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The contribution of geophysical investigations to the geological understanding of Hudsonian and Svecokarelian plate subduction and continent-continent collision

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Tittel:
The contribution of geophysical investigations to the geological understanding of Hudsonian and Svecokarelian plate subduction and continent-continent collision

Bidrag fra geofysiske undersøkelser til geologisk forståelse av plate subduksjon og kontinent-kontinent kollisjon i de Hudsonske og Svecokarelske orogeneser.

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Sammendrag:
Litteratur om geofysiske undersøkelser av mulige kontinent-kontinent kollisjoner innenfor de Trans-Hudsonske og Svekokarelske orogenene er gjennomgått. Den sør-østre delen av den foreslåtte Trans-Hudson orogenen faller sammen med en elektrisk leder. Denne anomalien kan skyldes skiver av hydrert skorpemateriale av havbunns-type. Et magnetotellurisk profil over den foreslåtte Svekokarelske suturen indikerer en lignende anomali i Finland. Den elektriske lederen i Nord-Amerika sammenfaller med en lavhastighetssone. Refleksjonsseismikk vest for denne sonen viser flere tydelige refleksjoner med svakt-middels fall mot vest. Disse reflek-sjonene kan være skyvesoner innenfor den tilgrensende Churchill provinsen. Re-fraksjonsseismikk over den foreslåtte Svekokarelske orogenen i det nordlige Fenno-skandia viser skiftende høy og lav hastighetslag i et en echelon mønster. Disse lagene kan også tolkes som basaltiske fragmenter av arkeisk eller proterozoisk havbunnsskorpe fra en subdaksjonssone. Langs store deler av de foreslåtte 2000-1800 mill år gamle suturene opptrer parallelle positive og negative anomalier. Dette er en indikasjon på at kratonene som er adskilt av suturene har forskjellig tetthet og tykkelse. Forskjell i skorpetykkelse er også påvist ved seismiske undersøkelser. Aeromagnetiske kart benyttes for å kartlegge avkutting i et arkeisk magnetisk mønster av yngre magnetiske strukturer. Både gravimetriske og aeromagnetiske kart er dessuten de viktigste data for å fastlegge forlengelsene av suturene under phanerozoiske sedimenter og skyvedekke.
De paleomagnetiske undersøkelsene er ikke motstridende til de stadig økende antall indikasjoner på proterozoisk platetektonikk. Antall paleomagnetiske observasjoner fra Proterozoikum er imidkertid ikke tilfredsstillende.

Emneord		
	Proterozoikum	Seismisk metode
Geofysikk	Tektonikk	Gravimetri
Berggrunnsgeologi	Elektromagnetisk metode	Fagrapport

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The contribution of geophysical investigations to the geological understanding of Hudsonian and Svecokarelian plate subduction and continent-continent collision

ODLEIV OLESEN

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Geophysical studies regarding plate subductions and continent-continent collisions within the Trans-Hudson and Svecokarelian orogens are reviewed. Along large portions of the proposed 2000 – 1800 Ma old geosutures, paired gravity anomalies occur which indicate that cratons separated by the sutures have different crustal densities and thicknesses. This can be explained by a model involving plate convergence, collision and suturing. The difference in crustal thickness is also indicated in seismic surveys. Aeromagnetic maps have been used to delineate truncation of Archean magnetic fabric by younger magnetic structures of the accreted terrains. In addition, gravity maps as well as aeromagnetic maps are the principal data for extrapolating the sutures beneath Phanerozoic cover. The southeast section of the Trans-Hudson Orogen correlates with a crustal-scale electric conductor, known as the North American Central Plains anomaly. This anomaly may be caused by buried slices of hydrated oceanic-type crustal material. A magnetotelluric profile across the proposed Svecokarelian suture indicates a similar anomaly in Finland. The electric conductor in North America coincides also with a low-velocity zone. This anomaly can also be related to hydrated basaltic material. A seismic reflection survey to the west of this zone shows a number of prominent reflections with shallow to moderate westerly dips. These reflections may be thrusts within the bordering Churchill Province. A seismic refraction line across the Svecokarelian Orogen in northern Fennoscandia indicates alternating high- and low-velocity layers in an en echelon pattern. These layers can also be interpreted as basaltic fragments of Archean or Proterozoic oceanic crust "stranded" beneath a thin sialic crust by very shallow subduction zones. When regarding paleomagnetic evidence none of these is inconsistent with plate tectonics. The record is however fragmentary. It is concluded that these geophysical studies have contributed to the growing evidence for Proterozoic plate tectonics and that the studies provide new information and new ideas about the plate subductions and continent-continent collisions during the Early Proterozoic.

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Introduction

In the discussion of how far back in Precambrian times modern plate tectonics has been working, it is claimed that in the absence of obducted ophiolites, uniformitarian views can not be upheld (Kröner 1981). The existence of large areas of reactivated basement within the Early Proterozoic Hudsonian and Svecokarelian belts have led some authors to conclude that the belts developed by remobilization of a pre-existing crystalline basement (Kröner 1981, Witschard 1983). Hence they propose various models for intracontinental mobile belts based on the concept of ensialic orogeny. However, although these Early Proterozoic mobile belts lack any sign of ocean floor spreading, extensive geochemical, petrological and field data support tectonic models of orogenies involving active plate margin environments and continental collision (Hoffman 1980, Gaal 1982, Barbey et al. 1984, Krill 1985, Lewry et al. 1985). A model based on the stability of the oceanic tectonosphere has been proposed by Hynes (1982). It predicts a gradual change from the Early Proterozoic orogenies, characterized by the development of small ocean basins, to modern plate tectonics due to progressive cooling of the mantle .

In this paper geophysical techniques used to estimate paleo-plate movement, as well as to delineate geosutures and their characteristics will be discussed. Low-angle thrusts have for instance optimal chances to survive and remain detectable after erosion of an orogen.

The geophysical methods used are:

- Gravity
- Aeromagnetic
- Geomagnetic depth sounding
- Seismic (reflection and refraction)
- Paleomagnetism

The last method is mostly used to estimate the paleo-plate movements.

I have chosen to discuss geophysical investigations in the Trans-Hudson and Svecokarelian Orogens because they contain large volumes of juvenile Early Proterozoic crust (Hoffman 1987). Consequently, they have optimal chances to contain detectable geosutures. I will give a short description of the regional geology of these areas in the Baltic and Canadian Shields where these orogens occur. Over a decade ago the overall character and evolution of these Early Proterozoic orogenies were little understood. Both Archean and Early Proterozoic rocks and thermotectonism were involved but their relative extent and importance were generally uncertain. But during the last ten years a large number of studies have been performed, and overall knowledge has increased extensively.

General geology

Introduction

Proto-Laurasia, cratonic North America and northern Europe, is thought to be formed by convergence and suturing (1950-1800 Ma), of several Archean microcontinents (Fig. 1), followed immediately by a 1000 km southward accretion (1800-1600 Ma) of juvenile Proterozoic crust (Hoffman 1987). Of the interior belts only the Trans-Hudson preserves significant juvenile Proterozoic crust (ruled in Fig. 1). Of the early peripheral belts, juvenile Proterozoic crust definitely underlies interior parts of the Svecokarelian (Svecofennian) Orogen (Hoffman 1987). Because of the wide belts of Early Proterozoic age within the Trans-Hudson and Svecokarelian Orogens, these orogens are of special interest in the search for Early Proterozoic plate tectonic events.

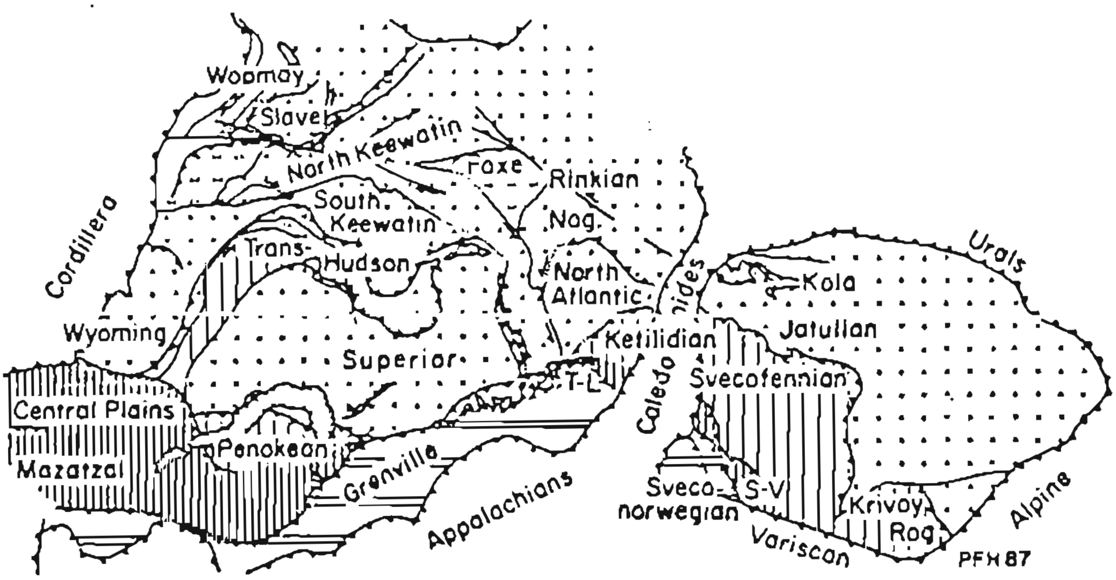


Fig. 1. Proto-Laurasia, consisting of cratonic North America and northern Europe, is formed by several Archean microcontinents (Wyoming, Superior, Slave, North Keewatin, South Keewatin, North Atlantic, and Jatulian) separated by 1950-1800 Ma old interior belts (Thelon, Intra-Keewatin, Foxe, Dorset, Torngat, Labrador trough, Rinkian, Nagssugtoqidian and Kola) and surrounded by (1950-1800 Ma) peripheral belts (Wopmay, Penokean, Ketilidian-Svecofennian (Svecokarelian)). This confluence was followed by a 1000 km southward accretion (1800-1600 Ma) of juvenile Proterozoic crust (Mazatzal – Central Plains – Trans Labrador(T-L) – Småland-Värmland(S-V) belts) (after Hoffman 1987).

Trans-Hudson Orogen

The Churchill province is comprised of disparate elements of the complex Early Proterozoic Trans-Hudson Orogen (Hoffman 1981), which extends eastwards, into Greenland, and southwards into mid-continental United States (Lewry et al. 1985). The main features of the orogen are related to thermotectonic events c. 2000 to 1700 Ma, which are broadly referred to as the Hudsonian Orogeny.

Four major lithotectonic zones (Fig. 2a) are broadly distinguishable in the Churchill Province segment of the Trans-Hudson Orogen and its bounding cratonic platforms (Lewry et al. 1985):

Zone 1 comprises Aphebian supracrustal rocks which are little deformed, or form an autochthonous to parautochthonous foreland fold-thrust belt regime, overlying cratonic Superior Province basement.

Zone 2 comprises Superior basement and Aphebian cover which is more highly deformed than the cover forms allochthonous fold-thrust sheets. Aphebian supracrustal units in both Zones 1 and 2 are generally of rifted margin and stable platform to miogeoclinal passive margin character.

Zone 3 is the main Hudsonian Mobile Belt, which suffered general intense plastic to ductile deformation and/or major magmatism under predominantly high grade metamorphic conditions. Much of Zone 3 is underlain by thoroughly remobilized Archean continental basement. A substantial part of this zone is also characterized by eugeoclinal Aphebian sedimentation and arc volcanism in the west.

Zone 4 is the northwestern cratonic foreland region of Archean basement and remnant Aphebian cover, and is termed the Amer Lake Zone. It is characterized by generally low grade, Early Proterozoic metamorphic overprint, restricted brittle to plastic, zonal reworking, extensive granite plutonism and isotopic resetting. Aphebian supracrustal units include passive margin platformal to miogeoclinal assemblages and local foreland basin sequences.

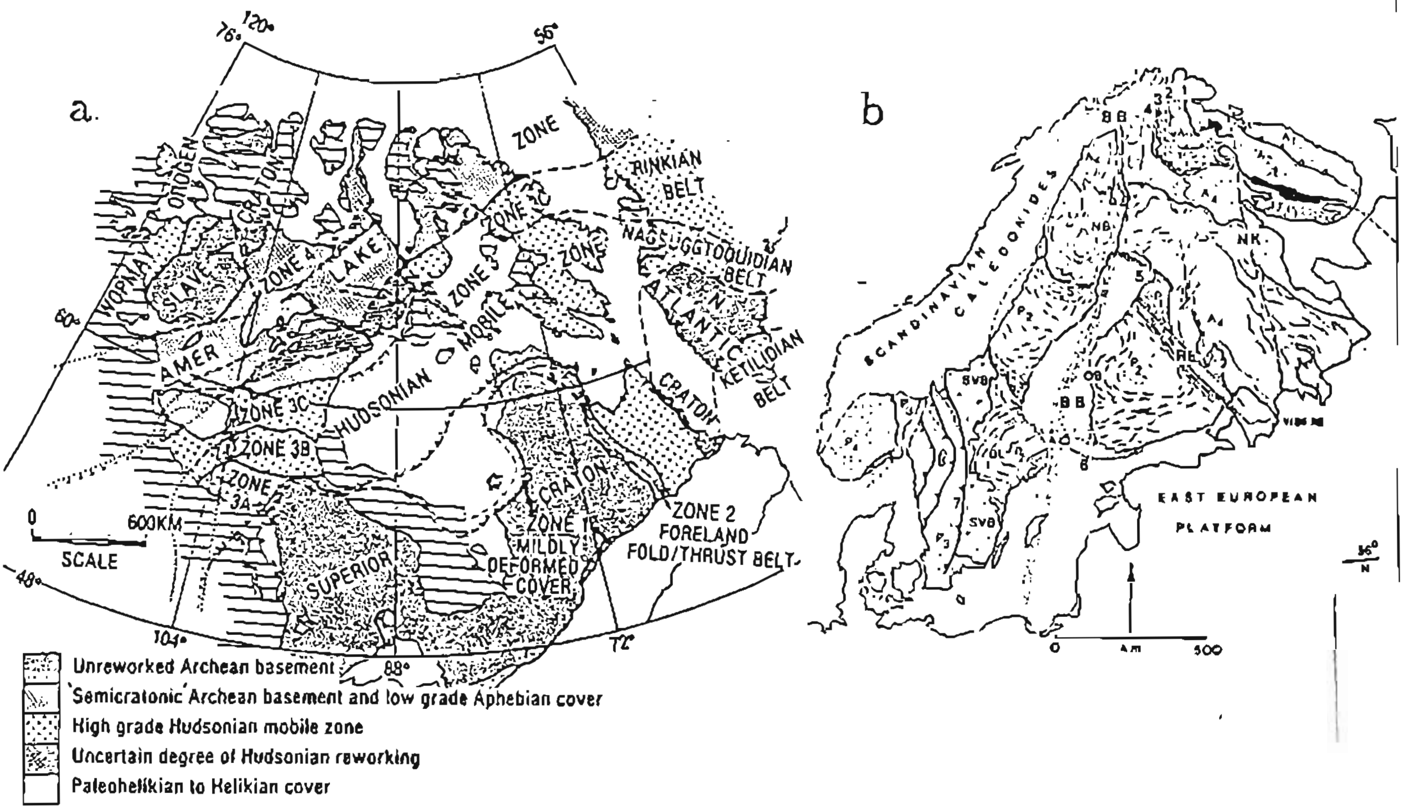


Fig. 2. a) Major lithotectonic elements of the Trans-Hudson Orogen, including cratonic foreland and other adjacent regions (Lewry et al. 1985). Greenland is restored to approximately pre-drift position relative to Canada. Phanerozoic cover is indicated by horizontal lined pattern. b) Major tectonic elements of the Baltic Shield (after Berthelsen & Marker 1986). $A_1 - A_4$ - units with Archean crustal ages, $P_1 - P_2$ - units with Early Proterozoic crustal ages ($\sim$ 2.0 – 1.85 Ga), $P_3 - P_4$ - units with Middle Proterozoic crustal age ($\sim$ 1.7 – 1.5 Ga). 1 - Kola belt, 2 - marginal thrust of the Inari microcontinent, 3 - marginal thrust of the Granulite belt, 4 - marginal thrust of the Tanaelv Migmatite Belt, 5 - former margin of Archean proto-Shield, possible collision suture, 6 - possible collision suture, 7 - Sveconorwegian/Grenvillian front, NB - Norrbotten, S - Skellefte field, OB - Southern Ostrobothnia, BL - Bergslagen, SVB - Småland-Värmland granite belt, RL - Raahe-Ladoga megashear, NK - North Karelian megashear, BB - Baltic-Bothnian megashear.

These data indicate Early Proterozoic subduction and collisional orogeny within Zone 2 and 3 of the Churchill Province (Lewry et al. 1985).

Svecokarelian Orogen

The Svecokarelian Orogeny had long been thought to consist of two separate orogenic belts, the Karelian Orogeny in the east and the Svecofennian orogeny in the west (Eskola 1963). New age determinations have however proved that they are of the same age, and hence they have together been renamed the Svecokarelian Orogeny (Gaal 1982).

Fig. 2b shows a tectonic sketch map of the Baltic Shield (Berthelsen & Marker 1986). The "Archean nucleus" in the northeast is divided into a southern and a northern compartment , comprising respectively, units A_4 and A_1+ A_2. A narrow crustal segment with Early Proterozoic crust (P_1), consisting of a greenstone belt, a migmatite belt and a granulite belt (Barbey et al. 1984, Krill 1985), separates the southern and northern compartments. The granulites represent miogeoclinal sediments intruded by 2000-1900 Ma old calc-alkaline rocks and an inner magmatic arc (Barbey et al. 1984, Krill 1985). The underlying migmatite belt, separated from the granulite belt and the greenstone belt by thrusts, is found to represent an outer volcanic arc.

The continental crust of the Central Baltic Shield (P_2 in Fig. 2b) evolved by accretion towards the southwest during the Svecokarelian Orogeny 1700-2200 Ma ago (Gaal 1982). This orogenic belt is characterized by flysch-sediments with serpentinite masses and pillow lavas, linear high-grade metamorphic zones, island-arc type volcanic belts and late tectonic batholiths. The features of both Early Proterozoic provinces P_1 and P_2 are consistent with a plate tectonic mechanism involving subduction of oceanic crust below an Archean craton in the east (Hietanen 1975, Gaal 1982, Krill 1985).

Gravity

Gravity data have during the last ten years been used to delineate possible geosutures in exposed Precambrian Shields as well as to extrapolate these sutures beneath Phanerozoic cover. A distinctive gravity signature mapped along parts of the Circum-Superior fold belt (Gibb et al. 1978, Mukhopadhyay & Gibb 1981) has been attributed to collision and suturing along this boundary. The signature is identified as a negative - positive pair of Bouguer gravity anomalies parallel to the structural boundary (Fig. 3). Thomas & Gibb (1985) have observed that the negative anomaly is consistently within the older province and/or straddles the younger province. They further suggest that this feature can be explained reasonably in the context of Dewey & Burke's (1973) model of continental collision-basement reactivation (Fig. 4a). Following consumption of all the oceanic lithosphere between converging continental plates, further convergence is at first attempted by subduction of the continental lithosphere beneath the overriding plate. Such subduction is limited by the buoyancy of the lithosphere, and further convergence is likely to take place by thickening of the continental crust. This thickening process causes partial melting of the lower crust. Granitic liquids are produced and rise upward to form a granite-rich upper crust, while dehydration of the lower crust produces

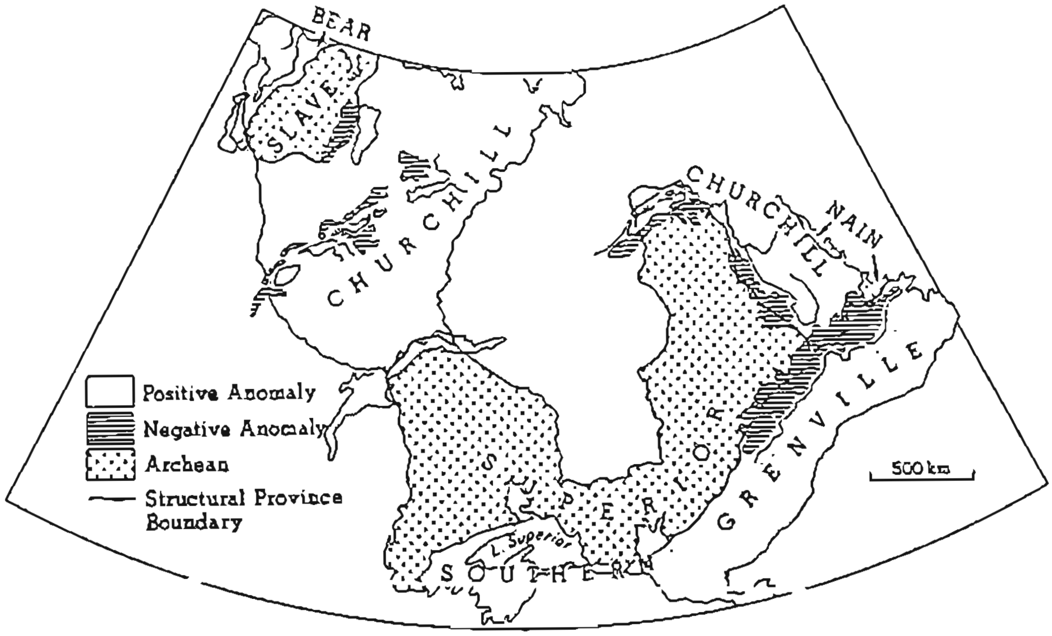


Fig. 3. Major Bouguer gravity anomalies at or near the structural province boundaries in the Canadian Shield (Thomas & Gibb 1985). Positive-negative paired anomalies regarded as collision-related phenomena are well developed at the Slave-Churchill and eastern Superior-Churchill among others. Another example of paired anomalies may occur at the Slave-Bear boundary, but here the negative is relatively weakly developed and is not illustrated in the figure. A prominent positive anomaly along the western Superior-Churchill boundary (Nelson Front) is also in places attended by a weak negative anomaly, but such a possible pairing of positive and negative anomalies does not conform to the pattern of paired anomalies at other boundaries where the positive is located without exception in the younger structural province. Linear anomalies distributed along a northeasterly trending belt in the central part of the western Churchill Province may indicate a suture here.

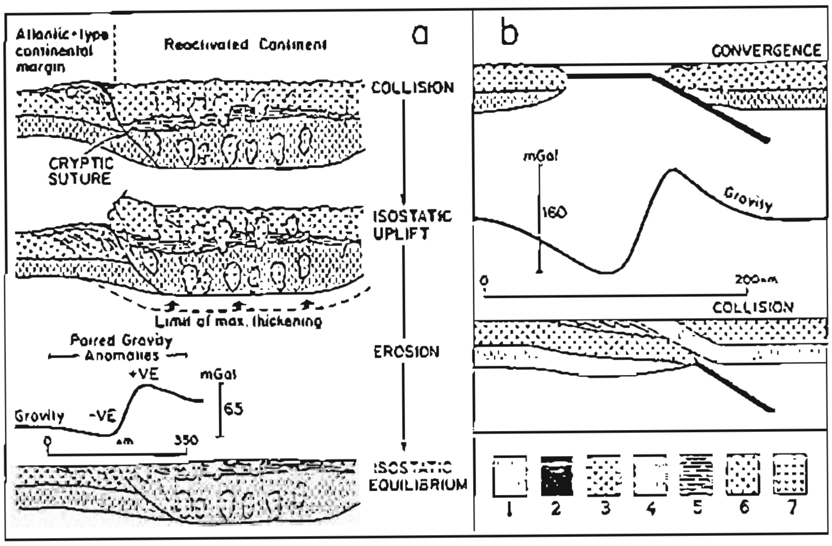
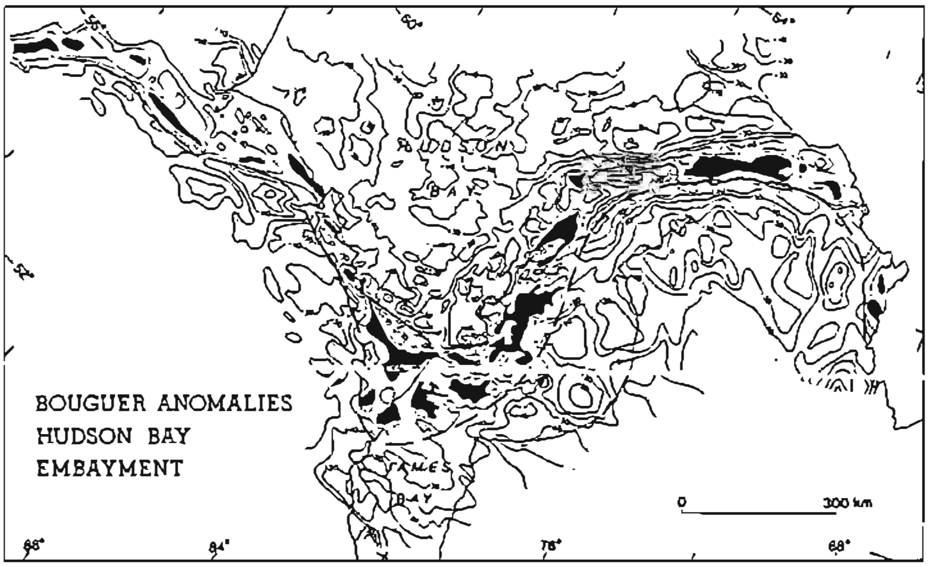


Fig. 4. a) Series of crustal sections illustrating crustal evolution, controlled by vertical movements induced by a combination of erosion and isostasy, following continent-continent collision. b) Plate convergence-collision model showing lower crust uplifted by obduction following collision. Legend for a and b: 1 - sedimentary rocks; 2 - oceanic crust; 3 - upper crust; 4 - lower crust; 5 - migmatite; 6 - granitic rocks; 7 - anorthosite and gabbro (Thomas & Gibb 1985).

granulite, mangerite and anorthosite. Following a period of erosion and isostatic adjustment, successively lower levels of crust will be exposed in the reactivated crust. Limited subduction of the passive continental plate margin might have maximized the crustal thickening near the suture. Such uplift of dense lower crust

a



b

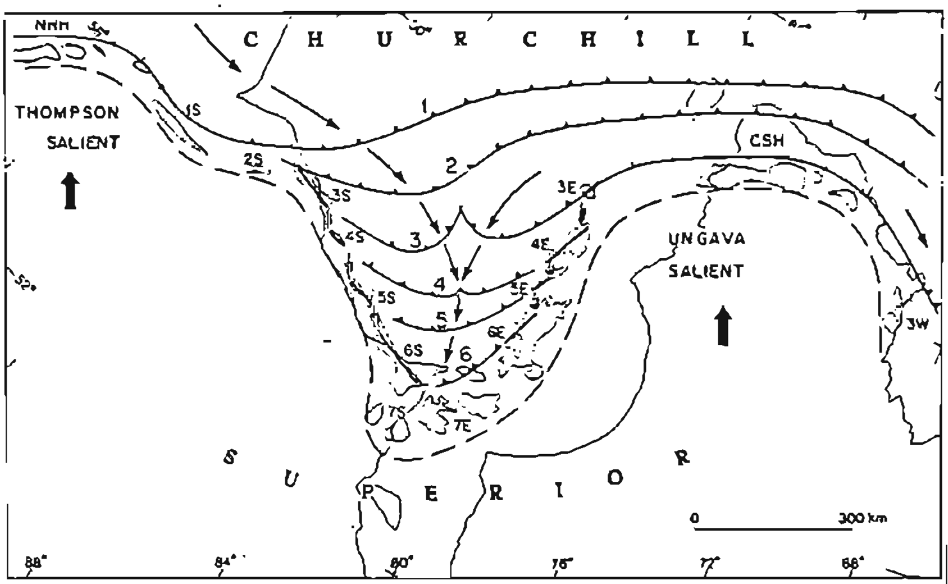


Fig. 5. a) Bouguer gravity anomaly map (10-mGal contour interval) of southeastern Hudson Bay (Gibb 1983). Similar discontinuous belts of positive anomaly (black) in southern and eastern Hudson Bay are related to mafic and/or ultramafic rocks of proposed circum-Superior suture. b) Schematic map showing symmetry and pairing of positive anomalies (stippled) on either side of Hudson Bay embayment (Gibb 1983). Anomalies are offset by faults inferred the from asymmetrical anomaly pattern. Legend: 1 to 6 - positions of the migrating Churchill trench as indentation proceeds and material is extruded into embayment (small arrows); positions correspond to preserved oceanic crust underlying the gravity anomalies. NRH - Nelson River gravity 'high'; CSH - Cape Smith gravity 'high'.

offers one explanation for the siting of the positive gravity anomaly (Thomas & Gibb 1985).

Fountain & Salisbury (1981) have suggested a different explanation for the anomalies (Fig. 4b). Again continental convergence terminated by collision is the primary mechanism, but obduction of crust of the overriding active plate is responsible for bringing lower crustal material to the surface rather than a combination of erosion and isostatic uplift.

The proposed Svecokarelian geosuture in northeastern Fennoscandia (Krill 1985) (zone 4 between units P_1 and A_4 in Fig. 2b) coincides also with a paired gravity anomaly (Olesen 1986). A similar model as proposed by Thomas & Gibb (1985) can consequently be applied for a part of the Svecokarelian Orogeny.

Based on gravity surveys in the Hudson Bay area Gibb (1983) interprets a symmetrical distribution of linear, positive anomalies (Fig. 5a) as being caused by double indentation tectonics (Tapponnier & Molnar 1976). The two belts of local positive anomalies in eastern Hudson Bay and the southern littoral zone meet near the mouth of James Bay. Successive anomalies are en echelon and are offset in both belts toward the Superior craton. The offsets which are dextral in the southern belt and sinistral in the eastern belt, are attributed to transcurrent faults (Fig. 5b). This symmetrical distribution of linear positive anomalies suggests a model in which suturing of the Superior and Churchill protoplates was accomplished by subduction of oceanic lithosphere and by progressive indentation of the rigid-plastic Churchill craton by the Thompson and Ungava salients (indenters) of the rigid Superior protocontinent.

Aeromagnetic

The continuation of the circum-Superior suture to the southwest of Thompson nickel belt into the Williston basin is interpreted by Green et al. (1985) using a.o. gravity and aeromagnetic methods. They inferred the truncation of the east-west trending magnetic fabric in the Archean by more north-south trending Hudsonian structures as the suture zone.

Hoffman (1985) used aeromagnetic and gravity maps together with metamorphic maps to show that the Cape Smith Belt is a klippe, separated from its root by a 60-90 km wide autochthonous basement antiform. This root zone is thought to be a part of the circum-Superior suture and is also characterized by an abrupt switch from broad north-south to narrow east-west magnetic anomalies in addition to a major deflection in the Bouguer gravity field.

In northern Fennoscandia ~~aeromagnetic~~ interpretations of aeromagnetic maps have been used to delineate thrusts in the Lapland granulite belt and Tanaelv Migmatite Belt (Geol. Surveys of Finland, Norway & Sweden 1986). Fig. 6 shows a simplified version of the interpretation map (Henkel 1987). The curved major magnetic discontinuity marked 1 in Fig. 6 corresponds with the geosuture proposed by Krill (1985) and Olesen (1986).

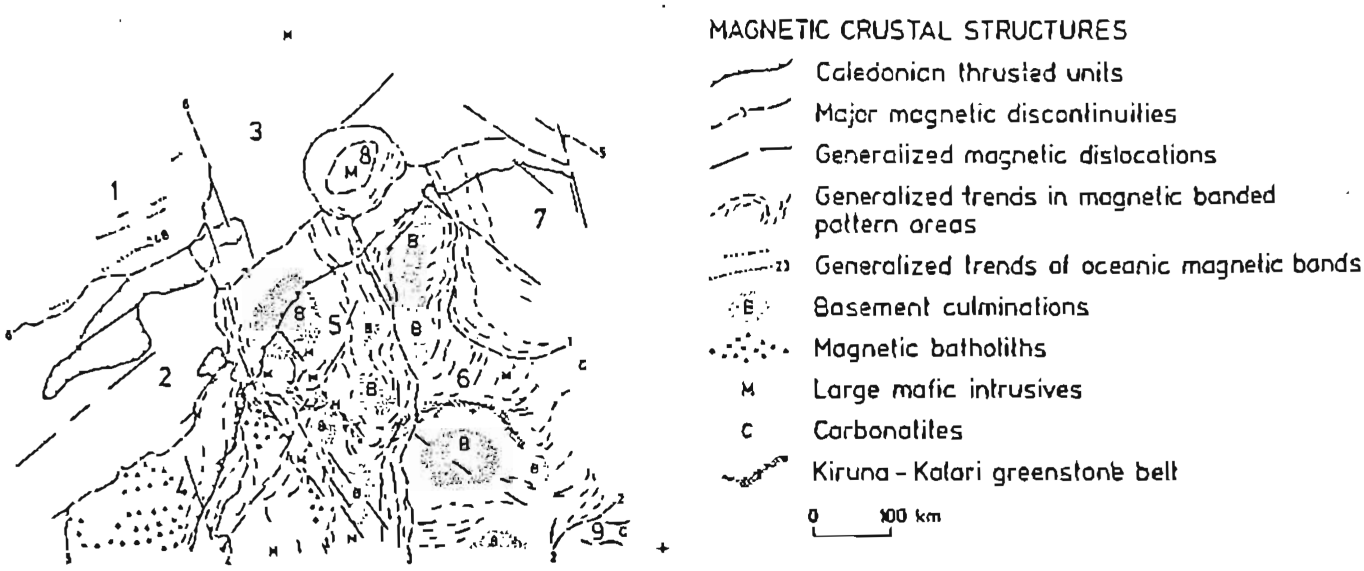


Fig. 6. Large scale structural features interpreted from aeromagnetic maps in northern Fennoscandia, north of the 66th parallel (Henkel 1987). The area covers the transition from oceanic crust to the Baltic Shield, a section of the Caledonides and part of the Arctic platform. The curved major magnetic discontinuity marked 1 abruptly crosscuts N-S trending steeply dipping structures. To the east of the discontinuity the curved magnetic bands dips gently to the NE. The discontinuity is interpreted to be a geosuture.

Geomagnetic depth sounding

The crustal-scale electric conductor, known as the North American Central Plain anomaly (Fig. 7), has been mapped by geomagnetic depth sounding methods from the northern Laramie range in Wyoming across the exposed shield in Saskatchewan to the Hudson Bay basin (Gupta et al. 1985, Handa & Camfield 1984). Handa & Camfield (1984) suggested that the electrical conductivity anomaly might be caused either by conductive mineralization or by saline waters migrating through an enormous fault that once connected the La Ronge-Lynn Lake volcanic island arc (Fig. 8) and related structures with similar features in the northern Laramie range. Green et al. (1985) suggest however, that the anomaly may be caused by buried slices of hydrated oceanic-type crustal material. They find that the anomaly is most closely associated with the magnetic quiet zone of the Reindeer-South Indian Lakes belt (Fig. 8) which is interpreted to a remnant of a back-arc basin (Lewry et al. 1985). Such underthrust oceanic-type material might also explain the spatially related seismic low-velocity zones (Green et al. 1985).

Joint Finnish-Hungarian MT and AMT measurements have been carried out in Finland by Ádám et al. (1982). A profile consisting of five MT and 150 AMT stations was located across a proposed Svecokarelian geosuture and a large fault zone, Raahe - Lake Ladoga, (Fig. 2b). The depths of the conductive layers from SW to NE along the studied MT profile are: 4.0, 16.5, 4.8, 10.5 and 34.0 km. As the distance between the points are 35-75 km, the conductive layers may not be explained by the effect of a single conductive body.

The main information deducible from the MT measurements is however the existence of conductive bodies in the proposed geosuture.

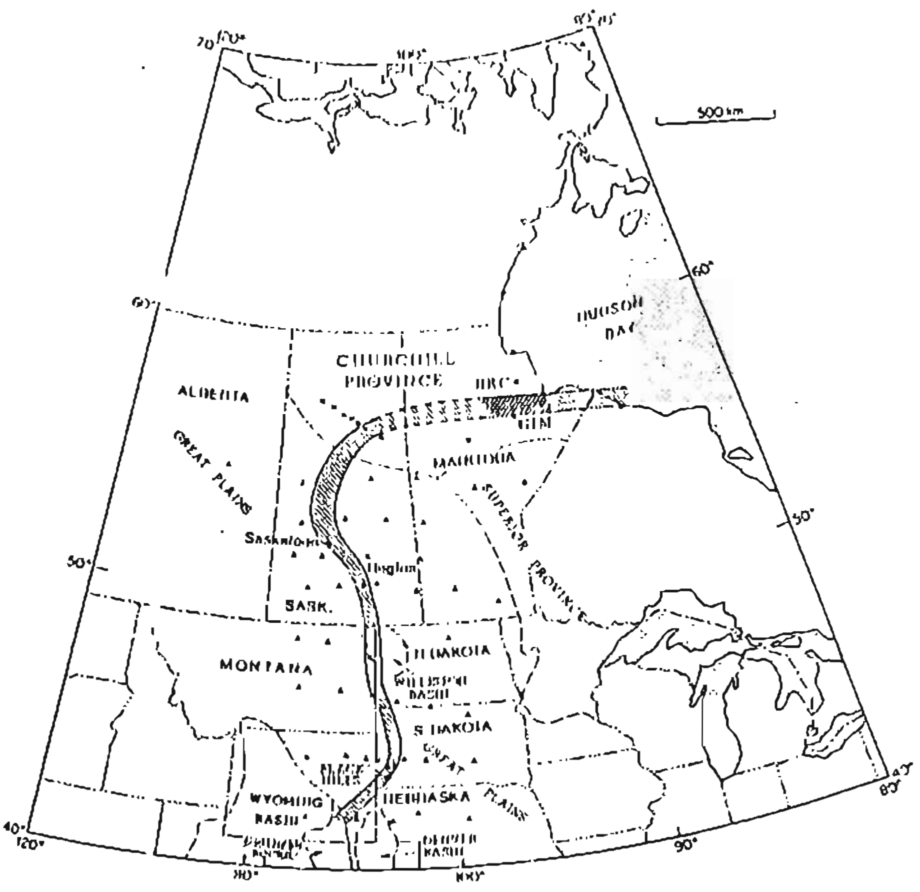


Fig. 7. Location of the North American Central Plains conductive body (broad shaded area) (Gupta et al. 1985).

Seismic

Seismic techniques have, so far, had only a limited application to problems of geological mapping in the Early Proterozoic belts in Canada and Scandinavia. But during the last few years some studies have been undertaken, mostly in Canada. The search for reflections from steeply dipping features across the contact between the Churchill tectonic province and the Thompson nickel belt in northern Manitoba (Fig. 8) was however not successful (Green 1981), probably due to the complex character of such features. But based on refracted P-wave and S-wave arrivals, Green (1980) concluded that this contact is a fault zone which correlates with the occurrence of mylonites.

The most successful of the seismic surveys seem to be the surveys by Hajnal et al. (1984) and Green et al. (1985) for delineating the Proterozoic structures beneath the Phanerozoic Williston basin of south-central Canada and north-central United States. Reversed seismic refraction profiles and four short multicoverage seismic reflection lines were recorded across the Williston basin (Fig. 8) to a.o. obtain information on the nature and structure of the Superior-Churchill boundary zone and the North American Central Plains electrical conductivity anomaly.

The depth of the crust-mantle discontinuity varies from a minimum of 37-41 km beneath the Superior craton to a maximum value close to 48 km beneath the Reindeer-South Indian Lake belts (Fig. 8). A similar thickening which is consistent with the geological/density models of Gibb & Thomas (1976), has been observed across the Superior-Churchill boundary zone in northern Manitoba by Mereu & Hunter (1969) and Hall & Hajnal (1973).

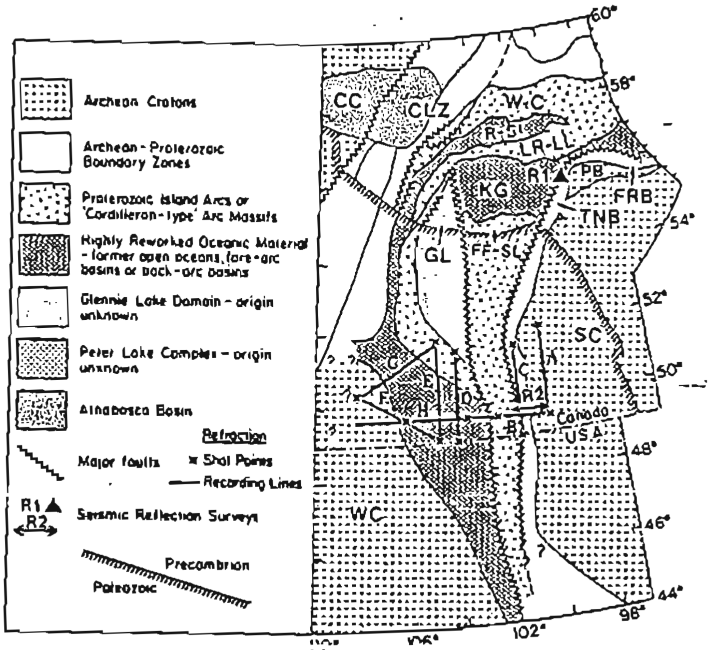


Fig. 8. Tectonic provinces of the Canadian Shield in Manitoba, Saskatchewan, North Dakota and parts of South Dakota, Montana and Wyoming (Green et al. 1985). The boundaries beneath the Phanerozoic sediments are mainly interpolated from aeromagnetic and gravity data. The seismic refraction lines from Green et al. (1980) and Hajnal et al. (1984) and the seismic reflection line, R1, from Green (1980,1981) are shown. Seismic reflection line R2 is shown in Fig. 9. CC - Churchill Craton, CLZ - Cree Lake Zone, FF-SL - Flin Flon-Snow Lake Belt, FRB - Fox River Belt, GL - Glennie Lake Domain, LR-LL - LA Ronge-Lynn Lake Belt, KG - Kisseynew Gneiss Belt, PB - Pikwitonei granulites, R-SI - Reindeer-South Indian Lakes Belt, SC - Superior Craton, TNB - Thompson Belt, W-C - Wathaman-Chipewyan Batholith, W-C - Wyoming Craton.

Fig. 9 shows a composite line interpretation of the reflections observed along the four seismic reflection lines (Green et al. 1985), shown as R2 in Fig. 8, together with an electrical resistivity model and the appropriate E-W trending aeromagnetic and gravity profiles. A portion of one of the 1200 % common reflection point record sections is shown also in Fig. 9. Although most of the deep reflections recorded within the Superior craton and the eastern region of the Superior craton margin are of relatively low quality, there does seem to be a weak pattern of westerly dipping events. Towards the western side of the margin, approximately coincident with the postulated seismic low-velocity zone and its overlying high-velocity lid, the data quality improves markedly with the appearance of a number of prominent reflections that have shallow to moderate westerly dips up to 36°.

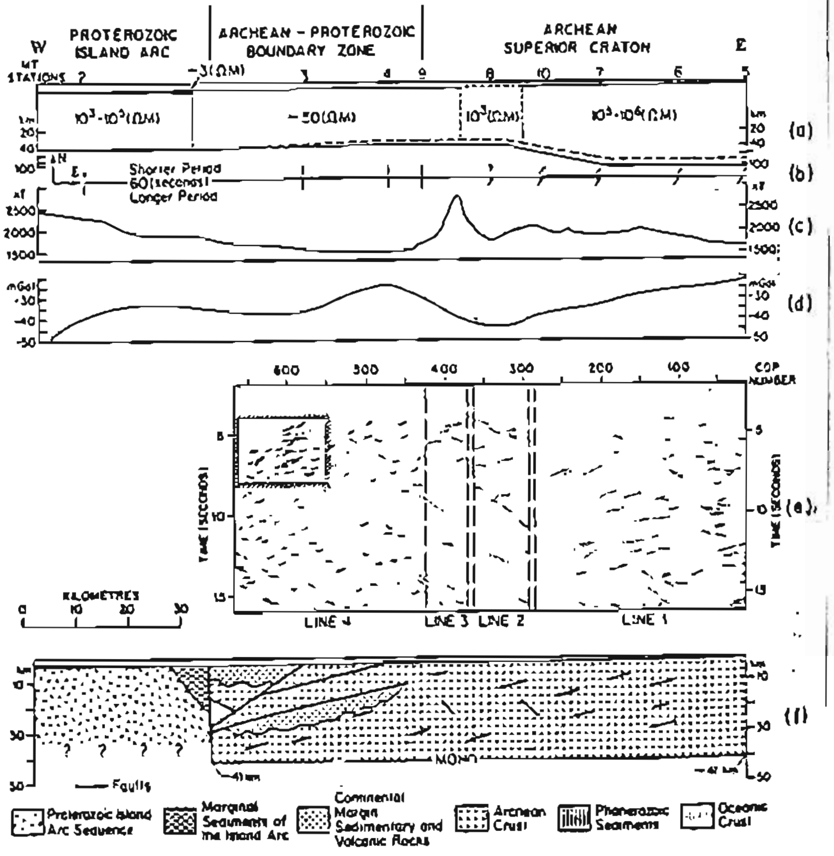


Fig. 9. Selected geophysical information from the Superior-Churchill boundary zone in southern Canada (Green et al. 1985). a) Resistivity model based on magnetotelluric soundings. b) Orientations of the principal axes of the impedance tensors. c) Aeromagnetic profile. d) Gravity profile. e) Line interpretation of the seismic reflection data. f) Cartoon representation of the final stage of the tectonic development of the Superior-Churchill boundary zone.

Interpretations of FENNOLORA seismic refraction profile (Fig. 10a) across the Svecokarelian Orogen in the northern Baltic Shield revealed an en echelon pattern of P-wave first arrivals (Fig. 10b) (Olsen & Lund 1984). This pattern is observable in both north- and south-trending directions from shotpoint G (Fig. 10a). This suggests a fine structure of the upper crust to depths approximately 20 km consisting of several alternating high- and low-velocity layers, each about 1 or 2 km thick. Olsen & Lund (1984) think that these anisotropic layers are basaltic fragments of Archean or Proterozoic oceanic crust that were "stranded" beneath thin sialic crust by very shallow angle subduction zones.

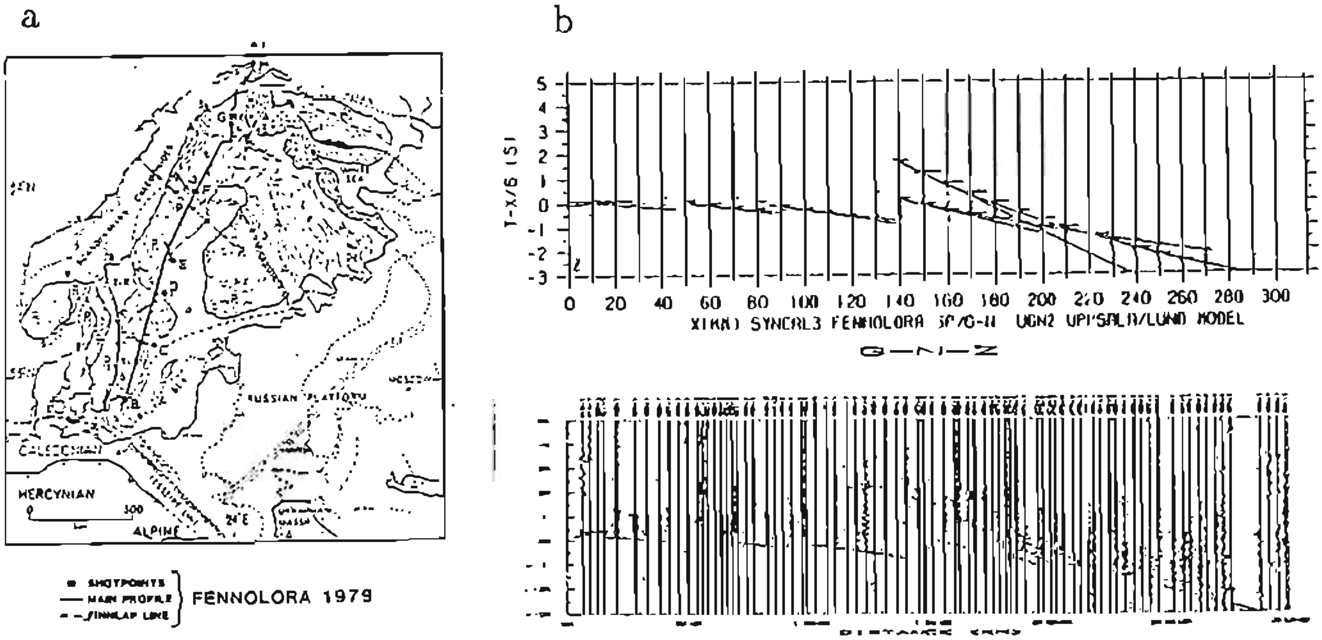
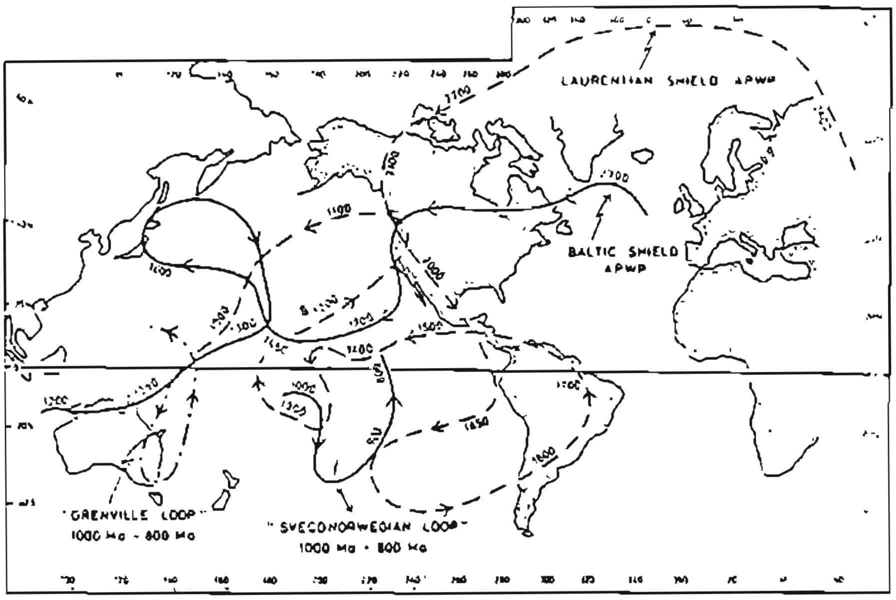


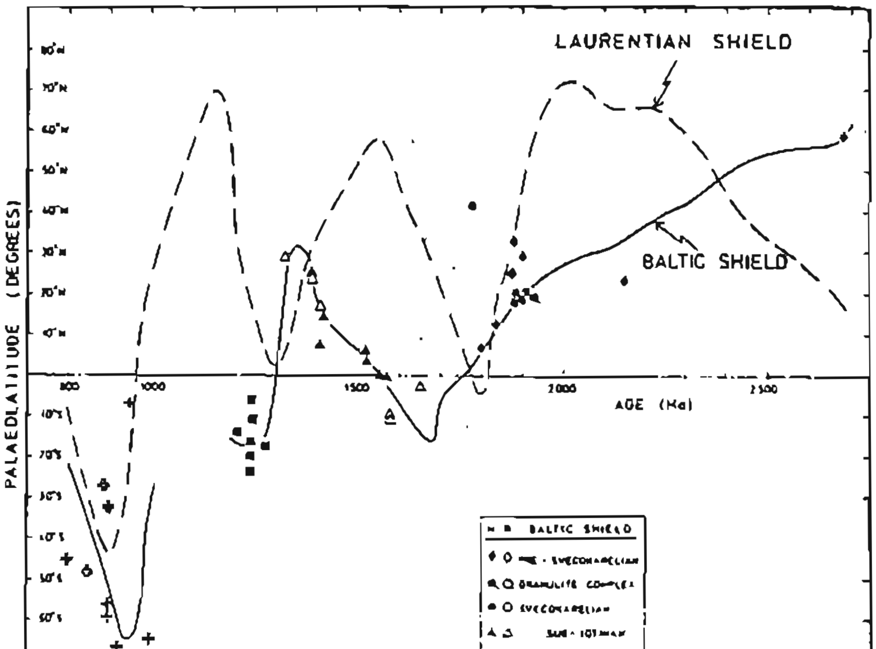
Fig. 10. a) Tectonic map of Scandinavia with the shotpoints (B, C, D, E, F, G, H, and I) and recording lines for the Fennolora profile superimposed (Olsen & Lund 1984). The tectonic base map is an older version of Berthelsen & Marker's (1986) map shown in Fig. 2b. Note that the labeling of the tectonic provinces is changed, e.g. A_3 to P_1. b) Vertical component record section for FENNOLORA shotpoint G-north (G-N) below and synthetic section above. Bandpass filtered 1-20 Hz.

Paleomagnetism

Paleomagneticians generally agree that the continents were moving in Proterozoic time in much the same way as present day plates. For example, Irving & McGlynn (1981) conclude that large but as yet very poorly described motions, have occurred relative to the pole for Laurentia during Early Proterozoic time. Paleomagnetic results further indicate that, except for the Grenvillian and Sveconorwegian Provinces the Canadian and Baltic Shields were single entities since Early Proterozoic time (Irving & McGlynn 1981, Pesonen & Neuvonen 1981). The shape of the APW path of the Baltic Shield differs from that of the Canadian Shield (Fig. 11a), indicating independent drift of the shields at least during part of the Precambrian (Pesonen & Neuvonen 1981). The dissimilar paleolatitude (Fig. 11b) curves of the two shields support this idea. However, during the Svecokarelian/Hudsonian Orogenies the two shields had similar paleolatitudes. A juxtaposition of the shields may have been caused by collision during the Hudsonian/Svecokarelian Orogenies (Pesonen & Neuvonen 1981). In Early and Middle Proterozoic rocks the paleomagnetic signature of local rotations about vertical axes is observed, and Irving & McGlynn (1981) argue that such rotations were common in Proterozoic terrains as they are in Phanerozoic foldbelts.



a



b

Fig. 11. a) Comparison of the APW paths of the Baltic and Laurentian (Canadian) Shields (Pesonen & Neuvonen 1981). Closing the Atlantic Ocean into its pre-Mesozoic state would move the Baltic Shield poles approximately 38° to the west. b) Paleolatitude curves for the Baltic and (Laurentian) Canadian Shields (Pesonen & Neuvonen 1981).

The APW speed (c. 0.35°/Ma) of the Baltic Shield during the Precambrian is significantly lower than that of the Canadian Shield (0.50°/Ma). Remanent magnetization with "normal" polarity is dominant in the Baltic Shield (Pesonen & Neuvonen 1981).

Discussion and conclusion

The evidence for Precambrian plate tectonics is increasing steadily and the concept has found growing acceptance. The geological evidence is belts of calc-alkaline volcanic and plutonic rocks and structural, lithological and age discontinuities. Advances in geophysical techniques are however also providing high-resolution constraints for tectonic modeling.

In the Trans-Hudson and Svecokarelian Orogens, fossil plate boundaries or sutures can be defined by an abruptly terminated magnetic pattern, paired gravity anomalies, electrical conductivity anomalies, low velocity layers and gently dipping seismic reflections. It can be argued that some of these characteristics do not seem to occur along the whole of the proposed geosutures. But they are all found along one or more sections. We know also that modern continent-continent collisions are very complex involving large-scale faulting in addition to multiple continental thrusting (Allègre et al. 1984). Evidence for the association of paired gravity anomalies with proposed Early to Middle Proterozoic geosutures is also documented from other shields: the Indian shield (Eastern Ghats granulite belt), (Narain & Subrahmanyam 1986) and the South African Shield (Limpopo-Kaapvaal fossil plate boundary), (Emenike 1986). A similar pattern is also described for Late Proterozoic to Early Phanerozoic mobile belts in western Africa and Brazil (Pan African and Brazilian belts), (Lesquer et al. 1984) and Australia (Peterman Ranges), (Forman & Shaw 1973).

None of the paleomagnetic evidence is inconsistent with plate tectonics but the record is fragmentary (Irving & McGlynn 1981). We do not know if there was as significant contribution to APW from true polar wander. If the latter is negligible then these minimum drift rates are very rapid indeed and comparable to the rates of motion of oceanic plates of today.

Fig. 12 shows proposed plate tectonic models for the Hudsonian and Svecokarelian Orogenies. They show an initial phase of rifting and rupturing followed by closing of the oceanic basin by subduction and a final stage continent-continent collision. They all illustrate the subduction of an oceanic plate taking place approximately 1800 Ma ago. The motion of these plates during subduction is indicated by the paleomagnetic data. The location and appearance of the geosutures can be interpreted from aeromagnetic, gravity, seismic and geomagnetic sounding. It can be concluded that geophysical techniques are essential for delineating and studying plate motion and continent-continent collisions within the Proterozoic.

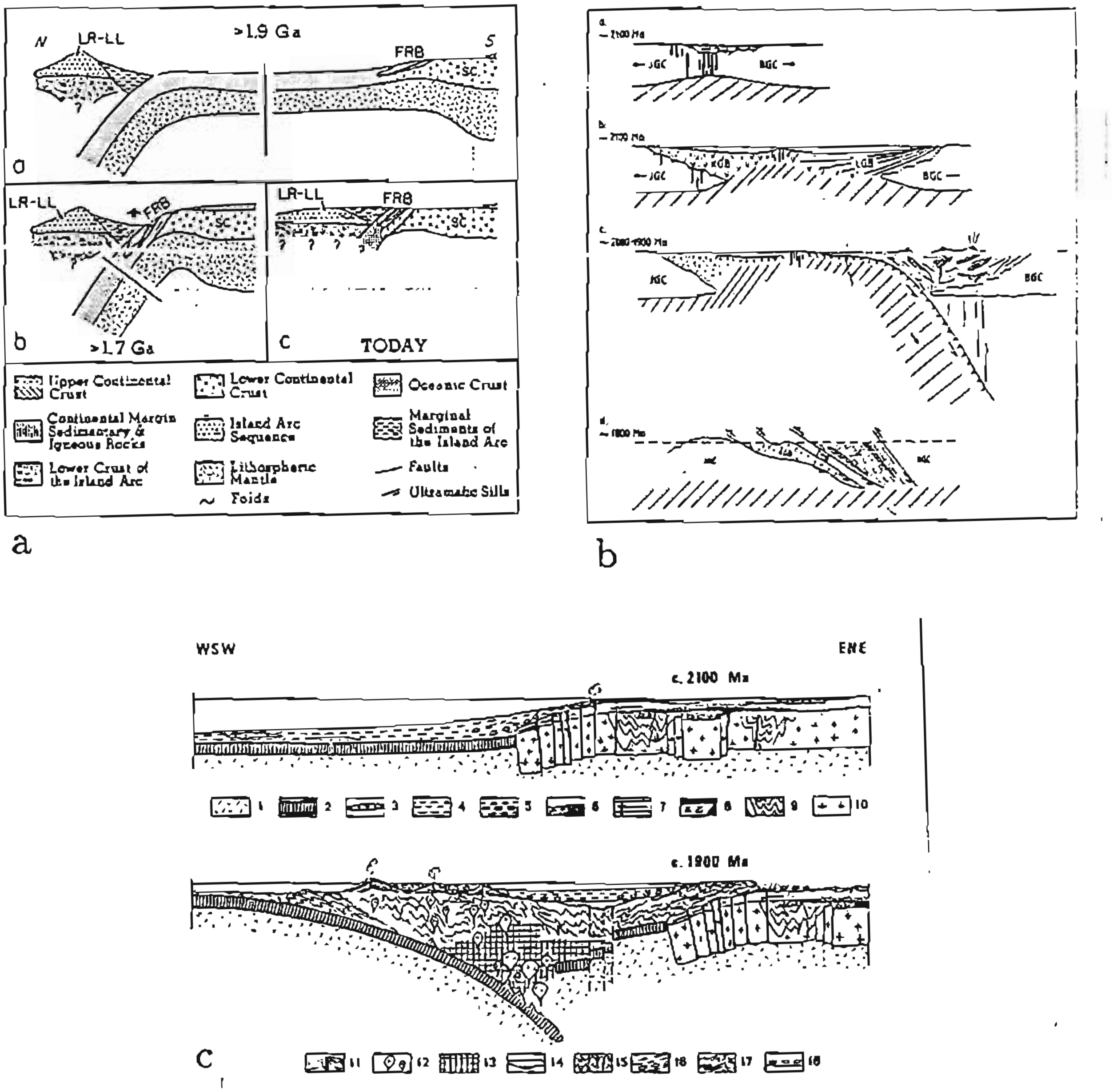


Fig. 12. a) Suggested evolution of the Hudsonian Orogeny in northern Manitoba and Saskatchewan (Green et al 1985). P - Pikwitonei, FRB - Fox River belt, TNB - Thompson nickel belt, LR-LL - La Ronge-Lynn Lake belt. b) Proposed tectonic development of the Svecokarelian Orogeny (P_1 in Fig. 2.b) in the Karasjok-Levajok area (Krill 1985). JGC - Jer'gul Gneiss Complex, BGC - Baišvarri Gneiss Complex, KGB - Karasjok Greenstone Belt, LGB - Levajok Granulite Belt, TMB - Tanaelv Migmatite Belt. c) Plate tectonic model of the Svecokarelian Orogeny (Gaal et al. 1984), P_2 in Fig. 2.b. 1 - Upper mantle, 2 - Oceanic crust, 3 - Serpentinites, 4 - Distal turbidites, 5 - Proximal turbidites, 6 - Tholeiitic volcanics, dolomites and iron formations, 7 - Jatulian quartzites, pre-Jatulian weathering and diabase dykes, 8 - Conglomerates and mafic volcanics, 9 - Greenstone belts, 10 - Archean granitoids, 11 - Calc-alkaline volcanics, 12 - Granitoid diapirs, 13 - High-grade metamorphism of low-pressure type, 14 - Tholeiitic volcanics, 15 - Deep-seated faults, 16 - Svecofennian turbidites with conglomerate intercalations, 17 - Folded older turbidites with serpentinite, 18 - Molasse.

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