 1979
Green, A.G., Stephenson, O.G., Mann, G.D., Kanasewich, E.R., Cumming, G.L., Hajnal, Z., Mair, J.A., West, G.F.: Cooperative surveys across the Superior-Churchill boundary zone in southern Canada. Can. J. Earth Sci. **17**, 617–632, 1980
Haak, V.: Relations between electrical conductivity and the petrological parameters of the crust and upper mantle. Geophys. Surveys **4**, 57–69, 1980
Hall, D.H.: Partial melting and mineral-stability boundaries and their bearing on the seismic exploration of the lithosphere in Canada. Can. J. Earth Sci. **14**, 2638–2650, 1977
Hall, D.H., Hajnal, Z.: Deep seismic crustal studies in Manitoba. Bull. Seismol. Soc. Am. **63**, 885–910, 1973
Healy, J.H.: A comment on the evidence for a worldwide zone of low seismic velocity at shallow depths in the Earth's crust. In: The Structure and Physical Properties of the Earth's Crust, Geophys. Monogr. Ser. Vol. 14, J.G. Heacock, ed.: pp. 35–40. Washington, D.C.: Am. Geophys. Union 1971
Hirschleber, H.B., Lund, C.-E., Meissner, R., Vogel, A., Weinrebe, W.: Seismic investigations along the Scandinavian "Blue Road" traverse. J. Geophys. **41**, 135–148, 1975
Housley, R.M., Oliver, J.R.: Electrical characteristics of igneous Precambrian basement rocks of central North America. In: The Earth's Crust, Geophys. Monogr. Ser. Vol. 20, J.G. Heacock, ed.: pp. 181–195. Washington, D.C.: Am. Geophys. Union 1977
Hutton, V.R.S., Dawes, G., Ingham, M., Kirkwood, S., Mbipom, E.W., Sik, J.: Recent studies of time variations of natural electromagnetic fields in Scotland. Phys. Earth Planet. Inter. **24**, 66–87, 1981
Hutton, V.R.S., Ingham, M.R., Mbipom, E.W.: An electrical model of the crust and upper mantle in Scotland. Nature **287**, 30–33, 1980
Hyndman, R.D., Hyndman, D.W.: Water saturation and high electrical conductivity in the lower continental crust. Earth Planet. Sci. Lett. **4**, 427–432, 1968
Jacobson, J.J.: Deep electromagnetic sounding technique. D.Sc. Thesis T-1252. Golden, Colorado: Colorado School of Mines 1969
Jentsch, M.: Reinterpretation of a deep-seismic-sounding profile on the Ukrainian shield. J. Geophys. **45**, 355–372, 1979
Jones, A.G.: Geomagnetic induction studies in Scandinavia – I. Determination of the inductive response function from the magnetometer array data. J. Geophys. **48**, 181–194, 1980
Jones, A.G.: On the electrical crust-upper mantle structure in Fennoscandia: No Moho, and the Asthenosphere revealed? Geophys. J.R. Astron. Soc., in press 1981
Jones, A.G., Hutton, R.: A multi-station magnetotelluric study in southern Scotland – II. Monte-Carlo inversion of the data and its geophysical and tectonic implications. Geophys. J.R. Astron. Soc. **56**, 351–368, 1979
Jordan, T.H., Frazer, L.N.: Crustal and upper mantle structure from S_p phases. J. Geophys. Res. **80**, 1504–1518, 1975
Keen, C.E., Hyndman, R.D.: Geophysical review of the continental margins of eastern and western Canada. Can. J. Earth Sci. **16**, 712–747, 1979
Keller, G.V.: Electrical studies of the Crust and Upper Mantle. In: The Structure and Physical Properties of the Earth's Crust, Geophys. Monogr. Ser. Vol. 14, J.G. Heacock, ed.: pp. 107–125. Washington D.C.: Am. Geophys. Union 1971
Kosminskaya, I.P., Pavlenkova, N.I.: Seismic models of inner parts of the Euro-Asian continent and its margins. Tectonophysics **59**, 307–320, 1979
Kovtun, A.A.: Induction studies in stable shield and platform areas. Acta Geod. Geophys. Montan. Acad. Sci. Hung. **11**, 333–346, 1976 (paper originally presented as a Review at the Third IAGA Workshop on Electromagnetic Induction in the Earth, Sopron, Hungary, 4–10 July 1976)
Kovtun, A.A., Chicherina, N.D.: Results of magnetotelluric investigations in the central Russian depression. In: Magnetotelluric methods for studying the structure of the Earth's Crust and Upper Mantle (in Russian). Moscow: Nauka 1969
Kurtz, R.D., Garland, G.D.: Magnetotelluric measurements in eastern Canada. Geophys. J.R. Astron. Soc. **45**, 321–347, 1976
Kutas, RI., Lubimova, E.A., Smirnov, Ya.B.: Heat flow studies in the European part of the Soviet Union. In: Terrestrial Heat Flow in Europe, Inter-Union Comm. Geodyn. Sci. Rep. No. 58, V. Cermák and L. Rybach, eds.: pp. 301–308. Berlin: Springer 1979
Lachenbruch, A.H., Sass, J.H.: Heat flow in the United States and

the Thermal Regime of the crust. In: The Earth's Crust: Its nature and physical properties, Geophys. Monogr. Ser. Vol. 20, J.G. Heacock, ed.: pp. 626–675. Washington D.C.: Am. Geophys. Union 1977

Landisman, M., Mueller, S., Mitchell, B.J.: Review of evidence for velocity inversions in the continental crust. In: The Structure and Physical Properties of the Earth's Crust, Geophys. Monogr. Ser. Vol. 14, J.G. Heacock, ed.: pp. 11–34. Washington D.C.: Am. Geophys. Union 1971

Lund, C.-E.: Crustal structure along the Blue Road Profile in northern Scandinavia. Geol. Fören. Stockholm Förh. **101**, 191–204, 1979

Manghnani, M.H., Ramananantoandro, R., Clark, S.P.: Compressional and shear wave velocities in Granulite Facies rocks and Eclogites to 10 kbar. J. Geophys. Res. **79**, 5427–5446, 1974

Massé, R.P., Alexander, S.S.: Compressional velocity distribution beneath Scandinavia and western Russia. Geophys. J. **39**, 587–602, 1974

Mereu, R.F., Hunter, J.A.: Crustal and upper mantle structure under the Canadian shield from project early rise data. Bull. Seismol. Soc. Am. **59**, 147–165, 1969

O'Brien, P.N.S.: Lake Superior Crustal Structure – A Reinterpretation of the 1963 Seismic Experiment. J. Geophys. Res. **73**, 2669–2689, 1968

Patton, H.: Crust and Upper Mantle Structure of the Eurasian Continent from the Phase Velocity and Q of Surface Waves. Rev. Geophys. Space Phys. **18**, 605–625, 1980

Pavlenkova, N.L.: Generalised geophysical model and dynamic properties of the continental crust. Tectonophysics **59**, 381–390, 1979

Phillips, W.E.A., Stillman, C.J., Murphy, T.: A Caledonian plate tectonic model. J. Geol. Soc. Lond. **132**, 576–609, 1976

Porath, H.: A review of the evidence on low-resistivity layers in the Earth's crust. In: The Structure and Physical Properties of the Earth's Crust, Geophys. Monogr. Ser. Vol. 14, J.G. Heacock, ed.: pp. 127–144. Washington D.C.: Am. Geophys. Union 1971

Press, F.: Seismic velocities. In: Handbook of Physical Constants, S.P. Clark, ed.: pp. 195–218. New York: Geol. Soc. Am. Inc. 1966

Rao, R.U.M., Jessop, A.M.: A comparison of the thermal characteristics of shields. Can. J. Earth Sci. **12**, 347–360, 1975

Reddy, I.K., Rankin, D.: Magnetotelluric measurements in central Alberta. Geophysics **36**, 739–753, 1971

Richter, D., Simmons, G.: Microcracks in crustal igneous rocks. In: The Earth's Crust, Geophys. Monogr. Ser. Vol. 20, J.G. Heacock, ed.: pp. 149–181. Washington D.C.: Am. Geophys. Union 1966

Ringwood, A.E.: Composition and Petrology of the Earth's Mantle. New York: McGraw-Hill 1975

Sellevoll, M.A., Warrick, R.E.: A refraction study of the crustal structure in southern Norway. Bull. Seismol. Soc. Am. **61**, 457–471, 1971

Srivastava, S.P., Jacobs, J.A.: Determination of the electrical resistivity at Meanook, Alberta, Canada, by the Magnetotelluric method. J. Geomagn. Geoelectr. **15**, 280–288, 1964

Sternberg, B.K.: Electrical resistivity structure of the Crust in the southern extension of the Canadian Shield – layered Earth models. J. Geophys. Res. **84**, 212–228, 1979

Tkachev, G.N.: Experiment of abyssal magnetotelluric soundings on the Ukrainian shield (in Russian). Geofiz. Sb. **52**, 62–65, 1973

Vanyan, L.L., Berdichewski, M.N., Fainberg, E.B., Fiskina, M.V.: The study of the asthenosphere of the East European platform by electromagnetic methods. Phys. Earth Planet. Inter. **14**, P1–P2, 1977

Volarovich, M.P., Parkhomenko, E.I.: Electrical Properties of Rocks at High Temperatures and Pressures. In: Geolectric and Geothermal Studies (East-Central Europe, Soviet Asia), KAPG Geophys. Monogr., A. Ádám, ed.: pp. 319–369. Budapest: Akadémiai Kiadó 1976

Vozoff, K., Ellis, R.M.: Magnetotelluric measurements in southern Alberta. Geophysics **31**, 1153–1157, 1966

Westerlund S.: Magnetotelluric experiments in the frequency range 0.01 Hz to 10 kHz. KGO Report No. 72:10, Kiruna Geophysical Observatory, Nov. 1972

Wickens, A.J.: Variations in lithospheric thickness in Canada. Can. J. Earth Sci. **8**, 1154–1162, 1971

Wickens, A.J., Buchbinder, G.G.R.: S-wave residuals in Canada. Bull. Seismol. Soc. Am. **70**, 809–822, 1980

Williams, H.: Appalachian orogen in Canada. Can. J. Earth Sci. **16**, 792–807, 1979

Zablocki, C.J.: Electrical properties of serpentinite from Mayaguez, Puerto Rico. In: A Study of Serpentinite of the Amsoc Core Hole Near Mayaguez, p. 1188. Washington D.C.: National Academy of Sciences, National Research Centre 1964

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