THE *LITHOPROBE* PROJECT
“PROBING THE LITHOSPHERE”
TEXT to ACCOMPANY SLIDE PRESENTATION

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SLIDE # 1: Title slide with funding acknowledgment.

SLIDE # 2: Title page of brochure.

I. INTRODUCTION

SLIDE # 3: Global map, showing continents and ocean basins.

(Leave slide # 3 on until we come to slide #4). LITHOPROBE is conducting the first multidisciplinary study of a whole continent. Canada is the first nation to do this.

I. 1 OCEANS AND CONTINENTS

When we look at the globe, or at a map of the world, we can't help being impressed by the vastness of the large oceans: the Pacific, Atlantic, and Indian Oceans, even the Arctic Ocean.

Airplanes take long hours crossing them, ships several days and sometimes weeks. Oceans seem to tell us they have been there forever, mighty, powerful, and permanent.

They are all of that -- or almost. They are quite young, measured in geological time. By and large, they are not older than 180 million years (Ma); which, of course, is quite old, but not compared to the age of the continent we are living on, which had its beginnings more than 20 times farther back in time.

So, where do oceans go when they grow old? Good question! We shall know more about this after the slide show is over.

Most of us will be surprised to hear that in many parts of our country -- where today we grow grains, raise livestock, and mine resources -- an old ocean once may have been, dotted by beautiful islands, small and big. Or, a majestic mountain chain, which would have blocked our view, may have towered there had we been around that early in Earth's life.

SLIDE # 4: Tectonic element map of North America.

Canada, that is the old Canadian Shield in the centre, and the younger additions surrounding it, started to grow from at first smaller pieces of land not long after our planet Earth had been born about 4,600 million years ago (4,600 Ma).

The oldest rocks found on Earth are dated at about 4,000 Ma and are exposed in the western Northwest Territories, in the Slave Province, one of the older "Archean cratons" from which the Canadian Shield eventually was formed.

SLIDE # 5: Geological time table.

Canada contains the oldest and some of the youngest rocks on Earth, and most of what came in between. It is an ideal place to study how Earth's continents and oceans were formed.

I. 2 THE LITHOPROBE PROJECT

The LITHOPROBE project is propelling Canadian earth scientists into the next century -- ahead of other nations' comparable efforts.

This continues a century-and-a-half-long Canadian tradition of excellence in this sector of science.

SLIDE # 6: Map showing the national extent of participation in LITHOPROBE.

The LITHOPROBE project is unique for its choice of subject, its national scope, its complementary use of relevant earth-science disciplines, and its collaboration among federal and provincial geological surveys, the earth-science departments of most Canadian universities, and private industry. It is a multidisciplinary, all-Canadian undertaking in which Canadian earth scientists take justifiable pride.

SLIDE # 7: Graph showing the integration of the various earth-science disciplines in the LITHOPROBE project.

Canada is the first nation to fully probe how the lithosphere of a whole continent was forced together, and sometimes torn apart, during thousands of millions of years of drifting, squeezing, pulling and tearing, ever since Earth formed within our solar system about 4,600 million years ago.

Probing Canada's lithosphere involves some 500 specialists from the various fields of the earth sciences who lend their talents to the LITHOPROBE Project, Canada's national inner space program, the first national, multidisciplinary and deep exploration of the roots and growth of a continent.

I. 3 PROBING THE DEEPEST SECRETS OF OUR CONTINENT

So, let's go to the biggest of Earth's oceans, the Pacific. We start our journey into Earth's inner space at a beach, to look out at the place where the LITHOPROBE project got started a decade ago: Long Beach, at the mighty Pacific, on Vancouver Island, where people holiday and watch whales.

Out to sea, just over the horizon, and on the sea floor below the waves, the face of the Earth is being resculptured. How?

In a big way. Our continent is colliding with a part of the Pacific Ocean, bulldozing its unstoppable path across the ocean floor, and scraping off the ocean sediments to slowly add to the westward growth of North America.

Big as our mightiest ocean is, it is shrinking slowly but steadily, being squeezed by surrounding continental regions.

Thus, the west coast and its offshore are a good place to study this gigantic happening, which only is the most recent of several more such events which occurred earlier.

Indeed, it was here where Canada's LITHOPROBE Project, the pioneering study of our continent's growth over geologic time -- from small microcontinents to today's size -- had its beginning.

SLIDE # 8: Cartoon showing the subduction of an oceanic plate under a continental plate.

This schematic cartoon shows the outer layers of Earth's crust. The solidified lithosphere is some 100 km thick.

The phenomenon which causes processes such as shown in this schematic view of "**subduction**" of the "**oceanic plate**" under the continent is popularly known as "**continental drift**", but more correctly is called "**plate tectonics**."

These terms describe the constant shifting and jostling among adjoining crustal plates, which are like pieces in a mosaic which forms the hardened outer shell, the so-called lithosphere, of our planet.

SLIDE # 9: Global map of major tectonic plates.

Where Canada meets the Pacific something has got to give. It is the Pacific ocean floor which slides under Vancouver Island and the continent. We mentioned how the continent scrapes over the ocean floor, clearing off the soft sediments above the hard, igneous ocean crust like a bulldozer clears a street of snow. Here is an actual picture of this.

SLIDE # 10: Sidescan of ocean floor off Vancouver Island.

A marine side scan imaging system produced a sonar image of the sea floor, which is comparable to an aerial photograph of a land surface. This side scan was taken just at the position where the Juan de Fuca Plate is plunging beneath North America.

This causes sediments of the ocean basin to be scraped off the plate and thus attached to the continent.

The straight, blank strip crossing the middle of the image is the northwest-directed track which the survey ship is following. The scanner makes a 10-km wide image of the sea floor (see the scale), but leaves out the blank area directly below the ship.

The light grey image area with no features, seen below the blank strip, shows the flat ocean bottom. Above the strip, the darker grey areas depict the first rumpling and thrusting of the sediments covering the ocean floor. As the heavier Juan de Fuca Plate slides under the lighter North American continent, the latter acts like a bulldozer pushing the sediments resting on the ocean plate into hills and ridges which are hundreds of meters high.

SLIDE #11: Cross section through the lithosphere of the west coast.

Our west coast is an example of plate tectonics in action. New oceanic crust continually forms where magma is oozing from the Juan de Fuca Ridge, some 200 km west of Vancouver Island. The new crust is subducted under Vancouver Island and largely recycled into magma when it reaches greater depth under the Coast Mountains, where volcanoes vent excess gases, fluids and magma through cracks in the crust.

I. 4 EARTHQUAKES and VOLCANOES

So, where we are standing, at Long Beach, the Juan de Fuca plate is dipping under. As it is squeezing under the continental crust, some of the overlying layers get caught in it.

Imagine the layers of the overriding continental crust as thin layers of sheet metal, getting caught on the uneven ocean floor. They will bend and be dragged along until something will give.

When eventually they do break loose, they literally tend to snap back with a bounce. Nature lets us know about this event quite forcefully -- through an earthquake. It can be very strong, whipping up giant waves (tsunami) in the ocean, which will slam into the coast, often causing widespread destruction. On land, earthquakes also create waves -- ground waves -- leaving even worse consequences in their wake.

Meanwhile, the oceanic plate continues its downward path under the continent (at the high speed of 4 cm/yr), becoming ever more heated and pressured. Water trapped in pores and minerals is released, solid rock turns into a melt, and subducted, lighter and super-pressured material seeks its escape through cracks in the continental crust above.

Presto, you generate a volcano, actually a whole string of volcanoes, located inland from the earthquake zone. Mount St. Helen’s was the last one to pop; Mount Garibaldi did the same somewhat earlier. The most recent eruption of a volcano in B.C. was Mt. Meager, about 2,350 years ago. For those in S.W. British Columbia, the volcano that erupted most recently in their area is not in Canada - it’s Mt. Baker, just south of the border. The last significant eruption there was in 1872 and minor eruptions have occurred since.

The Pacific Ocean is surrounded by such a "ring of fire." Earthquakes and volcanoes show us how active plate tectonics are; where Earth's lithosphere, its hard outer shell, is changing.

I. 5 A GROWING OCEAN

Let's follow our national motto and go to Canada's other shore, from sea to sea, "a mari usque ad mare," from Vancouver Island to Newfoundland.

Now we are looking out on the **Atlantic**, a still growing ocean as the North American continent is moving away from Europe.

SLIDE #12: Topography of the Atlantic Ocean and surrounding continents.

Canada's east coast is a "passive" continental margin, which is widening, while our Pacific coast is an "active" continental margin, overriding the ocean floor.

The Atlantic Ocean still is growing, some **180 million years** after it began to open, when our continent rifted away from Europe and Africa. Northward, in the North Atlantic, rifting started later. This rift, out of which the Atlantic eventually grew, broke up a former supercontinent, called Pangaea. One can say that eastern Newfoundland once was part of western Africa.

The Atlantic continental shelf is wide here, providing spawning beds on the sea floor, and deep, sediment-filled basins below. Some sediments are rich in oil and gas, and include the famous Hibernia oil field.

SLIDE #13: Map depicting the relationship between surface geological units (named segments) and underlying, deep crustal blocks (coloured).

Look for line 86-2 which we show in the next slide.

LITHOPROBE is looking deep below the beaches and even the oil fields. LITHOPROBE is investigating the relationship between the deep crustal plates and overlying terranes along the Continental Margin of the Maritimes. How?

SLIDE #14: Seismic cross section line 86-2 illustrates the relationships of overlying rocks to the underlying crustal blocks. Upper portion shows seismic data; lower portion is an interpretation of the same data.

*By sending **seismic** signals, really sound waves, from the surface to great depths, and recording **reflections** from there. In a later slide, we'll find out more about how this technique works. This is how LITHOPROBE's scientists obtained the deep reflection data from which they could construct this "**seismic cross section**."*

These visits to the Pacific "active" and Atlantic "passive" continental margins have given us some idea of the **dynamics** of plate tectonics.

Now, let's move into the heartland of the continent, onto -- and into the inner space of -- the Canadian Shield.

II. THE GROWTH OF CANADA DURING 4,000,000,000 YEARS.

SLIDE # 15: Tectonic map of North America.

The Superior Province is the heart of the continent. It is ringed by additions which were welded to it along "collisional belts," among them the Grenville Province and the Trans-Hudson Orogen. In a moment, we shall look at how such collisions occur.

Like the Superior Province, the Hearne-Rae, Slave, and Nain Provinces are of Archean age.

The Appalachians and Cordillera, on the other hand, are the most recent additions to our continent, which occurred during the Phanerozoic. That is the last big chapter in our planet's history, remember, when Earth already was alive with many forms of advanced life, some small fraction of which we now find preserved in fossils.

Let's refresh our memory and go back to the geological time table we saw earlier.

II. 1 THE PRECAMBRIAN HEARTLAND

SLIDE # 16: Geological time table.

You find the ages of the heartland of the Canadian Shield in the bottom, old part of the table, and of the younger ones in its upper part, and, on the map we just saw, toward the edges of the continent.

The oldest continental crust originally was transformed from colliding plates of oceanic crust which eventually became stable cratons, the foundations of a growing continent. The North American craton is one of the oldest, and probably the largest, craton in the world. Its core is the heartland of our continent.

SLIDE # 17: Tectonic elements of North America, with the sedimentary cover removed.

It looks a bit different from other maps in that the Baltic Shield is shown where it once had been, and Greenland is restored to where it had been before it rifted away from North America. And it shows more detail than the earlier map of tectonic elements. The yellow boxes outline LITHOPROBE's 10 study areas (or transects): SC, Southern Cordillera; SNORCLE, Slave-Northern Cordillera Lithospheric Evolution; AB, Alberta Basement; THOT, Trans-Hudson Orogen Transect; WS, Western Superior; KSZ, Kapuskasing Structural Zone; GL, Great Lakes International Multidisciplinary Program on Crustal Evolution; AG, Abitibi-Grenville; LE, Lithoprobe East; and ECSOOT, Eastern Canadian Shield Onshore-Offshore Transect.

II. 1.1 ARCHEAN CRATONS — REAL OLDTIMERS

A SHORT PRIMER ON HOW GEOLOGICAL TIMES ARE CRYSTAL CLEAR.

We already heard that the Archean protocraton is an aggregate of six former microcontinents, named "provinces" (e.g. Superior Province). Each of the six provinces is a Late Archean, crustal aggregate containing variable proportions of Early and/or Middle Archean crust; they each have an internal, evolutionary history. Look for the red and purple colours on the slide.

This Archean protocraton has been named Laurentia. It contains the Slave, Nain, Superior, Wyoming, Hearne and Rae provinces, all former microcontinents.

The oldest known rocks on Earth, about 4,000,000,000 years old (that's 4,000 million years old or 4,000 Ma), occur in the western part of the Slave Province.

Although each of the six Archean provinces had a different history, they all have had major crustal growth between 2,800 and 2,600 Ma. New lithosphere formed from underlying, partially molten rocks.

During the Early Proterozoic, rifting occurred in these oldest provinces. Subsequently, these Archean microcontinents were welded together by enormous and lengthy collisions which raised mighty mountain belts (orogens) between them, primarily from 2,000 to 1,800 Ma. The continent of North America began to take shape.

A SHORT PRIMER ON HOW GEOLOGICAL TIMES ARE CRYSTAL CLEAR

How can we know when something that long ago actually did take place? By looking at a long-range time clock which nature has built into certain minerals and elements.

SLIDE # 18: Mass spectrometer.

This slide shows a mass spectrometer, which allows precise measurements of isotopes contained in minerals.

Geochronology is a special branch of geochemistry, related to isotope physics, that involves determining the time of formation of rocks, minerals and fossils. Geochronologists examine materials ranging in age from a few years to billions of years old, mostly utilizing the principle that radioactive isotopes present at the "birth" of a mineral will decay at a certain fixed rate. Measurement of relative abundances of the "parent" and "daughter" isotopes can determine the age of the rocks.

One example of the use of radiogenic isotopes is the uranium-lead (U-Pb) method of dating zircons.

SLIDE # 19: Zircon crystal. Image is from a scanning electron microscope. Red shades show high uranium content; green shades show low uranium content.

Zircon occurs in small quantities in many crustal rocks and contains a small amount of uranium (U), which decays to lead (Pb), with a half-life (of 4,500 Ma) approximately equal to the age of the Earth (4,600 Ma). By measuring the abundances and isotopic ratios of U and Pb in zircon, the age of the rock can be determined with a precision on the order of 2 to 5 Ma, i.e. better than one part in a thousand.

In LITHOPROBE, geochronology is important in providing the detailed age control for surface rocks and intrusives that is essential to unraveling their local geological history.

II. 1.2 PROTEROZOIC TIMES STITCH LARGE QUILT

Back to building the really old, central parts of Canada! Now, the old cratons get stitched together into a giant quilt which will cover much of the continent.

SLIDE # 20: Tectonic elements of North America, with the sedimentary cover removed.

When the old microcontinents collided, they pushed all that had been between them together into collisional orogens, including newly formed magmatic material (called "juvenile" rocks) and accreted oceanic terranes, such as islands and groups of islands.

*Take a look, for example, at the northwestern corner of North America. The ancient **Slave** geological province is surrounded by three different domains called Wopmay (in the west), Taltson (to the south), and Thelon (on its east side). What are they?*

*The **Wopmay** terrane was already over the hump at about 2,400 to 2,000 Ma years when it was attached or "accreted" to the Archean Slave protocraton between **1,900 and 1,700 Ma**, forming the Wopmay orogen. The **Taltson** terrane, on the other hand, is a magmatic arc and relative youngster, whose plutons are **1,990 to 1,950 Ma**. The **Thelon** terrane also is an orogen, i.e. a mountain belt. It was formed through an oblique collision between the Slave and Rae provinces. This happened **1,970 to 1,920 Ma**. It is the oldest orogen along which Archean provinces were welded to each other.*

*The **Superior Province** is the largest component of the old continent, a typical part of the **Canadian Shield**. The Superior province collided with the **Hearne** and **Rae Provinces** to the north and northwest, which also are of Archean age, at about **1,900 to 1,800 Ma**.*

*This collision formed the **Trans-Hudson Orogen**. It extends from the central United States across Manitoba and Saskatchewan. Then, it turns east and northeast across the Hudson Bay to northern Quebec and Ungava Bay, where the orogen is named **New Quebec Orogen**, completing the long weld or stitch between the Superior, Hearne and Rae Archean provinces.*

*To the northeast, the **Nain Province** includes rocks older than **3,800** Ma, which have been highly metamorphosed. By **2,600** Ma, Nain province was complete, including its eastern extension into Greenland (and beyond, to Europe). Remember how we can tell the ages of rock formations? By looking at the earth scientists' reliable atomic clock — by measuring the known rate of decay of radioactive isotopes.*

*Look again at our map, the **"Tectonic elements of North America,"** this time at the northeast corner, where the northeastern edge of the Superior Province juxtaposes the southwestern one of the Nain Province. One would have been ill advised to stand between them, because these two old cratons did what eventually they seem destined to do, squeeze and crunch together what lies between them, compressing wide regions, oceans, and so on, into relatively narrow mountain belts or orogens.*

In this case, it happened to include an eastern extension of the Rae province which, we saw earlier, was involved in squeezing the Trans-Hudson Orogen against the Superior province, creating in this region the New Quebec Orogen, an easterly relation of the Trans-Hudson Orogen.

*On the other side of the Rae Province (also known as Eastern Churchill Province here) the crunch from the Nain Province created the **Torngat Orogen**. Perhaps, we should switch to a detailed sketch of this area.*

SLIDE # 21: Tectonic provinces of the North Atlantic region.

*Earth's dynamic forces (or tectonics) didn't stand still at the southeastern side of Nain Province, either. Here the **Makkovik Orogen** was formed about **1,800 Ma**.*

Have a look at the heavy, serrated lines on this map. They show the contacts along which one geologic unit was thrust against the other. Thus, they denote regions of gigantic thrust faults. The notches point into the direction *whence the thrust came. Actually, that isn't quite precise to say. The notches are on the side of those rock formations which were thrust on top of the formations on the other side. Now, where these lines of thrust, or thrust faults, meet, there is only one survivor — namely the last one, which overrides all the imprints which had been left before.*

We can see this on the map, where the later ***Labrador Orogen*** *thrust cuts across the former New Quebec and Torngat Orogens (or mountain ranges), as well as the central core of the Rae (Churchill) Province between them. The thrust of the* ***Labrador Orogen*** *occurred at about* ***1,700 to 1,650 Ma****, or 100 to 150 Ma after the Makkovik thrust. The reason for the seemingly imprecise figures is that these processes don't happen in one bang, but proceed over a longish geological time period. Continents and ocean plates don't move as fast as an express train, but they are even harder to stop. Some 600 Ma after the Labrador Orogen had been pushed together another, and much stronger, push from approximately the same direction created the mighty* ***Grenville Orogen,*** *reworking the eroded remnants of the Labrador Orogen in the process.*

SLIDE # 22: Total magnetic field map of the ECSOOT region showing relationship of magnetic images to tectonic features.

When igneous or sedimentary rocks are formed, the minerals with magnetic properties contained in them align themselves parallel to the force of Earth's ***magnetic field****. Intensities of magnetic minerals, and their alignment, will vary from place to place. With the help of computers we can display the different magnetic intensities as colors on a rather striking map, which shows up the different tectonic elements.*

On the left of the slide we see the northeastern corner of the Superior Province, and on the upper right the southwestern extent of the Nain Province. These two Archean cratons crunched between them all of the tectonic terranes which are aligned along the roughly north-northwest trending fault lines in the centre and upper portion of the map -- the eastern extension of the Trans-Hudson Orogen. The great Grenville Orogen cuts across it all with a mighty push from the south, wiping out the pre-existing tectonic signatures with its roughly east-west trending features.

SLIDE # 23: Tectonic elements of North America, with the sedimentary cover removed.

When we started out we mused about old oceans lying buried inside our North American continent. Without wishing to look dreamy about it, one could conjure up visions of archipelagoes in the south Pacific. So, let's dream about it. Where? In the middle of our prairies, of course, in Saskatchewan, and in parts of Manitoba.

We are coming back to the ***Trans-Hudson Orogen (THO)****, which now is the eroded remnant of a series of collisions. Once it had posed as an ocean with island arcs in a rather milder setting — before the big crunch of Superior Province (in the southeast) against Hearne-Rae Province (in the northwest) put an end to this, about* ***1,900 to 1,800 Ma****. The THO encompasses a particularly complete example of tectonic events which welded together a number of pre-existing minicontinents into the North American continent. In Saskatchewan-Manitoba this orogenic belt is 500 km east to west, one of the best preserved examples of a collisional orogen.*

It includes areas in which mining companies have shown a keen interest. And west of the THO lies the **Alberta Basement** which also is of interest to exploration companies, mostly with respect to oil and gas. We will go west right after we have looked at the THO.

We ourselves are, of course, not an exploration company, and we are not looking for gold or oil or diamonds. LITHOPROBE is engaged in fundamental research. Nevertheless, our studies help trace and understand the geological framework in which minerals and oil and gas deposits form, and diamonds may find their way to the surface through volcanic pipes, from very deep-seated sources. And where appropriate we address the problem of why we have earthquakes or volcanoes.

SLIDE # 24: Geological map of the exposed Early Proterozoic Trans-Hudson Orogen between the Archean Superior craton to the

southeast and Archean Hearne craton to the northwest.

Geologists wax enthusiastic about the Trans-Hudson Orogen because it is one of Earth's great examples of a preserved collisional belt. Perhaps, they cherish the orogen's very complexity, an outcome of a colourful tectonic history, represented by rift and strike-slip as well as compressional styles, juvenile oceanic crust to remnants of an old Archean craton, and just about everything else in between.

In Saskatchewan-Manitoba the Trans-Hudson orogenic belt is subdivided into four major tectonic zones which our slide shows. We see a southeastern foreland zone (yellow with TB and adjacent dark red), a large internal zone of juvenile Proterozoic crust (includes FFB, KD, HLB, GD and RD), an Andean-type magmatic arc batholith (red with WB), and a northwest hinterland zone (yellow with WD).

The southeastern foreland zone is the narrow Churchill or Boundary Zone, which includes the Thompson belt (in dark red and yellow). The zone forms a dogleg going from southwest to east along the edge of the Superior craton. Petrochemistry of ***volcanic*** *rocks in this zone suggests that the volcanics and the associated metasediments (= sediments altered or metamorphosed by heat and pressure), formed in a* ***rift*** *(where the crust partially split).*

The internal Reindeer Zone extends over to the other side of the THO (to the opposite fold belt marked in yellow). The Reindeer Zone is a 400-km-wide collage of Early Proterozic ***(1.9 to 1.8 Ga) island-arc volcanics, plutons*** *(underground magma intrusions), volcanogenic (derived from eroded volcanoes) sediments, and younger molasse (= detritus from mountain ranges) derived from newly formed mountains. These Early Proterozoic* ***island-arc terranes*** *were severely deformed by the vice action of the* ***collisions****, and include imbricated sheets of rock formations* ***thrust*** *upon and into each other. Remember that between them the Superior and Hearne-Rae Provinces crunched the whole works together.*

Geochronological analysis using isotope measurements has shown the Wathaman-Chipewyan batholith (red with WB) to have been emplaced at about ***1,855 Ma****. (A "****batholith****" is a large-volume magmatic intrusion into overlying rocks, and comprises many individual plutons.) It sits between the arc terrane of the Reindeer zone to the southeast and reworked continental rocks previously eroded from the Archean Hearne-Rae craton to the northwest.*

The fourth zone is the hinterland of the sequence, the Wollaston Fold belt (yellow with WD). This zone also is highly deformed and metamorphosed, and complexly interfolded with Archean basement rocks.

Many disciplines of the earth sciences contribute to the research sorting out this complex overall picture of past tectonic events. Comparisons of this old orogen are made with, say, the western part of the modern Himalayas where comparable oceanic rocks are sandwiched between two converging continents (India northward against Eurasia). Let's cut a vertical slice through this map, crossing its tectonic trends.

SLIDE # 25: A geological cross-section showing the principal tectonostratigraphic units of the Trans-Hudson Orogen. It is based on seismic reflection profiles (whose locations, lines 2, 3 and 9, were shown in the previous slide), as well as on geological information obtained at the surface and from drill cores, and on potential field maps. The stippled lines indicate in a schematic fashion the dip and frequency of seismic reflections.

LITHOPROBE's seismic cross sections show a THIRD Archean craton to be present (purple blob above "Reflection Moho"), over which the overlying rock layers were pushed and shoved and now drape, to the west on its west side, to the east on its east side. (See the schematic cross section shown on the screen.) This discovery of a formerly unsuspected, additional Archean remnant between the Superior and Hearne-Rae cratons, and within the general THO domain, came as a complete surprise to the geoscientists. Although hidden underground from direct view there are several "basement windows" in the Glennie Domain which may belong to the same, newly discovered craton.

This find in central Saskatchewan's underground also has a deep crustal root, as is expressed in the local thickness of the crust, whose base is defined by the (seismic)

***Mohorovicic discontinuity**, or "**Moho**" for short. (See the lowest unit in the schematic cross section.) The question now is how far this third Archean block extends to the north and south. Is it an ancient microcontinent, does it connect somewhere? Diamond hunters are interested in this find in that wherever the crust is thick and Archean, the potential for diamonds is great. Kimberlite occurrences (the volcanic pipes which are potential sites for diamonds) appear to be associated with this Archean block.*

We want to remember the assembly of THO, the map showing the tectonic units, and the schematic cross section which crosses them to give us a 3D image. This is because at the same time the THO came about through continental collisions, the same happened over the area which now underlies Alberta. It seems to have been a more or less simultaneous (or coeval) series of events, a sort of double billing, with two large mountain belts having been formed side by side, as it were, separated only by the Hearne Province, which itself was deformed and imbricated (different slices of it thrust on intermingled, thereby forming a stack).

SLIDE # 26: Tectonic elements of western Canada. Dark blue lines denote seismic reflection profiles and the dashed red line shows the northern limit of sedimentary cover.

*We recognize the old **Archean** cratons, the **Superior, Rae** and **Hearne** in pink. Pay attention to the **Snowbird Tectonic Zone** which we again will encounter in maps of the **Alberta Basement**. The **Snowbird Tectonic Zone (STZ)** is a very prominent, very important, once very active, now very old tectonic feature along which truly gigantic tectonic battles were fought between contending continental plates.*

*Follow this line southwest, into the **Alberta Basement transect** area, where the STZ abruptly ends at the eastern edge of the **Rocky Mountains**, cut by a mighty thrust fault (line with teeth) which we can see today from the air and on the ground.*

*The Cordillera represents the youngest addition to our continent, one which, really, still is ongoing. Remember when we stood at the Pacific coast, at Long Beach on Vancouver Island, looking west to where, under the ocean, a Pacific oceanic plate is moving (or subducting) under our continent? It is moving **now**, while we are looking at the map.*

*Anyway, the **STZ** can be followed from the Rocky Mountain foothills northeast, and then east, all the way to Hudson Bay ...... Earth scientists can pick this tectonic zone out in many **outcrops** on the ground, on aeromagnetic and gravity maps, and, sometimes, on seismic reflection lines which cross it.*

We remember that this is a map from which we have stripped the sedimentary cover where it exists today (in most of Alberta, say), hiding the crystalline underground and the old tectonic units from our eyes. The only orogens (mountain belts) which still are visible to the eye today as a picture similar to that when they were formed are those which have not yet been fully eroded or covered by later sediments, those which still are mountains, like the Appalachians in the east and the Rocky Mountains in the west.

*How do we know that the **basement** below the sediment cover is there? Good question! That's what the LITHOPROBE project is all about, that is to see not only where rocks are exposed but also far below them, down to their roots. On this map, for instance, we can follow the tectonic and rock units from the Canadian Shield into the areas where the Shield becomes covered with sediments. One way we do this is by using an aeromagnetic map such as this one.*

SLIDE # 27: Aeromagnetic potential field map of western Canada. White lines denote seismic reflection profiles.

Note that patterns from the exposed rocks in the Shield can be followed below the sedimentary cover.

*Let's remember how units on the western side of the **Trans-Hudson orogen** dip into the **Alberta Basement** transect area. The geological cross section we just looked at runs about east to west near the southern edge of THOT. Follow this westward across the AB transect and we cover about 1,000 km as we cross the **STZ**. Within this distance we have two huge, once mighty and now eroded, mountain chains which comprise the THO and the Alberta orogen, which still is unnamed; its* *discovery is that new. By the way, what would **YOU** call the mountain chain in the Alberta Basement? Any suggestions? Think about it as we look the Alberta Basement over.*

SLIDE # 28: Tectonic domains in the basement of Alberta and northeastern British Columbia. These maps were imaged from the interpretation of potential field data (aeromagnetics) and geochronological analyses (uranium-lead isotopes) of drill cores taken from the basement rock.

When LITHOPROBE's earth scientists check out the covered Alberta Basement they use all the tricks of the earth-science profession. We mentioned that they follow the exposed units in the bare Canadian Shield as they dip under the sediments, also that certain properties of the rocks underneath the surface can be measured by remote means: the resistance to electric currents induced in the earth by large sheet currents flowing in the earth's magnetosphere 10s to 100s of kilometers above the surface, for instance; or the different rock densities that perturb the gravity field; or variations in the content of magnetic minerals in rocks that affect the magnetic field, as well as other properties of the rocks below.

*But the sedimentary cover itself, the sediments deposited in the **Western Canada Sedimentary Basin** or **WCSB**, have many stories to tell. First, there is the undeniable fact that the basement had to sink to allow the basin to be formed. Also, from the exposed Shield to the front formed by the Rocky Mountains, the basin progressively becomes deeper, thus the rate of subsidence was faster closer to the mountains than close to the Shield. Think of sediment layers as wedges which are thin toward the Shield, and become progressively thicker toward the mountains.*

*And doesn't the map of the tectonic elements we are looking at give the sense that the **AB** really is quite a mosaic of different tectonic units? And those are just the big units; within themselves they also display differences.*

To make a quite complex story short, different parts of the basement have behaved differently over geological time. Quite possibly, they still do. Those portions in the basement which sank less rapidly than adjacent parts, or even rose, will have developed a thinner sedimentary cover during their times of differential movement.

*The **WCSB** has been poked into and even through by an immense number of wells. Their records have been kept. Seismic reflection and refraction surveys have provided many seismic cross sections which allow us to correlate between these wells. [And now you know what geophysicists and geologists in the oilpatch are doing for a living.]*

*We know the times of deposition of various sediment intervals from fossils they contain, and from isotope geochronological methods. So, by measuring the various sediment layers in the **WCSB** through well bores and by correlating seismic reflection surveys, we can tell when and where certain parts of the basin sank faster than adjacent ones, or when the reverse may have happened. It means a lot of work! Why do we go to all this trouble?*

*We are trying to establish this **interaction between basement floor and sedimentary cover** to determine in which manner the basement has exerted influence on the types and rates of sedimentation and/or erosion at certain times. This goes beyond mere **thickness** differentials and includes **types** of sediments deposited (i.e. sand or carbonates or clay), and what happened to them later when **formation fluids circulated** through the sediments.*

Again, the question is did the basement exert an influence, and how? Why, for instance, did reefs (often associated with porous structures that trap oil and gas) grow in Devonian times along certain lines and areas of the Alberta shelf? Why are there intervals with good porosity in some and not in other areas, often side by side?

*Such questions have immense implications for the oil and gas industry. For instance, the flow of formation fluids, and their chemical makeup, determine where **oil** and **gas** may migrate to, and where **porosity** may have been opened up through recrystallization of the sediments or else plugged by these processes. This explains why exploration-minded oil and gas companies take such an interest in the LITHOPROBE project.*

*But, we now want to get at the **basement** itself. How did this mosaic of different crustal units of varying ages and composition come about, and when? The oldest tectonic units we see on the map are shown in pink, and they are **Archean** in age. In the southeast are parts of the **Hearne** and in the northeast of the **Rae Provinces**. In the west lies what is called **Nova** here, but may be part of the **Slave Province** (which lies farther to the north).*

*Next oldest are the dark blue units, what is called **accreted terranes** here, units added on to what had been there before. Of similar, **Early Proterozoic** age are the purplish magnetic lows, **2,400 to 2,000 Ma**. And then come the hot orange terranes, including magmatic arcs which form where plates collide and rupture. This was the time of real tectonic action for the Alberta Basement, and also elsewhere along the western Shield, **2,000 to 1,800 Ma**.*

*In very general terms, the **Hearne** craton in the southeast collided with the accreted terranes and the **Slave Province** (or portions thereof) in the northwest, and, farther northward, the **Rae Province**. A later, northeast directed movement pushed the **Rae** and **Hearne Provinces** alongside each other.*

*And here we meet the mighty **Snowbird Tectonic Zone (STZ)** again, along which the northwest shoulder of the Hearne and southeast side of the Rae crunched alongside each other, eventually joining them. Remember it from our discussion of the **Trans-Hudson Orogen**? The **THO** was formed when the **Rae-Hearne Province** collided with the **Superior Province** to the southeast. Now you know why the **STZ** is such a mighty and persistent feature, being the fault line along which the **Rae** and **Hearne** moved relative to each other.*

*When we move from the THO map southwest along the **STZ**, the STZ eventually merges into the wider **Thorsby Low** (the purplish T area on our map). In central Alberta the Hearne and Rae don't rub each other, but left space between themselves. In fact, the Rae is gone as it angles in a clockwise move into the more northerly parts of the Hearne. Since we are at it, we might as well complete this complicated discussion. To do this, perhaps, we should look at the larger North American perspective once more. But before we switch slides, picture the **Rae** in the northwest, the **Superior** in the southeast, and the **Hearne** coming up between them. **Hearne** and **Rae** fuse along the **STZ**, then both squeeze the **Trans-Hudson Orogen** toward the **Superior Province**. Farther south, **Rae** to the northwest and **Hearne** did not fuse directly, but left oceanic and other crust between them. Orogens formed in THO, east of Rae-Hearne, as well as west of Hearne in Alberta. Part of what pushed things in the northwest was the **Slave** craton. Somewhat similar to what Rae did to Hearne in the north, the Slave moved alongside the Rae in a northeasterly motion, eventually fusing with the Rae. These wrenching movements took place along another enormous fault zone, known as the **Great Slave Lake Shear Zone** (GSL on the map), along which the northwest shoulder of the Rae and southeast side of the **Slave** crunched alongside each other.*

*At the risk of offending the experts, we might recall the recent **California** earthquakes — those which happened along the San Andreas fault, also a wrench fault. The similarity lies in the fact that the Pacific plate west of it is moving along the fault plane northward in relation to the North American plate. One difference with the **STZ** and the **GSL** shear zone is that along them **continental plates** were rubbing shoulders along much of their extent, the **Rae** and the **Hearne**, opening in the southwest, and **Slave** and **Rae** cratons, with the latter shear movement also squeezing the Thelon Orogen between them.*

If we are really daring we can look at some schematic sketches of our discussion:

SLIDE # 29: The Slave-Rae collision.

*Geochronological dating allows a sequential hypothesis, starting well back, and looking at the northwest corner of the previous slide. You see the **Slave** and **Rae** plates move towards each other but also starting the wrenching movement which centres along the **GSLSZ** in the right-hand portion of the slide.*

SLIDE # 30: Showing the relative movements of the Rae, Superior and Hearne cratons to each other, mostly in the Trans-Hudson domain, but also in parts of Alberta.

We have moved farther south here, and we should take in the position of the STZ.

SLIDE # 31: Oblique Rae-Hearne collision.

*Here we see the interaction between the **Hearne** and the **Rae Provinces**. In the northeast, they are one on one along the **STZ**, but farther south an opening is developing between them, notwithstanding the simultaneous movements which, however, are oblique to each other.*

*Some of the studies in the **Alberta Basement** transect are well advanced, such as regional magnetic and gravity maps, and geochronological investigations, even fluid movements. But others have only been partially done, with a lot more to come, especially with respect to deep seismic reflection surveys. So, we hesitate to include more maps as several only will become available during the coming years.*

Before we leave the prairie provinces let's look once more at the relevant portions of the:

SLIDE # 32: Tectonic elements of North America.

We should take in the two great fault zones, the **STZ** and the **GSLSZ**. And now, after the gigantic fusion processes of the **Early Proterozoic**, a much enlarged **Canadian Shield** entered a long period of relative tectonic quiet.

II. 1.3 THE COMPLETION OF THE CANADIAN SHIELD — 1,000 Ma AGO

There was only one orogenic intermission, so to speak, in the ECSOOT transect, which brought us the **Labrador Orogen** at about **1,700 to 1,650 Ma,** before the **supercontinent,** amalgamated from microcontinents, got set upon again by yet another squeeze from another geotectonic plate. There were long millennia of relative tectonic peace and quiet in North America, for at least 350 Ma, that is the time between the formation of the **Labrador** and the later **Grenville orogens**. During this period much anorogenic (non-orogenic) magmatism occurred.

*But then, following this period of placid stability, the biggest crunch ever came when the **Grenville Orogen** was formed by thrusting of previously deeply buried rocks upon the supercontinent by continents or microcontinents of uncertain affinity situated to the southeast. The Grenville Orogen arguably was the largest mountain system earth ever has seen. Its formation completed the main Proterozoic assembly of the continent, really a supercontinent now known as Laurentia.*

Think of how the Himalayas are being formed today as the old India craton is pushing its way against the underbelly of Eurasia. That's what happened then to what now is North America's easternmost Precambrian mountain belt, the Grenville orogen. We don't know the Precambrian equivalent to today's India, only that the resulting orogen probably was even bigger than the Himalayas are today.

*Have a look at the regions which are marked by the grass-green "**Grenville Orogen**". They include southeastern Ontario (places like Parry Sound, London, Kingston, Toronto or Ottawa), much of Quebec (Montreal, Sept-Isle), and much of Labrador. And note how long this orogen is, some 5,000 km long, starting in the south in northern Mexico, through the United States, eastern Canada, and, after leaving the Labrador coast, continuing into southern Sweden, where it is known as the **Sveconorwegian Province**. The missing piece in between is taken up by the Atlantic, which is a new rift. Actually, before the Atlantic started to rift another ocean had opened and closed, forming the Appalachian - Caledonide orogens in the process - about which we shall hear shortly.*

Think of the enormous height and width of the Grenville Orogen or mountain system! Even the remnant which we can map from geological and geophysical evidence today, is only part of the width the system once occupied, before it was torn asunder by Earth's relentness tectonic forces.

It takes a bit of imagination, but try to imagine high peaks like Mt. Everest, and frigid, windswept highlands like Tibet, where today one half of Canadians live, now on the very *roots of the Grenville orogen. Its mountains have been eroded away by rains and rivers and glaciers, the individual grains of its former majestic peaks distributed far and wide, some having been found 3,000 km away in the Arctic Islands. What remains today are rocks which once resided 30 to 35 km deep, like these mylonites exposed on the shores of Georgian Bay, where one can walk on rocks thrust there (onto the Superior province) when the Grenville continent was sliced up, thickened by a factor of 2 or 3 through stacking of the slices and then partly eroded, all more than one billion years ago. This formed an enlarged North America which is referred to later as* ***Laurentia****. Mylonites, by the way, are strongly deformed rocks typically found in thrust faults and zones.*

SLIDE # 33: Outcrop at Georgian Bay.

These rocks from the northern shore of Georgian Bay once were deeply buried. Having been thrust upon the North American craton during the Grenville Orogen, they now are proof of this event which took place prior to ***1,000 Ma****, that is one billion years ago!*

This is an example of using geological field mapping for tracing events which took place in the distant past and at various depths within the crust of the lithosphere. This includes the use of **geochemical**, **geochronological**, and **petrological** methods to determine the constituents (**source**), history (**time** of formation), and **depth** (temperature and pressure at formation) of the exposed rock units and the minerals contained in them.

Other surface observations which can be made in **outcrops** include the orientation of **magnetic minerals**, which **aligned** themselves with the magnetic field at the time of their solidification. (We already touched upon this earlier.) Their preserved orientation depends on their geographic location when their alignment occurred, that is their geographic latitude. Thus, the very concept of plate tectonics can be tested here, since these rock units were transported as their host plates moved.

Thirdly, their juxtaposition in relation to other rock units has to be taken into account since tectonic forces moved some rock units into new positions, as was the case with the thrust rock unit shown in the slide. All of the above observations come into play when one undertakes to unravel the present position of observed rock units.

Of course, we want to know what is going on below the surface, deep inside the lithosphere on which we live.

Remember the **seismic** cross section from the Atlantic coast? The **sound waves** we send from the surface to great depths in the lithosphere return as echoes (**reflections**) to the surface, where we measure them with **geophones**. More about the **seismic reflection technique** later; it is quite fascinating!

SLIDE # 34: Deep seismic reflections from the Grenville Front Tectonic Zone.

This seismic cross section gives you a coherent, underground picture of the gigantic ***thrusting*** *which built the* ***Grenville Orogen.*** *Think of it as a gigantic X-ray (or even better an ultra-sound) picture. The outcrop we just saw is but a tiny sliver within this package of many rock units, which contains many tens of kilometers of cumulative thickness. The tectonic push came from the right of the cross section.*

SLIDE # 35: Location of GLIMPCE seismic reflection profiles.

The seismic cross section we just saw was a portion of profile J in northern Lake Huron, from its intersection with the Grenville Front eastward, i.e. into Georgian Bay.

SLIDE # 36: Line diagram and simplified model based on reflection data along the eastern part of profile J.

And here we see more of the same seismic line. The top portion gives us the same reflections we saw in the previous seismic cross section, but in a simplified form. We can see the same thrust faulting reflected in the heavier lines, and above the section the actual frontal fault zone is indicated. Below is the geological interpretation of the seismic picture, which clearly shows how the ***Grenville Front*** *truncates and thrusts upon the ramp provided by the* ***Superior Province*** *and a small overlying* *terrane called Manitoulin.* *But before rocks of the Grenville were thrust up and over Superior and other rocks, earlier they themselves had been overridden by northwesterly moving microterranes (e.g. Britt domain) which depressed the Grenville rocks to lower crustal levels where they were metamorphosed (changed by high temperature and pressure conditions) to what we call "high-grade" rocks. Then further NW-directed thrusting cut into the crust and ramped Grenville Front tectonic zone rocks to the surface as indicated by the geological interpretation.*

SLIDE # 37: Tectonic elements of North America and location of LITHOPROBE transects.

Before looking at the largest recorded rift on earth, the ***Keweenawan Rift System*** *or* ***KRS*** *(marked on this map in striped green as KR within the oddly shaped transect marked GL) we should have another look at the heartland of the Canadian Shield. This is the old craton of the Superior Province, which also is the largest of the world's* ***Archean*** *cratons (1.6 million* km^2*). The reason is that we want to know more about the earliest stages of the formation of the first cratons which form the nuclei of the North American continent.*

The ***Superior Province*** *offers an unrivalled perspective on early* ***crustal*** *genesis. It received additions of* ***juvenile*** *material (new rock formed from magma) to Earth's lithosphere during the* ***Mid*** *to* ***Late Archean*** *(approximately* ***3,100 to 2,600 Ma****). Farther on we shall discuss the* ***Abitibi*** *subprovince, which is the largest building block of this* ***juvenile crust****. Geochemical data indicate that it was derived directly from the Late Archean* ***mantle****.*

Given the occurrence of these various, and very old, terranes within the most prominent old craton invites the study of their internal makeup, of how these various types of terranes came to be together, or accreted. Was the mechanism the same which we have been observing in more recent **plate-tectonic processes**?

This is the purpose of a new study area or transect now being activated by LITHOPROBE, the ***Western Superior Transect.*** *It follows a detailed study of the Kapuskasing Structural Zone, a transect for one of the earliest LITHOPROBE studies. Note the transect areas for each as outlined on the map* (slide # 37).

SLIDE # 38: Geological map for western Ontario showing subprovince divisions of the Superior province and planned seismic lines.

The ***Superior*** *craton shows some remarkable features. It comprises a series of* ***granite-greenstone "belts,"*** *each 100 to 200 km wide, which trend approximately east-west. (Granites are formed when magma cools; greenstone belts are roughly linear bodies of mostly volcanic rocks, whose metamorphosis caused their greenish colour, with some plutonic rocks. They are typical for Archean cratons.) Canada's* ***rich mineral resources*** *largely occur in them. They are divided by a series of sedimentary subprovinces. Their lithology (rock type), age and metamorphic grade (degree of alteration by heat and pressure associated with deeper burial and/or tectonic stresses) differ from one another. They are known as* ***subprovinces*** *(of the Superior province). Four primary types of such belts have been observed, and they have analogs in similar belts caused by modern plate tectonics.*

They include ***volcanic-plutonic*** *terranes (greenstone-granite belts, here coloured in greens and pinks) which resemble island arcs. We all know what a volcano is. A* ***pluton*** *is a magmatic intrusion which, unlike a volcano, did not break through to the surface. We still need to know the meaning of "****terrane****." It describes a distinct piece of crust,* ***homogeneous*** *in its* ***tectonic style and makeup****, and separated by discontinuities (e.g. faults) from adjacent terranes displaying different characteristics. Some plutonic complexes could be slivers from continents.*

Some belts consist primarily of just plutonic rocks, large tracts of magma-derived rocks (shown in pink).

Yet another type found consists of ***metasedimentary*** *(i.e. containing sediments altered by metamorphism) belts (yellow colours) which resemble accretionary prisms. (Originally, these prisms likely were large bodies of sediment, perhaps residing on a subducting ocean plate, which have been* *attached to the craton by tectonic forces. This is the mechanism which currently is attaching new material against the west coast of Vancouver Island.) The prisms were altered by high temperatures and pressures due to being buried.*

*Then there are high-grade **gneiss** complexes (purple and grey shades). (Gneisses are banded rocks formed under a high degree of regional **metamorphism**, exerting strong pressure on the rocks.) Their high degree of metamorphism probably signifies that they represent **deeper** levels of the various other terranes found, meaning that what had been above them was eroded.*

*There is a general age progression from north to south in the Superior Province, from approximately **3,100 to 2,650 Ma**, which has been interpreted as resulting from the tectonic assembly of successively younger arc terranes. One explanation is that the evolution of the Superior province was dominated by a province-wide, southeast-facing, arcuate, north-dipping **subduction zone** at approximately **2,730 Ma**. After this time, the evolution of the Superior craton was controlled by the **accretion** of **ocean crust** and **island arc** fragments. The last **collisions** occurred approximately from **2,690 to 2,680 Ma**. For our purpose it's enough to know that these were in the **Late Archean**.*

We mentioned the importance of greenstone belts to our mining industry, one of the resource pillars of the Canadian economy.

SLIDE # 39: Locations of Abitibi and its surrounding subprovinces and the Grenville Province within the Canadian Shield.

*As we had seen earlier, the **Abitibi** subprovince was the largest building block of the newly created **juvenile crust**. Geochemical data indicate that it derived directly from the **Late Archean mantle**. It is a young greenstone belt (relative to the others) displaying "**juvenile**" magmatism (extruding "original" magma, i.e. not remelted former rock).*

***SLIDE # 40: Schematic geological map of Abitibi greenstone belt and surrounding geological features.** (Locations of seismic reflection lines are identified by numbers.)*

*This slide shows the extent of the **Abitibi greenstone belt**, the most prominent of its type in the Superior Province. It is bounded on the southeast by the **Grenville Front** we looked at just a minute ago. Another fault borders the belt on the west and northwest, separating it from the **Kapuskasing Structural Zone (KSZ)**. Within the greenstone belt occur several types of rock formations as indicated in the legend. The named townsites are well-known **mining** communities, and the Abitibi greenstone belt contains many important precious and base metal mines.*

SLIDE # 41: Generalized geological map of the Kapuskasing Structural Zone (KSZ) and surrounding region.

*The inset in the map shows the location of the map with respect to subprovinces of the Superior province. The **KSZ** is shown by the magenta colour. We shall come back to this slide in a minute. Line A-B-C-D is the location of a cross section which is a typical **multidisciplinary** interpretation using seismic reflection, seismic refraction, other geophysical, geochemical, geochronological, and geological data. Here is the cross section.*

SLIDE #42: Cross section of Kapuskasing Structural Zone.

*Large-scale **thrust-faulting**, as we have seen, can bring old, and deeply buried, sheets of **crustal** rock to the surface. One exposure of very **old rocks** from down **deep** is found in LITHOPROBE's Kapuskasing Structural Zone **(**KSZ**)** transect area. Because this exposure lets us look into the past, geologists call it a "**window**."*

*As we had seen before, the predominant **structural grain** of the Superior Province is east-west. The **KSZ** cuts this trend obliquely in a NE-SW direction for at least 400 km. It is marked by gravity and aeromagnetic **anomalies**, as we can see in slide # 43.*

SLIDE # 43: Aeromagnetic map with colour-shaded relief, set parallel to Matachewan

dykes to suppress the dyke signature and emphasize local structure.

Let's switch back to the previous two slides.

SLIDE # 41: Generalized geological map of the Kapuskasing Structural Zone (KSZ) and surrounding region.

The ***KSZ*** *is a block of lithosphere that at one time resided 20 km below the surface. In one or two immense heaves of the Earth, between* ***2,600 and 1,900 Ma****, these rocks from the deep were thrust 70 km eastward and up to the surface, where we can walk on them today.*

The map area is crossed by an ancient fault line, the ***Ivanhoe Lake Fault Zone****, which shows clearly on gravity and aeromagnetic maps. The fault line runs from Lake Superior to James Bay. Along this west-dipping fault plane the* ***KSZ thrust*** *carried highly altered rock units from the deep onto less altered rocks of the* ***Abitibi*** *subprovince east of it.*

SLIDE # 42: Cross section of Kapuskasing Structural Zone.

We also see the fault plane on the cross section, where it is shown that the fault flattens at depth, and eventually peters out.

The upthrust rocks themselves represent a critical period of continental growth from ***2,800 to 2,600 Ma****, when a large portion of the craton formed and stabilized. Now uplifted, the* ***KSZ*** *represents a "****window****" through which the architecture and growth patterns of old* ***Archean continental crust*** *can be seen. Such exposed features can be mapped, and the physical and chemical properties and ages of exposed rocks measured directly. Remote sensing methods (such as seismic reflection) enable us to follow the mapped layers into the depths of the lithosphere.*

Let's also look at the lowest level shown on the cross section. It is a geophysically defined discontinuity, the ***Mohorovicic discontinuity****,* ***Moho*** *for short. [If we consult the supplied glossary we can read that the Moho is the level at which the velocity of seismic waves increases rapidly (to 7.8 km/sec.) It defines the* ***crust-mantle boundary****. The depth of the Moho is determined from seismic refraction surveys.]*

The ***Moho*** *tends to be at a relatively uniform depth in each region. Exceptions can be observed sometimes along critical structural areas, as is the case here under the* ***KSZ****, where the crust (whose bottom is defined by the Moho) reaches almost 55 km in thickness, or 10 km or more thicker than the regional norm. [Earlier we saw a localized deepening of the Moho in the Trans-Hudson Orogen cross-section.]*

One more look at the stunningly expressive aeromagnetic map of the KSZ.

SLIDE # 43: Aeromagnetic map with colour-shaded relief, set parallel to Matachewan dykes to suppress the dyke signature and emphasize local structure. White lines show seismic reflection profiles.

This artificial sunshine and its calculated expression in shadows, as if the magnetic values shown were an actual surface relief instead of colours, is a wonderful usage of computer power. It highlights structural or depositional trends and features. In this case, the predominant structural expression of the numerous, roughly north-south trending dykes in the eastern part of the map was ***diminished*** *by lining up the imagined sunshine with the direction of the dykes, so that the dykes themselves would not throw a predominant shadow.*

We can trace the ***Ivanhoe Lake Fault Zone*** *from the upper right to the lower left corner of the map. This line is the surface expression of the* ***west-dipping fault plane*** *along which the rocks from the left were heaved onto those on the right of the fault line. As we can see, there are many more features on the aeromagnetic map which represent the varying magnetic intensities of various faults and rock units and their orientation. To understand them all would help get you close to a degree in geophysics.*

Before we leave Precambrian times, we should look at another giant tectonic event, one which almost tore our continent apart. It lies in the south, in the Great Lakes region, and is called the **Keweenawan Rift System (KRS)**.

SLIDE # 44: Location of LITHOPROBE geophysical profiles on a simplified geological map of the Great Lakes region.
*This area is a junction of several major tectonic features. On the right we recognize the **Grenville Province** and the **Grenville Front Tectonic Zone**, along which the Grenville Province was thrust onto the **Superior Province**, cutting in the process across other tectonic units then existing. Among these are the **KRS** and the **Penokean** fold belt. Even more so than the Grenville Orogen, the **Penokean** fold belt has been deeply eroded, due to its older origin, **1,890 to 1,820 Ma**, the 70-million-year period during which this fold belt originated.*

*The **Keweenawan Rift System** dates back to an extensional period during which the continent was split deeply to its very crustal roots, but still stayed together, if just. The **KRS** formed during a 20-million-year interval, **1,110 to 1,090 Ma**, and is today an arcuate structure that extends 2,000 km from Kansas in the south over Lake Superior and northern Lake Michigan into Michigan. Only in the Lake Superior region are Keweenawan rocks exposed.*

And here is how this enormous scar in Earth's crust looks on a seismic reflection profile. Before we switch slides have a look at its location, line F on the Great Lakes map. After it we shall see a model constructed from complementary geophysical information, line A, which also crosses Lake Superior just west of line F.

SLIDE # 45: Seismic record section of the central portion of line F. The prominent layering of the syn-rift deposits between 10 and 30 km depth are shown clearly.

*Seismic and other data have now shown that this is the **deepest rift** on the planet. How deep was the rift? In some places more than 35 km, so deep that it almost split North America into two separate continents. An astounding 20 to 25 km depth of the gigantic rift valley were filled with interfingered lava flows and sediment carried in from the surrounding highlands (shown by the layered reflections below 10 km depth); then another 10 or more kilometers of sediments filled in after the rift had formed.*

*Below the rift, the crystalline **crust** had **thinned** to just one quarter of its original thickness. This enabled molten rock from even greater depths to force its way up — providing the enormous volume of volcanics that have been found, and perhaps completely fracturing the crust in some places.*

SLIDE # 46: Stylized model of the upper crustal velocity structure along profile A. HZ - Hinge zone; IRF Isle Royale fault; KF - Keweenaw fault; SS - Superior Shoals. Note the vertical exaggeration of 3:1.
*This model gives us a more immediate impression of the rift profile, partly because of its triple vertical exaggeration. Note the fault lines; of course, the borders of the deep portion, i.e. the central rift itself, also are bordered by faults, that's the very definition of a rift. Unlike the previous image based on reflection data, this model was constructed from seismic **refraction** data which measure the velocity of sound waves inside formations. More about this aspect of seismic measurements later on.*

Other geophysical methods also can give us impressive signatures of the Keweenawan rift valley. Just take a look at the gravity picture over Lake Superior.

SLIDE # 47: Gravity map for Lake Superior and surrounding regions. Note the strong positive contrast of the rift valley to its surrounding rocks. The reason for the positive anomaly was not understood until the results of our studies in the Great Lakes - the large volume of dense volcanics in the rift valley causes the anomaly. *Data compilation and plotting by the Geophysics Division of the GSC (Geological Survey of Canada.)*

Even more striking, perhaps, is this aeromagnetic map.

SLIDE # 48: Aeromagnetic map for Lake Superior and surrounding regions. *Data compilation and plotting by the Geophysics Division of the GSC.*

Again, note the strong contrast of the rift and its fill of volcanics and sediments to the geologically different surrounding regions. The smoother appearance of the pattern in the rift valley results from the damping (or blanketing) effect of the top layer of non-magnetic sediments.

II. 2 NORTH AMERICA GROWS YOUNG -- or HOW YOUNG AMERICA GREW

And now, after having stitched together the Precambrian Canadian Shield -- the Grenville Orogen had been its last addition, we remember -- we have a choice. We now could discuss the theoretical and practical aspects of the various disciplines and tools which LITHOPROBE's earth scientists have trained on the deep secrets of the continental plate; but this would just be for having a change of topic, albeit not pace.

Instead, let’s think about how we started out, by looking at a shrinking ocean with its surrounding earthquakes and volcanoes, the **Pacific** ring of fire, and at the more peaceful shore at the growing **Atlantic** ocean.

II. 2.1 SUPER CONTINENT BREAKS, JOINS, AND SPLITS AGAIN

Following completion of the Grenville Orogen about a billion years ago, North America seems to have taken a bit of a breather. For a period of almost 400 Ma, it wasn’t nearly as tectonically active as it had been for the previous 400 Ma. That doesn’t mean nothing was happening, only that what was going on was not at the same grand scale as the events that we have been describing. On the eastern part of the continent at around 600 Ma, a continental rift was generated and an ocean, the predecessor of our Atlantic Ocean, formed. After growing very large, it began to shrink due to the action of other tectonic forces, and was eventually closed. Some time later another rift opened up and the present Atlantic Ocean was born. We’ll consider this in more detail shortly but let’s remind ourselves of where we have gotten to.

SLIDE # 49: Simplified tectonic element map of North America with transects marked. The boxes outline the areas in which LITHOPROBE is studying some of the major features we have discussed. Soon we’ll be considering the LE (for LITHOPROBE East) region.

*By now, these outlines of the major tectonic provinces of the continent must look familiar to us. Look again at the outline of the **Grenville Orogen**, or what's left of it after erosion has ground Earth's mightiest mountain chain down by thousands of meters. At any rate, this is the outline of the roots of the former system as earth scientists can describe it to us now. Actually, even this outline isn't the full extent Grenville had been, because, as we already have heard, Grenville itself or Grenville with some additions of which we are not aware, was split.*

*Imagine behind it, to its east, another part of itself plus another continent, the one which had pushed it to where it now is anchored. All of this stretched far to the east, very far. Next, put some of the interior Earth's hot spots under the Grenville Province (which then extended quite a bit farther to the east then it does now), and we have the beginning of a **rift**, a big one, and splitting right down to the very roots of the **crust**. And so, an **ocean** formed, at about 600 Ma. How?*

Well, perhaps in a manner similar to what is happening under the Atlantic right now. Along that ocean's geologic median, the crust is splitting and magma is oozing out, adding new ocean floor which, in turn, is carried away by convection flows in Earth's interior.

All of which sounds very neat, and probably is old hat to some of us. Splitting an ocean seems tough enough, but splitting a continent as well? It would take a lot of convective heat flow underneath! It does.

What probably helps the heat accumulation under the continental crust is that it is thicker and lighter than oceanic crust is, and thus a better insulator or barrier for the heat which continually is escaping from Earth's interior, its inner space. (Whereto? Into outer space, of course.)

A lot of magma is pushing out of the mid-ocean ridges in our oceans. And a stupendous volume of oceanic plates is being subducted, in turn, along the edges of closing oceans. The energy required for these massive transfers of volumes of magma and cooled crust is hard to imagine. In the vernacular (what we talk outside our school's doors) it would be beyond the capacity of all the world's conventional power stations, even if we included the nuclear plants as well. But here we are getting close to what makes the Earth's tectonic plates go push and bang, and up and down.

HEAT GENERATION

One question often asked by interested earth watchers is why does the Earth get hotter, and hotter as we penetrate deep into the crust, say in a deep mine? What is the source of this heat? **Atomic energy**, i.e. the radioactive decay of potassium, uranium and other radiogenic elements. One could say, whether we like it or not, our planet is being heated, and life on Earth sustained, by nuclear energy! In addition, the heat contained in the deep Earth's interior (e.g. the molten iron outer core), from when the planet formed 4.6 billion years ago, slowly escapes by conduction and convection through the mantle and crust.

The **uneven distribution** of heat generation inside Earth, and the differing heat retention by variously composed crustal plates, causes **heat convection flows**, which facilitate **plate tectonics**, the movement of crustal plates within Earth's outer shell.

Our mountain ranges are just a byproduct of Earth's nuclear power generation. As the saying goes, it's pretty neat, but it's also hard to imagine it all. Which is why earth scientists are so special (they think).

Yes, nuclear power helped split us from Gondwana. Scientists have called the then evolving ocean the **Iapetus Ocean.** As we already heard, that was about **600 Ma**. Iapetus grew big, like an ocean should, and had its time of glory during the **Cambrian** and **Ordovician**. But not long after splitting, it already was contracting again, being swept up by, you guessed it, yet another converging continent, which pushed the whole of Iapetus plus itself onto what the Iapetus split had left of our continent Laurentia.

II. 2.2 APPALACHIA, YOU STILL LOOK BEAUTIFUL!

The result was the creation of the beautiful **Appalachian** mountains; and because they aren't so very old yet, they still are there, and inspire us with their beauty. Iapetus was "closed" (in science speak), or crunched together (in the vernacular) between about **475 to 275 Ma**, in other words it took a while, 200 Ma. How come?

It was a big job and took a series of separate orogenies (or mountain building episodes) until what had come in between the former borderlands of the ocean had been swept up, and the converging continents eventually came to rest against each other.

For the record, these events were the Mid-**Ordovician** Taconian Orogeny (around **~475 Ma**), the **Silurian** Salinic Orogeny (**~420 Ma**), the **Devonian** Acadian Orogeny (**~380 Ma**), and, finally, the **Permo-Carboniferous** Alleghenian Orogeny (**~280 Ma**). Let's place these geological age names into their proper slots on our geological time scale.

SLIDE # 50: Geological time scale.

*All of the times mentioned above, the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian (from oldest to youngest) belong to the **Paleozoic**. The Paleozoic, in turn, is the oldest chapter of the Phanerozoic, which followed the Precambrian (all of what had gone before it). The Precambrian had seen the completion of the Canadian Shield with the addition of the Grenville Orogen. We now are firmly in the Phanerozoic, and soon will turn to the youngest orogeny, added on to the west in **Mesozoic** times. And, as we have known from the beginning of all this, this adding on to the west coast still is continuing today, when we are in the **Quaternary**, part of the **Cenozoic.** Have one more look at the geological time scale, before we switch one slide BACK again, to*

SLIDE # 49: Simplified tectonic element map of North America.

The Paleozoic-age Appalachian Orogen extends from the southern United States, up the *east coast of North America to Newfoundland and is continued across the intervening Atlantic ocean (which is of Mezozoic age) into Britain and Scandinavia, there as the Caledonides and Hercynides.*

SLIDE # 51: Base map of the Newfoundland Appalachians showing tectonostratigraphic zonation, simplified surface geology, and the location of the three seismic reflection corridors (numbered black lines) used by LITHOPROBE.

There also is a portion of this mountain belt in West Africa, namely that missing eastern part of eastern Newfoundland whose parentage makes it African. That's what happens when you get into global-scale splitting. By the way, the central portion of Newfoundland is oceanic in origin (remember the Iapetus ocean?), and the western third North American.

SLIDE # 52: Interpretative cartoon of the final stage of the collision between the Laurentian and Gondwanan plates.

Missing here is the ocean part in the middle, left out to get to the point of interpreting what happened to the constituent parts of the two continental plates where they bashed into each other. What is postulated here is that the Laurentian plate was split into an upper and a lower portion (along the Mohorovicic discontinuity or ***Moho****).*

Remember the **hot spots** deep down below the crust? **Supercontinent**s -- this one, by the way, went under the moniker **Pangea** -- are not meant to last as the convection-driven hot spots become hotter under the insulating package of the continental crust.

At any rate, **Pangea** ruptured along the lines which we now see as the mid-Atlantic ridge, and its offset branches to the northeast and northwest. But the break was not the same which earlier had ruptured the previous supercontinent, in that process forming the Iapetus Ocean. This time, the break was farther to the east, thus leaving much of the Appalachians, and even a piece of the continent opposite, on this side of the Atlantic.

The **Atlantic** split open during the interval ~180 to 90 Ma, and still is growing, as North America is moving away from Europe, and as the split has been cracking the ocean floor progressively northward.

The **Appalachians** still are there in all their splendor, having their most northeasterly position on this continent on Newfoundland, which probably is the best exposed part of this mountain belt.

Now, let's move with the continent itself, namely westward, and visit the last stop on our continental orientation tour, the **Cordilleran** system, one of Earth's younger offspring of plate tectonics. The West still is growing. Remember the Juan de Fuca plate subducting under the North American plate? And where else are we gaining new crust? Yes, you've got it, where volcanoes blow and plutons intrude, also along and above the subduction zone.

II. 2.3 THE GROWING WEST

LITHOPROBE's intensive lithospheric study of the western North American Cordillera, from the eastern edge of the Rocky Mountains to the offshore west of Vancouver Island, was the first encompassing, multidisciplinary investigation of such a mountain system. Not surprisingly then, the Canadian portion of the Cordillera has been the birthplace of many new concepts in global tectonics.

An 1,100-km long cross section of these findings is shown in the brochure folder. By the way, it is true to scale, i.e. no vertical exaggeration was used. You are looking at a scientific first here, at a summation of tectonic and structural insights which is benefiting research into other mountain systems, on this and other continents, and with regard to features formed recently or farther back in the geological past.

For example, geological and geophysical studies in southwestern Canada, particularly over the past 25 years, have established that the lithosphere of the Cordillera has evolved through episodes of **rifting, sea-floor spreading**, and **plate separation**, followed by **subduction, ocean-basin closing**, and **plate accretion**. Of course, you do remember all of these concepts, don't you? We just discussed rifting and sea-floor spreading when we heard about the Iapetus and Atlantic Oceans. Plate separation is a bit hazy, in that this can involve more than mere separation by rifting, but also movement of one plate with respect to the other **along strike** (of the separating feature, generally a giant fault, such as the Queen Charlotte Fault just west of the Queen Charlotte Islands; this is Canada's equivalent of the San Andreas fault). Subduction, like that of the Juan de Fuca oceanic plate under Vancouver Island, we have got down pat. Ocean-basin closing is a clear case, and plate accretion we also have discussed, but will hear more about now.

The concept of **accretion** of far-travelled **crustal blocks** (**terranes**) that comprise plate fragments, island arcs, or microcontinents, was developed partly in the Canadian Cordillera. It now is used to interpret geological relationships observed in many other orogens of the world.

Again, let's not be frightened by words -- all they do is describe things and happenings. When you put two mud pies together you accrete them side by side. Depending on how hard you press them together, and what happens to the twosome thereafter, they may stick together. Island arcs? Think of the Aleutians, Indonesia or the Philippines; or, in a different setting altogether, the Hawaiian islands. You might say it's a loose, but still descriptive, term. What else have we got here? Oh, yeah, there are microcontinents; well, small continental plates, which we have discussed many times by now.

So, let's stir up these things and mix a tectonic cocktail of the real world.

SLIDE # 53: Map of the Canadian portion of the North American Cordillera that indicates the collage of accreted terranes.

Well, let's not opine too early here. It ***so*** *is clearer than mud. Consider, how these various patterns and colours (for the different* ***accreted terranes****) do provide some degree of clarity. Geologists and geophysicists generally start out with a dog's breakfast, sorting things out by rock type, position, age, and so forth. In any case, it's a descriptive map of what, seemingly, was a less than orderly collage. Nature can be that way. On the other hand, consider how orderly the sorting of your beach sand is, for instance! And this collage also follows or indicates certain patterns; one just has to know the why and how.*

At any rate, take in the big picture, the colours and borders. The big, dark red is the North American craton onto which (from the west) the Rocky Mountains, in light red, were shoved by plate tectonics. The borderline between the two designates the eastern edge of the thrust fault plane on which the outer mountains were carried onto the undisturbed craton. (And there are more such fault planes farther back into and throughout the Rockies, making the mountains form a stack of imbricated layers of rocks of different types and ages.)

Then, we have white and light green colours. The white is on land -- comprising the ***Intermontane composite terrane****, the green consists of islands and part of the western edge of British Columbia, which is the* ***Insular composite terrane****. Clear as mud pies! Which refers to the adjective "****composite****." All this word is meant to say (here) is that these terranes comprise accreted material which originated from near the west coast as well as from, presumably, much farther away, where they formed on oceanic crust and whence they were carried to the west coast.*

So, let's define our map some more. The old Precambrian craton is a clear case, so are the Rocky Mountains. Next to the west, the uncoloured portion is, like the green belt, a mix of accreted terranes. Curious scientists (who, in private, must be good at working Rube's cube) have found out which accreted terranes were formed near the west coast and marked them with a star (sorry, only on the legend, to keep the map demuddified).

Our continent gained, and grew westward, by the accretion of new terranes from near and far. There also was erosion and sedimentation of course, just as it is happening now, and there were volcanoes. The sediments also were added on as they reached the shore lines (having been carried their mostly by rivers) and were dumped in between whatever else was coming along as accreted terranes. Look at the Fraser River's sedimentary fan when you fly over it next time.

Researchers have figured out that since the Precambrian, the continent grew westward by about 500 km, adding a day's drive for land *lubbers on their annual summer run to the ocean beaches. That addition works out to a little less than 1 km for each one million years. But this growth was not a dull, even-measured affair; it came in spurts and periods. Much of the accretion took place during the interval* ***180 Ma to 58 Ma****, or from the* ***Jurassic*** *to the* ***Lower Tertiary****, which belong to the Mesozoic age (which comprises the Triassic, Jurassic, and Tertiary, from oldest to youngest). We remember that this* ***accretion****, and the* ***subduction*** *of a moving oceanic plate which underlies these accretions, is continuing* ***today****.*

Indeed, an important aspect of the Cordillera is that it is evolving in much the same way ***today*** *as it has for the last* ***200 Ma****, thereby providing an "actualistic model" (has a nice ring to it, `like, where it's at' in the vernacular), anyway, providing an ongoing model that can be integrated directly with earlier processes and deformation.*

LITHOPROBE's area of study or "transect" is marked on the map by the box. This ***S****outhern* ***C****ordillera* ***T****ransect gives us an outstanding opportunity to look into the* ***processes*** *that were responsible for westward* ***growth****, the processes that influenced the* ***crust*** *and* ***lithosphere*** *prior to the accretion of* ***terranes****, and the processes that were important in the subsequent* ***modification*** *of the Cordillera. This modification involves another, or several, subsequent process(es), such as lithospheric "****extension****" as observed in the Intermontane composite terranes (about which more later).*

The main tenor of LITHOPROBE's study of the Southern Cordillera is to carefully **integrate** all the various applicable earth-science **disciplines** and **methods** so that they all can advance, and check upon, each other. This integration, LITHOPROBE's **multidisciplinary** approach, includes **seismic reflection, seismic refraction**, and **electromagnetic images** of deep **crustal** and **lithospheric structure**. Hand in hand with this **subsurface** approach goes the work by geologists at the **surface**, understanding more about the **geology** and **geochemistry** of near-surface rocks, including the **paleomagnetism**. Then there are the **gravity** and **magnetic fields** which are measured over the region. We'll learn more about all of these shortly. All of this contributes to our understanding of how the westward **growth** of the continent took place, in which way and by what specific **events**. This knowledge, in turn, then can be applied elsewhere.

SLIDE # 54: Subduction of the oceanic Juan de Fuca plate under Vancouver Island.

LITHOPROBE's studies in the Southern Cordillera have been taking place since 1984 when the project's Phase I provided seismic and electromagnetic images of the oceanic Juan de Fuca plate that is being subducted under Vancouver Island; and of overlying fragments of the plates that have been added to the collage of accreted lithospheric fragments in western Canada.

This slide incorporates later findings as well. But the first crustal section from Phase I, across Vancouver Island, has been interpreted to indicate that both **tectonic erosion**, wherein some of the older lower crust is stripped off and **recycled** into the **mantle**, and subduction **underplating**, wherein new and younger rocks are added to the continent from below, are important **processes** that must be considered in global **models** of continental evolution and growth.

Continuing research has brought important insights, much of which is summarized in the large cross section in our brochure folder, representing 1,100 km of crustal profiling, from the Alberta plains in the east to the Juan de Fuca ridge 200 km offshore in the Pacific Ocean.

Some of the findings in a nutshell:

- **Microcontinents** advancing from the west collided with our continent and pushed thick sequences of rocks (which are up to **600 Ma** old) several hundreds of kilometers east onto the western margin of the **Alberta Basement** (the North American craton), to form the Rocky Mountains. So there was no giant collision between two giant continents here, as we had seen in the creation of the Grenville Orogen. But it shows just how effective these pushes and shoves can be, even from microcontinents.

- What was being shoved here had been deposited onto the western extension of the Alberta Basement over long times, including all the old and very old sedimentary sequences we find exposed in the Rocky Mountains today. How far did the shove go? Very far, perhaps, because there are indications that some of the fault planes accommodating this movement sole out by the Fraser River. The cross section shows the basement (mottled red) thinning and extending almost as far as the Fraser Fault, and the overlying deformed and metamorphosed sediments and other rocks (dark red) of pre-accretionary North America stretching to the fault itself.

- The collisions, and accretions of exotic Mesozoic terranes in central British Columbia and the Coast Mountains, occurred **180 to 58 Ma** ago, as we already have heard.

- Then, the convergence stopped. Now, remove the lateral pressure on something as big and heavy as newly crunched-up mountains. Things will slide back to find a new equilibrium. Thus, **compression** gave way to **tension**, and large structures were a bit undone. Compressional arches were "**unroofed**", i.e. lost part of their covers as layers and blocks slid down on them.

SLIDE # 55: Central portion of regional cross section through the Southern Cordillera.

- Those are the "**antiforms**" shown on the cross section, like the Nicola and Vernon antiforms. These subsurface structures are mighty high, with a covered relief of up to 25 km and a lateral extent of 100 km.

- Throughout, large strike-slip faults (like the San Andreas fault in California), sliced up the crust and carried parts of it as far north as Alaska. The most recent one is the Queen Charlotte fault (mentioned earlier) but older ones sliced much of British Columbia and the Yukon, emphasizing the north-south belts of the Cordillera as seen on a previous slide (#53).

The long crustal cross-section shown in the brochure folder cuts across the belts and extends westward across the subduction zone and out to the Juan de Fuca ridge where, today, submarine outpourings of basalt magma continue to form new lithosphere of the Pacific plate to the west and the Juan de Fuca plate to the east. Here are the major points again:

- The cross section chronicles a voyage of discovery, from Alberta to west of Vancouver Island, along an 1,100-km-long, deep cut through stacked, twisted, displaced, reworked and remolded rocks and formations.

- The **Canadian Shield** (mottled red), i.e. our old Precambrian craton, doesn't end with the **Alberta Basement**. We can follow the basement right under the mountains and on westward at least to below Okanagan Lake.

- In central British Columbia, between Kootenay Lake and the Fraser River, the features showing the most vertical relief lie buried: they occur as a series of huge underground arches, up to 25 km high. Mt. Everest could easily fit inside them.

- Geophysicists subdivide our lithosphere into an upper and a lower part, crust and mantle (continental mantle is shown in purple; oceanic mantle in grey), separated by the **Mohorovicic discontinuity** or **Moho**, below which seismic responses differ from those above it. Observe how steady the Moho is! Given the changing surface topography from the Rockies to the Strait of Georgia, one also may have expected some changes in the base of the crust, which is the Moho. Not so!

  The Moho is remarkably flat. This is a **fundamental discovery**. It means that mountain belts, resulting from collisions, were formed **above this flat base**, perhaps as a rug wrinkles when pushed about a flat floor.

- The explanation is that the rocks below the **Moho** possess qualities which differ from those above, including a higher density and great strength. And just try to imagine the forces which did the wrinkling above the Moho, and stacked up the Rockies!.

- Under the west coast, our seismic x-rays have revealed a complex, geological structure beneath the **Coast Mountains**. It is an intricate pattern representing older shingling and wedging rock plates which were **imbricated** when continental and oceanic plates collided and also caused the ascent of magma from frictional and other heating, forming all the granite rocks of the Coast Mountains and, of course, volcanoes such as Mt. Garibaldi.

- Beneath Vancouver Island and offshore, the **collision** continues today. We can "see" from our remote images how the lithosphere of the Juan de Fuca plate, moving eastward, is **subducting** beneath the North American plate, which is moving westward. We have been able to follow the subducted plate deep (70 km) beneath the mainland on the east side of the Strait of Georgia. We also know from chemical studies of the volcanic rocks that they formed from parts of this subducted plate, melted at depths of 100 km and more.

Well, there we are. This completes our sweeping investigation of the continent and its growth, down to its very roots and back to its beginnings. We have travelled through longer than four billion years in just, well how many hours?

III. LITHOPROBE MULTIDISCIPLINARY STUDIES
---- HOW IT'S DONE

III. 1 SEISMIC REFLECTION SURVEYS

LITHOPROBE's scientific work is spearheaded by the **seismic reflection** method because this is the geophysical technique which produces the best images of boundaries between rock units and of structures in the subsurface. It is the principal method by which the **petroleum industry** explores for hydrocarbon-trapping structures, that is oil and gas traps, in **sedimentary** basins. We don't have the time to explain oil and gas exploration here, but it, too, is a fascinating subject to get involved in.

Extension of the seismic reflection method to **deep crustal studies** began in the 1960s and since the late 1970s reflection technology has become the principal procedure for detailed studies of the deep crust.

SLIDE # 56: Seismic reflection method. Vibroseis sound source with geophone spread.

*In its simplest form, the method is an echo technique based on the same principles as **sonar**, i.e. bouncing sound waves off the boundaries between different types of material: water and bottom sediments for sonar, rock layers for crustal studies. The form of presentation of the data is similar to that of a geological **cross-section** and needs to be interpreted in terms of **geology**. Thus, geoscientists must work together to provide the most complete interpretation; this is the procedure followed in LITHOPROBE.*

In its application, the seismic reflection method is highly complex, involving a skilled acquisition crew with millions of dollars in **equipment**, whether on **land** or at **sea**. As in the petroleum industry, LITHOPROBE contracts the data acquisition to qualified industrial contractors.

***On land**, LITHOPROBE has been using large truck-mounted mechanical **vibrators** as sources (the "Vibroseis" method) because they are logistically appropriate and environmentally safe for the hard-rock areas in which we have worked; in one transect dynamite has been used for the purpose of sub-crustal imaging and may be used again, just as it sometimes is in industry. In all cases, federal and provincial environmental and permitting regulations are strictly followed.*

In a typical regional survey at the present time, 480 groups of 9 to 12 **geophone sensors** per group are spaced at 25-m intervals over a 12-km length to record ground vibrations caused by the Vibroseis units. Sensor outputs are **recorded** on a truck-mounted computer system.

In addition, high-resolution surveys have been undertaken with the participation and collaboration of industry and provincial government agencies. These very detailed surveys aim at geological targets (typically, the geological setting of ore bodies) in the uppermost crust, i.e. the practical depth range for mining. To achieve the desired greater detail, the 480 geophone groups are spaced at smaller intervals (5 to 10 m) over only 2 to 5 km.

SLIDE # 57: A Vibroseis crew at work in Ontario. Four Vibroseis (sound source) trucks

in the foreground; two recording trucks in the background.

These huge trucks work in unison, each lifting itself up on a vibrator plate which sends selected seismic signals into the ground, which then are reflected from underground reflectors and detected by the geophones placed into or on the ground. These, in turn, feed this information into amplifiers and then into computers which record and store the data. One television reporter called these large trucks "dancing elephants."

Here is a picture of one of these dancing elephants.

SLIDE # 58: Vibroseis truck in action. Note the wheels are lifted off the ground and all the weight of the truck is on the vibrating pad.

SLIDE # 59: Marine seismic reflection survey, a schematic with a representative seismic section.

***At sea**, large arrays of **airguns** (mechanical sources that rapidly eject compressed air) provide the **sound energy** which is detected by many **hydrophone sensors** typically forming a 3.5 km long, 240-channel **streamer** that is about 10 cm in diameter and towed behind the ship. Sensor outputs and other essential information are recorded by an onboard computer system.*

Sophisticated **computer processing** of the vast quantities of data is necessary before the optimal subsurface images of geological structure are obtained. The first phase of such processing is again done through contracts awarded on the basis of competitive bidding to specifications prepared by LITHOPROBE seismologists.

But only then do the experts really get to work. It's complicated stuff, a highly sophisticated "fine tuning" of **processing parameters**, and careful "massaging" of many aspects of the huge volume of seismic reflection data. This comes into play at different stages of processing, and can significantly augment the geological and other information that can be derived from the data. The second phase of processing addresses these aspects through **selective reprocessing** of the data.

In this, the **LITHOPROBE Seismic Processing Facility** at the University of Calgary and **Seismic Research Nodes** established at nine universities across the country, plus the major facility developed at the **Geological Survey of Canada** in Ottawa and subsidiary facilities at offices on the east and west coasts, are key contributors.

SLIDE # 60: Working at the LITHOPROBE Seismic Processing Facility.

A fellow scientist is interpreting seismic data with the manager of the LITHOPROBE Seismic Processing Facility.

SLIDE # 61: LITHOPROBE's director discusses a seismic cross section with fellow scientists at U.B.C.

LITHOPROBE's geoscience teams are multidisciplinary and collaborate closely concerning their research, exchanging ideas on an ongoing basis in small and large working groups.

III. 2 SEISMIC REFRACTION AND WIDE-ANGLE REFLECTION SURVEYS

Seismic refraction and **wide-angle reflection** (**R/WAR**) surveys are an essential complement to the deep reflection surveys. In contrast to the near-vertical-incidence seismic reflection surveys, seismic **R/WAR** surveys make use of the arrival times and amplitudes of waves **refracted through** the crustal **layers** and **reflected at oblique angles** from layer boundaries. The **sound energy** generated by large explosive sources (200 to 3000 kg) travels in **arcuate** paths, **primarily horizontal** for **refractions** and **obliquely** for **wide-angle reflections**, and is recorded at distances from the source of a **few to many hundreds of kilometers**.

SLIDE # 62: Schematic of seismic refraction technique.

*The goal of R/WAR surveys is to provide velocity and structural information with a resolution in the order of kilometers, rather than hundreds of meters, as in the case of reflection surveys. It gives us the **speed of sound** within individual layers. Because it covers greater distances, seismic refraction describes the **big, regional picture**, while seismic reflection pinpoints the detail in smaller areas. In particular, the refraction technique can provide:*

- ***quantitative values** for **velocity** variation with depth, including velocity gradients, information that is essential for translating seismic reflection data from **time to depth** sections (for which one needs to know the velocity of sound in the various layers through which the seismic reflection signal has travelled) and for determining the **composition** and **state** of the **crust**;*
- *an ability to map **laterally-varying velocity** structure economically over wide areas, especially allowing the high-resolution information determined along a two-dimensional reflection profile to be **extrapolated** away from that line to give a truly **three-dimensional image** of the crustal section;*
- *an ability to map the **topography** of prominent **velocity discontinuities** such as those frequently found within the crust and at its base, especially the **Mohorovicic discontinuity** or **Moho**;*
- *velocity functions for improved control on the stacking and migration procedures associated with reflection **data processing**, particularly the "**fine tuning**" needed for **reprocessing**.*

LITHOPROBE scientists need rather well adapted **instruments**, so they have been **innovators** in their development. The same goes for **interpretational procedures** which enable conversion of the vast data sets into “velocity models” of the lithosphere. Here are two shots of especially developed equipment. They look deceptively simple (they’re not), but are also very rugged to withstand extensive use in the field.

SLIDE # 63: Refraction seismometer (cylinder) and recording seismograph being deployed during field program.

SLIDE # 64: Portable refraction seismograph and field service unit used for setting all recording parameters, retrieving seismograph memory plus analysis and display of data in the field. A basic field service unit includes a portable computer, printer, and satellite-tuned clock. It serves up to 30 portable refraction seismograph instruments.

Refraction surveys tend to be big affairs, requiring many instruments and many people to deploy them. For example, during the 1993 refraction experiment in the Trans-Hudson Orogen, 525 individual portable seismographs were deployed over a total length of 2,000 km along three individual lines to record more than 40 separate shots by a crew of 55 persons using 30 trucks, 2 helicopters and railway cars.

III. 3 GRAVITY AND MAGNETIC STUDIES

Remember how geoscientists employ **gravity** measurements to create maps which can say a lot about what lies below the surface?

SLIDE # 65: Gravity method of exploration.

The **intensity** of the **gravity** field at the surface of the Earth is affected by the **shape** and **rotation** of the Earth (**latitude**), distance from the **centre** of the Earth (**latitude and elevation**) and the **density variations** of the **rocks** beneath the surface. Measuring the spatial (i.e. from one place to the next) **variation** of gravity, plus knowing the Earth’s shape and the instrument location, to take care of shape and distance factors, thus provides important information which can be used to **calculate density** distributions in the lithosphere. Interpretations of these distributions carried out in conjunction with seismic refraction and reflection interpretations gives us a powerful investigative tool because a well-established relationship between the density and seismic velocity of rocks provides a mutual constraint (i.e. check) on the modeling.

SLIDE # 66: Gravity data express density variations in the crust.

This slide shows the gravity map of S.W. British Columbia and offshore region. Reds are high, yellows are intermediate, and blues are low values. Can you see the outline of Vancouver Island?

Reconnaissance scale gravity data (station spacing on the order of 6 to 8 km) is available for much of Canada through the National Gravity Data Base maintained by the GSC. LITHOPROBE and other researchers make extensive use of these data but they are often not appropriate for detailed modeling. Thus LITHOPROBE now requires that the surveying for seismic reflection lines also meet the necessary specifications for gravity measurements, including absolute values determined from GPS (Global Positioning System) measurements. With such surveying, the acquisition of gravity data at station spacings of about 1 km along the seismic lines is readily accomplished. This procedure is now routinely carried out along LITHOPROBE reflection lines; additional measurements are made when necessary and/or possible. The gravity profile can then be interpreted with the reflection data.

SLIDE # 67: Magnetic method of exploration.

The **magnetic field** measured at or above the Earth's surface is dependent upon the **magnetization** and **iron content** of the rocks making up the crust. **Magnetic anomaly** data, derived after subtraction of time variations and broad-scale regional fields, can be a powerful interpretive tool for establishing the **geometry** and **nature** of **subsurface** rock formations. **Aeromagnetic surveys** on land and **marine magnetic surveys** at sea have contributed data to the National Magnetic Data Base compiled and maintained by the GSC. Much, but not all, of Canada is covered by such surveys. Through a GSC-LITHOPROBE/industry consortium, a large gap in the publicly available data base in central and southern Alberta has been filled as part of the Alberta Basement Transect scientific program.

Aeromagnetic surveys have been a primary **exploration tool** for much of Canada and are extremely important in providing **maps** from which unexposed geology can be deduced. On the color-coded aeromagnetic maps, the **geologic texture** of any region is immediately evident and major **discontinuities** are readily identified.

SLIDE # 68: An aeromagnetic map covering the Kapuskasing Structural Zone.
We remember an earlier slide of the same area. Here the induced sunshine is oriented to emphasize north-south oriented features. In this case, the linear features are from a dyke swarm (see Glossary).

New technological developments in computers, particularly interactive workstations and color monitors, have facilitated and enhanced the use of both types of potential field data. LITHOPROBE is taking advantage of these developments, as exemplified by recent work in the Kapuskasing Structural Zone (see slide) where some geological features have been better delineated and others extended beyond their mapped locations by means of processed gravity and magnetic maps. In the Lithoprobe East Transect, characteristic geological features on Newfoundland have been extended across the Gulf of St. Lawrence to Nova Scotia and New Brunswick on the basis of analysis of combined marine magnetic and aeromagnetic data.

III. 4 ELECTROMAGNETIC GEOPHYSICS

SLIDE # 69: Electromagnetic measurements reveal conductive (yellow) and resistive (greens) subsurface layers.

This slide shows a regional resistivity (inverse of conductivity) structure across southern British Columbia. The units (in colours) of resistivity (ρ) are Ωm. The arrowheads on top of both sections indicate the position of the recording stations. Note the vertical exaggeration is 5:1.

Scientists like checking up on their own work, preferably through methods different from what has led them to their conclusions. For instance, a chemist can establish through a chemical analysis that the nugget he is handed consists of pure gold; but so can a physicist by precisely measuring the nugget's volume and specific gravity (the latter is the Archimedes principle we have learned about in physics).

So, LITHOPROBE scientists who probe Earth's crust by employing seismic (sound) waves and their reflection by different layers in the crust use entirely different types of measurements to check up on the seismic results. Gravity data are one way of doing this, but these data rely on physical properties of the measured rock (namely their densities) which also influence the rocks' seismic responses.

Thus, geophysicists employ **electromagnetic** (**EM**) studies which reveal subsurface structure in terms of a physical property, **electrical conductivity** (or its inverse **electrical resistivity**), that is **independent** of the other physical properties on which seismic and gravity measurements rely.

Most of us have experienced electrical conductivity through an electric shock, which is even more effective when we are unfortunate enough to touch live wires with wet hands or a wet towel. Don't try it, but believe me that it would work even better if the fluid we have on our hands was salty. And if your worried buddy would grab you by the hand that same moment, both of you would be conductive. (It's advisable to turn the electricity off instead.) So, this is how effective a force electric conductivity can be.

Electrical conductivity also is **extremely sensitive to composition, texture and fluid** content within the rocks of the lithosphere and thus provides another facet to **integrated** programs of crustal study.

In the **continental crust**, **saline water** in interconnected **pores and fractures** is probably the most widespread cause of **high electrical conductivity**. Alternate explanations involve the presence of **graphite** or partial **melt** (molten rock), both of which are conductive. So, high electrical conductivity alerts us to the possible presence of fluids in the measured rock, or else graphite or melt. All of this can be measured without having to dig a hole down to where these electric responses are coming from.

Now, we already know that **fluids** within the continental crust are vitally important, both in the mode of deformation of rocks and in the genesis of **ore deposits**. The roles of volatile fluids in the crust are discussed further in the subsection on **Geochemistry**.

*In tectonically active regions, such as the Cordillera west of the Rocky Mountains, other fluids, silicate partial melts, can cause high electrical conductivities in the lower crust and upper mantle. Rocks are composed of a number of mineral constituents which melt over a range of temperatures. At a temperature within the melting range, a partial melt may occupy cavities in the solid matrix of the remaining minerals. As most silicate melts are excellent conductors, a rock with a few percent of melt in interconnected cavities may have high bulk conductivity. Thus **EM** geophysics may detect and map partial melt in anomalously hot regions, such as those along the Southern Cordillera Transect.*

By the way, where does the electricity (whose impact we are measuring here) come from? Glad you were going to ask. Also, let's cut corners here, because you touched a difficult spot of science, where not all there is to know is known yet. One reasonable explanation is that the core of the earth, together with heat-generated convection streams, rotate at speeds different to surrounding matter, thus friction and electricity is induced, i.e. the dynamo effect. This, in turn, is thought responsible for the electromagnetic field, or magnetosphere, surrounding Earth. This magnetosphere, in turn, induces electricity into the crust (from above). Since the surrounding magnetosphere is subject to solar winds (protons from the sun), it shows variations. These, in turn, provide all sorts of opportunities one can measure. At any rate, where does the electricity come from? From Earth's core dynamo, via the induced magnetosphere around Earth, which, in turn, induces electricity into the crust. Within the crust, different rocks and various fluid contents provide differing conductivities; thus these differences can be measured. Pretty neat, I 'd say!

LITHOPROBE's electromagnetic studies generally comprise two types of field surveys. **Broadband tensor magnetotelluric** (**MT**) soundings, which rely on the effects of Earth's magnetospheric field, is one. The other measures varying the effects of controlled, man-induced electricity, which is the **electro-magnetic (EM) method**.

The former, **magnetotelluric soundings (MT)** are recorded with station spacings of a few to tens of kilometers, and provide **regional coverage** along the transects. These make use of natural time-varying EM fields due to electric currents in the magnetosphere and ionosphere. These fields are recorded over a wide range of frequencies enabling derivation of conductivity structure from near the surface to mantle depths. Recently, the GSC has developed extremely "long-period recording magnetotelluric instruments" (LIMS), collecting data which can provide conductivity information to depths in excess of **500 km**! Thus, these can provide a "probe" into the sub-crustal lithosphere and upper mantle of Earth.

When specific geological targets or other features have been identified, high-resolution, controlled-source, electromagnetic methods are employed to better delineate **conductivity anomalies** in the upper crust.

Reconnaissance surveys and some special projects are carried out by university and GSC scientists who have the necessary equipment. Analysis of the complex data sets and presentation of results are greatly enhanced by the recent availability of powerful computer workstations with interactive and colour capabilities.

LITHOPROBE results and those from other countries have shown that in the study of a continental crust in which fluids are important, electromagnetic geophysics, reflection and R/WAR seismology are much more powerful **together** than each is alone.

III. 5 HEAT FLOW AND GEOTHERMAL STUDIES

We already have discussed that Earth itself is our biggest nuclear power station. The **Earth's internal heat** drives **tectonic processes** and is ultimately responsible for the formation of **mineral deposits** and the **maturation of hydrocarbons** in sedimentary basins. Thus any studies of these processes must include the contributions, past and present, of **heat flow**. Within the Earth, heat is produced by the decay of naturally occurring radioactive elements and by mantle cooling. Many tectonic processes generate local heat perturbations, as evidenced directly by volcanoes and hot springs.

Heat flow measurements are commonly made in drillholes on land or at sea with special probes into the soft sediments of the sea bottom and also in drillholes. While some holes are drilled specifically for heat flow measurements, many heat flow values are determined from previously drilled "boreholes of opportunity". To calculate heat flow values, **temperature gradients** and **thermal conductivities** of the rocks in which the temperature gradients are being measured must also be determined. Using measured heat production values and other thermodynamic properties, **thermal modeling** can provide estimates of temperatures today and in the past.

Temperature-dependent **rheological** properties (that is how stiff the rocks are; over long periods of time, such as those we deal with in geology, rocks can actually flow) control zones of strength and weakness in the crust and thus depths at which tectonic motions could take place. In sedimentary basins such as that east of the Rocky Mountains, movement of water in the rocks greatly affects measured heat flow. Geothermal studies of the fluid migrations are of great value because they detect water speeds of a few centimeters per year which can be discerned in no other way. Both university and government scientists have the necessary facilities and expertise and are actively participating in thermal studies relevant to LITHOPROBE.

III. 6 GEOLOGICAL MAPPING

SLIDE # 70: Geological field work provides the foundation for all other LITHOPROBE surveys.

Geological mapping is the **foundation** upon which all of the LITHOPROBE transects are based. Much of this work is complete at the reconnaissance level through the systematic geological mapping that is the responsibility of the federal and provincial governments. However, more detailed field mapping is required over those transects for which such information is not already available. To this end, geologists from the GSC, provincial government geological surveys and universities are making special efforts to carry out the detailed field mapping required for each transect.

Another aspect of geological mapping often occurs after the acquisition and preliminary interpretation of the seismic reflection data along a transect. **Results** inferred from the **seismic** sections point out the need for additional mapping to resolve ambiguities in the **interpretation** or to investigate specific seismic features in terms of their geological cause. This procedure has already been applied in most active transects.

SLIDE # 71: Geological map of eastern Labrador, showing the Grenville and Makkovik Provinces. The bottom inset shows major structural zones in relation to other LITHOPROBE transects studying the Grenville Province elsewhere. The top inset illustrates correlations between the Makkovik Province and the related Ketilidian Mobile Belt of Greenland.

Let's take in the vibrant colours of the map -- a better display than many dress ties would show. The first impression one gets is the contrast between the lower and the upper parts of the map. One sees not only different colours but also contrasting orientations. Both are important. The colours refer to two things: the ***types*** *and the* ***ages*** *of the rock units they represent (see the legend for this). The contrasting lineations, and the juxtaposition of the variations in colours and directions, originated from the collision of two large cratons. We remember the Grenville Orogen, and how it cut across everything that had existed prior to being thrust upon the pre-existing part of the Canadian Shield. That line of fault thrusting is the one along the "Grenville Front", along which the tectonic styles change so dramatically.*

One must marvel at the geologists and other earth scientists who contributed to this map. First one finds rocks of various types, then one describes units of them, next places them into their proper structural setting and orientation, and dates them, and then reads all of this as one dynamic story. Note, for instance, how the (red-coloured) Groswater terrane of the Grenville Province overrides two, much older terranes (in purple) of the Makkovik Province. Or see the younger "post-collisional granite plutons" which were intruded into the older rocks of the Pinware terrane (laid bare for us to see by subsequent erosion). At any rate, we get the drift of how much information is contained in such a geological map, and how it takes more than just one discipline to sort out the geological and tectonic situation.

III. 7 STRUCTURAL GEOLOGY

Structural studies are probably the type of **geological** investigation that most often complements the indirect methods of **geophysics**. Together with seismic reflection and other geophysical data, structural studies contribute directly to an understanding of how continental crust has been thickened or thinned. This is determined by establishing the **geometry** and **style** of **folding** that has affected the rocks, and the geometry and nature of the **faults** that cut them, especially the amount and direction of displacement along them.

These structures include strain markers such as deformed pebbles, crystals, vesicles (irregularly shaped spaces in the rocks), fossils, and various kinematic indicators which show the **degree** and **directions** in which the rocks have been **deformed**. In turn, these observations permit some inference of the direction of **paleostresses**, that is the stresses on the rocks at the time they were being deformed. When combined with **isotopic dating** methods, such strain markers make it possible to establish the **time** at which movement took place and hence the **age** and **duration** of **paleostresses**. Estimates of the temperatures, pressures and hence depths at which rocks deformed in the crust, and sometimes even the magnitude of the stresses required, are possible when the rocks contain certain co-existing metamorphic mineral assemblages, for which equilibrium temperatures and pressures have been determined experimentally.

SLIDE # 72: Structural geology captures the dynamics of a geological setting.

Here we see an interpretative diagram showing geological features of the Montreal - Val d'Or geotraverse (across the central Grenville corridor). Major terrane boundaries are indicated, and allochthonous slices (or packages of rocks which have been moved onto other rocks), as well as shear zones (along which movement took place) and intrusive *complexes (plutons). The red lines show seismic lines along which data were acquired in 1993.*

The **collaborative** interaction of structural **geologists** with **seismologists** that is planned for all transects is fundamental to achieving the most meaningful and complete interpretations of the seismic sections.

III. 8 IGNEOUS AND METAMORPHIC PETROLOGY

Conventional field, petrological and mineralogical studies of igneous and metamorphic rocks need to be supplemented by major and trace element geochemistry and by isotope tracer studies (see Geochemistry and Geochronology subsections) to provide an adequate chemical description of the rocks.

SLIDE # 73: Thin section of an olivine mineral. Olivine is one of the main constituents of the upper mantle.

With these additional geochemical data, it is possible to characterize the **geochemistry** of the **tectonic setting** in which the granitic and volcanic rocks were formed. It is particularly important to capitalize on exposures of **lower crustal rocks** by undertaking **petrological and geochemical** studies to elucidate lower crustal **petrogenesis** (i.e., the processes by which rocks in the lower crust formed).

Pressure and temperature data from metamorphic mineral assemblages and their fluid inclusions are being used to estimate rates of uplift and erosion. This may be achieved by comparing P-T (**pressure-temperature**) data for the time the rocks were originally metamorphosed with P-T data for the time the same rocks were known to be at a higher crustal level (calibrated, for example, from the time when subsequent granitic plutons or basic dykes intruded them) and finally from the time the rocks were brought to the surface and made available to erosion. Complicated? You bet! But, this kind of information not only reveals the rate at which crustal thickening and subsequent uplift took place but also suggests further lines of inquiry regarding the subsidence histories of sedimentary basins which received the products of erosion related to the uplift of the metamorphic terranes.

III. 9 STRATIGRAPHY AND SEDIMENTOLOGY

Studies of **sedimentary basins** crossed by the transects are devoted to the understanding of the nature, mode of **formation** and **tectonic setting** of the **basins**. Remember our discussion of the WCSB? What was it? Well, it is the **W**estern **C**anada **S**edimentary **B**asin which overlies the Alberta Basement and adjacent regions. Now we remember.

The focus in **stratigraphy** and **sedimentology** is on questions such as: how deeply and at what rate did the basin subside? By what sedimentary processes did the basin fill? Where did the sediment come from? What caused the basins to form where they did and how are their histories related to the development of the continental crust of Canada? How has water moved and migrated hydrocarbons within the sediments?

SLIDE # 74: Stratigraphic cross section of sedimentary basin formation.

A whole host of established **stratigraphic** and **sedimentological** approaches can be applied and coupled with data on the **temperatures** and **pressures** to which the sediments have been subjected. [Such P-T data can be derived from the **geochemistry** of contained hydrocarbons, vitrinite reflectance of coals, kerogen studies of organic matter, colour alteration of conodonts (a type of fossil), fission track and $^{40}Ar/^{39}Ar$ (argon isotopes) dating of detrital and authigenic (original) components, clay mineralogy and other low-grade mineral assemblages. At any rate, we can use many indicators here.]

SLIDE # 75: Boreholes drilled by oil companies have yielded a wealth of data from the WCSB.

Some of these data may be obtained from surface exposures. However, most commonly in basins in the middle of the continent and passive margin settings on the present continental margin, the information can only come from wells **drilled** by the petroleum industry or from mineral exploration drill cores in sedimentary basins. Studies of sediment provenance are of particular importance in establishing links between terranes.

III. 10 GEOCHEMISTRY

The processes involved in the formation and modification of continental crust -- igneous processes, erosion and formation of sediments, tectonic-metamorphic processes -- tend to have unique **chemical signatures**. Such signatures may involve the patterns of abundance of the elements, isotope systematics or the fractionation of light stable isotopes such as those of hydrogen, carbon, oxygen or sulphur.

Fragments of crust accreted as parts of the assemblage of a continent carry with them **records** of their **unique geochemical history**. Thus, geochemistry adds to information from paleomagnetism, geochronology and structural studies to form a more complete description of the processes of crustal generation and evolution.

It is now recognized that in all major parts of the plate tectonic cycle, **fluids** play a major role. At ocean ridges where new, hot lithosphere is formed, sea water interacts with igneous rocks and modifies both rock and ocean water. When ocean floor is subducted, fluids are mobilized, lubricate the subduction thrusts and eventually catalyse the formation of gassy, subduction-related volcanic products. When continental blocks collide (as in the Himalayan or Alpine mountain-building events), the great continental thrust structures are lubricated by the extrusion of fluids from the compressed and heated rocks pushed to greater depth.

Every time a geologic fluid moves, whether it is an igneous melt, metamorphic H_2O - CO_2, or fluids from a sedimentary basin, chemical and isotopic **changes** occur along the fluid pathways. The type of fluid can often be identified from its stable isotope systematics and its composition derived from the study of small inclusions of fluid preserved in the rock or chemical changes along the flow path. Thus chemical change can be used to identify tectonic processes both in terms of scale and style.

Almost all of our mineral and hydrocarbon resources are related to the movement of such fluids. Sulphides of iron-zinc-copper-silver are associated with sea water heated in the oceanic crust and cooled as it rises at ridges. Gold-silver-tungsten-copper-molybdenum deposits appear to be associated with fluid processes above subduction zones. Most of the great gold deposits of Canada appear to be associated with deep fluids from igneous and metamorphic processes. Every time large volumes of fluid are moved in tectonic processes, there is potential for the rearrangement of chemical components, at times into valuable **ore deposits**.

SLIDE # 76: A triangular (or ternary) diagram used to plot the chemical analysis of igneous rocks.

Such a plot allows us to determine the source of a magma from which a rock has solidified, and much about how this has happened. Yes, another detective story, Sherlock Holmes would have loved it. Is it difficult to do? Very! But the principles behind this scientific detective work are straightforward.
Let's start with a bottle of pop. Open it when it's very cold and the bubbles will escape, sometimes forming a froth. Open the bottle or can when it's warm and the same will happen, only more so, because the bubbles will wish to get out much faster yet. What we have here is a splendid demonstration of how pressure (under which the pop is sealed in its container) and temperature control the balance in which the carbon dioxide or CO_2 *is held in solution in the pop. Remove the pressure on the solution, that is remove the cap, and the bubbles no longer can be held in solution, they are "volatile" and escape. Increase the temperature and more* ***volatiles*** *will tend to escape. Easy? Surely, it is. Now, we must add the "solids" which also will fall out within a certain temperature-cum-pressure regime, something one has in shakes and sugar or salt solutions. Likewise, all minerals have their specific temperatures-cum-pressure ranges at which they will melt into or precipitate from a magma.*

The magma from which a rock-type(s) has solidified can have formed from an infinite selection of rocks and circumstances. It may have come from the mantle deep below the crust, or it may have formed when rock in the crust was melted. Then again, only certain parts of a rock may have melted, or all of it, or *much, or little. On its way upward, parts of the magma may have solidified, and what was left moved on, then being different in its chemical character because of the missing constituents.*

The possibilities are endless, depending on prevailing pressures and temperatures. One can only dissolve so much sugar in a cup of tea, and when it cools, some of the sugar will precipitate (or fall out).
And in that fact lies the handle to the scientific analysis of a solidified rock. The chemical constituents in the rock can indicate to the geochemist under what pressure and temperature conditions, and from which likely original mix of magma, the rock has formed. Pretty neat, eh?

*The triangular AFM diagram that we see allows the researcher to plot different "suites" of igneous rocks, which describe the environment (such as temperature and pressure) and the source of the rock's formation. The "**A**" stands for **a**lkalies, the "**F**" for iron (or **f**errous and **f**erric) oxides, and the "**M**" for **m**agnesium oxide. Exactly where each rock sample will be plotted on this diagram depends on the relative weight percentage of these three oxide groups found in the sample.*

Samples from the Garibaldi volcanic belt near Vancouver will plot dominantly in the calc-alkaline field. The granitic rocks from the Coast Plutonic Complex west of the volcanic belt also plot in the same field. In contrast, the freshly formed rocks from the magmas oozing out of the Juan de Fuca rift offshore Vancouver Island plot in the tholeiitic area of the diagram. If such rocks were subsequently thrust onto the continent (as happened in western Newfoundland), they could be distinguished from the volcanic rocks.

The role of geochemistry in LITHOPROBE is two-fold. Determination of the deep structure and processes of the crust requires, first, an understanding of the **pressure-temperature** (P-T) conditions applicable at depth and, second, of the **fluids** that are present. P-T conditions at depth can be estimated from the distribution of the elements and isotopes found in the rocks now exposed at the surface that were formerly buried, and from intrusive rocks that have risen from depth carrying elements or inclusions with them. The fluids at depth can be estimated both from the chemical traces that they have left behind and from the fluids that are currently escaping at the Earth's surface.

In a more general way, one can say that one way of reading the story of rocks is through the distinct chemical signature which igneous, metamorphic, erosional and sedimentary processes impart on the rock formations.

For instance, fragments of oceanic and continental crust which have joined our continent carry the records of their unique geochemical histories. Geochemistry and its tools add one more discipline for correlating information from several disciplines, such as seismic, structural, tectonic, and other studies.

III. 11 GEOCHRONOLOGY

Geochronology is a special branch of geochemistry, related to **isotope physics**, that involves determining the time of formation of rocks, minerals and fossils. Geochronologists examine materials ranging in age from a few years to billions of years old, mostly utilizing the principle that **radioactive** isotopes present at the "birth", or formation, of a mineral will **decay** at a certain fixed rate. Measurement of relative abundances of the "parent" and "daughter" isotopes can determine the age of the rocks.

SLIDE # 77: Minerals used in high-precision geochronological dating. Biotites (black mica) to left, zircons (clear) in centre, and hornblende (greenish) to right.

One example of the use of **radiogenic isotopes** is the uranium-lead (U-Pb) method of dating **zircons**. Zircon occurs in small quantities in many crustal rocks and contains a small amount of U which decays to Pb with a half-life (4,500 Ma) approximately equal to the age of the Earth. By measuring the abundances and isotopic ratios of U and Pb in zircon, the age of the rock can be determined with a **precision** on the order of 2 to 5 Ma.

SLIDE # 78: Computer plot of results of U-Pb analyses of zircons from a granite in N. Labrador. Each ellipse represents one analysis with its associated errors.

The graphs shows two ages of formation for different components of the granite. Note the errors of ±3 and ±5 Ma for a rock that is more than 2,500 Ma old. The graph on the lower right is an analysis of an additional component of the same rock indicating that its "clock" was reset by high temperature metamorphism at 1311 ±8 Ma.

A second application of radiogenic isotopes is the use of **samarium-neodymium** (**Sm-Nd**) ratios in granites to probe the lower crust. Granites are produced mainly by the melting of source rock in the deep crust. They travel upward, bringing with them a Sm-Nd ratio and Nd isotopic composition inherited from their source.

SLIDE # 79: An example from Newfoundland. *Isotopic results from late orogenic and post-orogenic, granitoid plutons. The yellow dots show where plutons were derived from the mantle (i.e. very deep). The black dots show where plutons were formed by melting of crustal (deep) and supra-crustal (shallow) rocks.*

Under favourable circumstances, the age of the deep crust may be determined. All this is particularly important in regions of **complex geology** where the upper and lower parts of the crust may have evolved independently and been structurally juxtaposed. Many other isotope systems and other geochronologic methods (e.g. "fission track" dating) provide critical chronological data.

Important economic applications of geochronology and radiogenic isotopes relate to the determination of the emplacement times of ore deposits and determination of the sources of their chemical components.

SLIDE # 80: A mass spectrometer allows precise measurements of isotopes contained in minerals. Their ratios determine their age.

In LITHOPROBE, geochronology is important in providing the detailed age control for surface rocks and intrusives that is essential to unravelling their local geological history. Isotopic dating is critically important where organic material and fossils are absent (as in most Precambrian settings) and is the only means that can securely establish timing of the intrusions and metamorphism that are associated with tectonic activity.

Dating of surface exposures is required to connect the observed rocks with the geophysically-determined geometry and domains at depth.

Isotopic geochronometric studies are planned along all transects to date the emplacement of all significant granitic and volcanic suites and the times of their metamorphism and deformation. Dates by several methods, including fission track counting, are used to establish times and rates of uplift of the metamorphic and plutonic rocks and basin deposits. World-class facilities for these studies exist at a number of Canadian universities, the GSC and the Royal Ontario Museum.

III. 12 PALEOMAGNETISM

The techniques of **paleomagnetism** are based on measuring the directions of magnetization "frozen" into rock formations having minute quantities of iron at their **time** of **origin** (time of solidification) or at subsequent times when they have been reheated or metamorphosed. By making careful corrections for the present attitude of a rock formation (how it has been folded or tilted) and comparing these directions with the known magnetic field at the time of their magnetization, it is possible to calculate the original **latitude** of the rocks. The unravelling of the movements through geological time of terranes and continents from the record of the Earth's magnetic field contained in appropriate rocks is a complex process. However, paleomagnetic studies have had remarkable success in providing the framework for measuring **continental drift** and plate tectonic movements and contributing to the ultimate proof that such movements have occurred.

In recent years, a major achievement of paleomagnetism has been the measurement and confirmation of the complex assemblage processes that have occurred in the western Cordillera. These are now seen to have involved major latitudinal shifts (indicating up to thousands of kilometres of movement) and block rotations. Although fossil assemblages and facies have been important in providing other geological evidence for these movements, paleomagnetism offers the opportunity for direct measurement. Determination of the latitude of origin of rock formations and, in particular, that certain rock formations now juxtaposed may have had origins many hundreds or thousands of kilometres apart, is critically important in understanding the **geotectonic developments** within a transect and thus the **evolution** of the continent.

Paleomagnetic field work involves field sampling of the selected rock types with close geological control (rock unit, age, attitude). Knowing the age of the rock, either from geochronology or fossil control, is critical. Notice how the different disciplines must interact to be effective.

III. 13 PHYSICAL PROPERTIES OF ROCKS

All geophysical observations relate in some way to the physical properties of rocks - seismic to compressional and shear velocities, gravity to density, magnetic to magnetic susceptibility, electromagnetic to porosity and electrical conductivity, geothermal to thermal conductivity and heat production, and paleomagnetism to various types of magnetization associated with rocks. Some of these properties must be determined as a requirement of the method itself; others are determined independently. Geophysical logging of boreholes made available by the mining industry can provide valuable information where this is applicable.

In many cases, it is important to determine physical rock properties under in situ conditions of temperature, pressure and fluid content. This requires specialized and complex equipment so that only a few laboratories in universities have appropriate capabilities. The appropriate rock samples are selected in the field usually with the collaboration of a mapping geologist, or are obtained from cores or cuttings from boreholes of opportunity from either the mining or petroleum industry. Particular success has been achieved in relating physical rock properties derived from borehole studies to seismic and electromagnetic data in mining areas.

For LITHOPROBE and other research, access to information about physical properties of a wide variety of rock types under varying conditions is highly valuable.

III. 14 SUMMARY ON EARTH-SCIENCE DISCIPLINES

Now that you’ve had a “crash course” on earth science methods, you’ll probably appreciate what efforts we must make to try to understand the structure and evolution of the very continent we live on. On its own, not one of these disciplines could provide sufficient information to even begin our understanding. But put them all together, along with the knowledge of the scientists who apply the methods, and then real scientific progress and understanding can be developed.

We hope that you have found our story on “Probing the Lithosphere” a fascinating one, and that in so doing you have even learned something. LITHOPROBE is acknowledged as the premier multidisciplinary earth science program operating on any continent or in any country. Canadians can be proud of our contribution to earth science and to understanding the very evolution of the land on which we live.

Acknowledgments

There is one more fact we should know -- that this knowledge which LITHOPROBE draws together from across and out of the depths of our land belongs to all of us. It’s ours not only to possess, but all of us are also paying for it. Here is how.

Most of our funding comes from, firstly, the Natural Sciences and Engineering Research Council of Canada (NSERC); and, secondly, the Geological Survey of Canada. They are the principal supporters of LITHOPROBE.
But there are more sponsors: direct (i.e. dollars) and indirect (support and services) contributions flow from provincial and territorial geological surveys. And LITHOPROBE’s intellectual input from the many scientists who have worked for or still are engaged in LITHOPROBE projects largely comes for free, since the scientists’ salaries are

being paid for by the universities and the geological surveys which, in the end, means by the general taxpayers of Canada. And then there are the mining and oil companies which recognize the benefit of LITHOPROBE's studies for their own undertakings. They contribute funds directly to certain surveys, donate data, and also their time and knowledge.

So, we should grab what we have learned here and run with it and put it to good use; say when the next earthquake rattles the dishes in the cupboard, or when we pass a mine, we might offer some thoughts about their origins. And who wouldn't be surprised to learn that the huge Pacific Ocean is shrinking (partly disappearing under Canada) and Europe is moving away from us or, rather, both from each other.

Happy "litho"-probing!

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