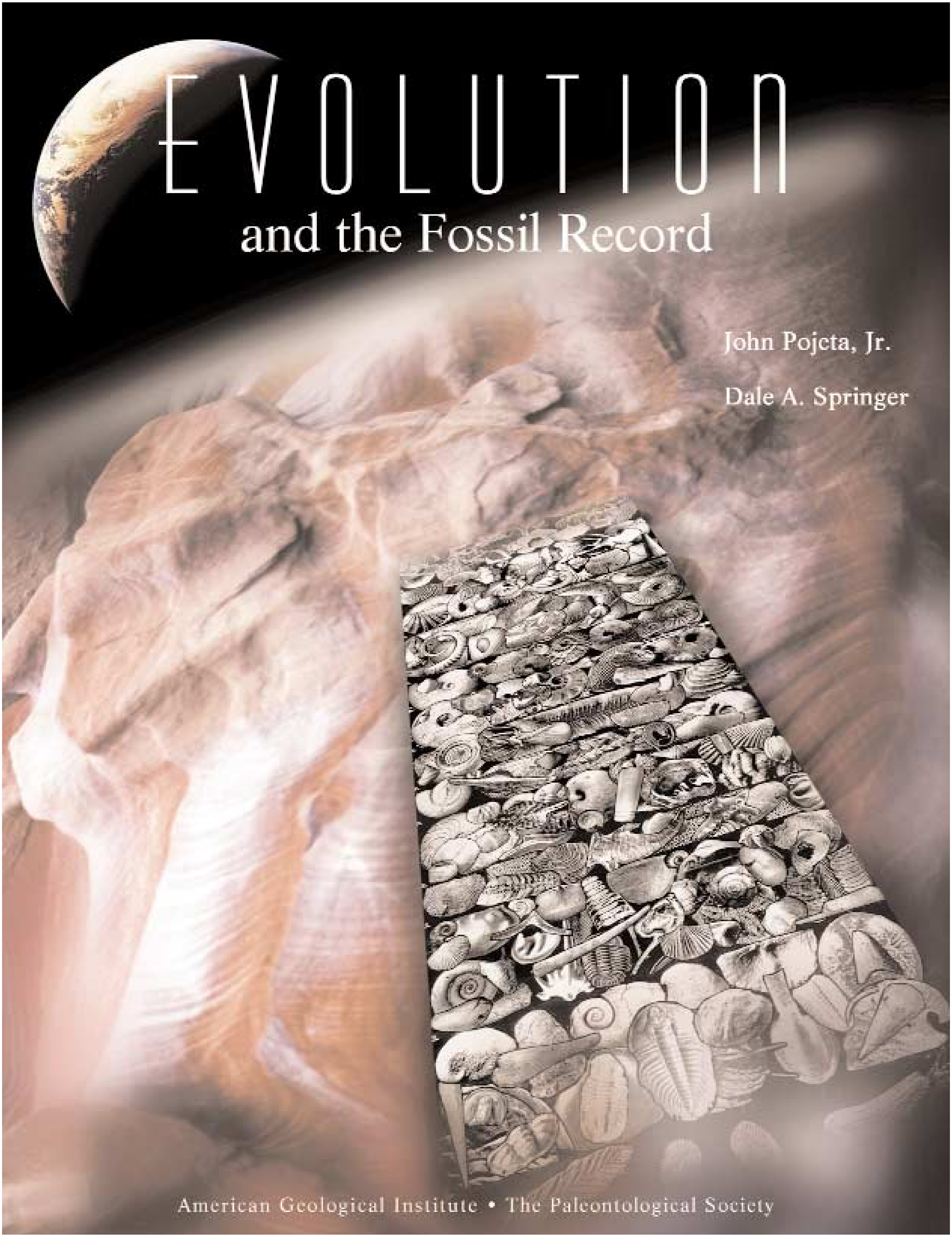
EVOLUTION
and the Fossil Record

John Pojeta, Jr.

Dale A. Springer



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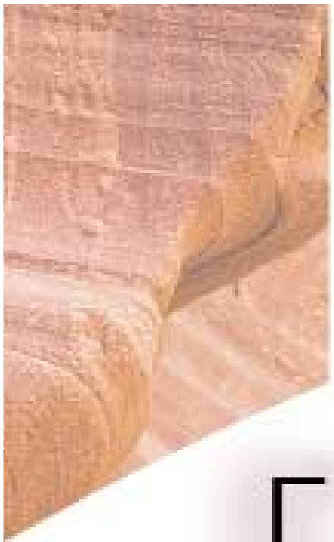

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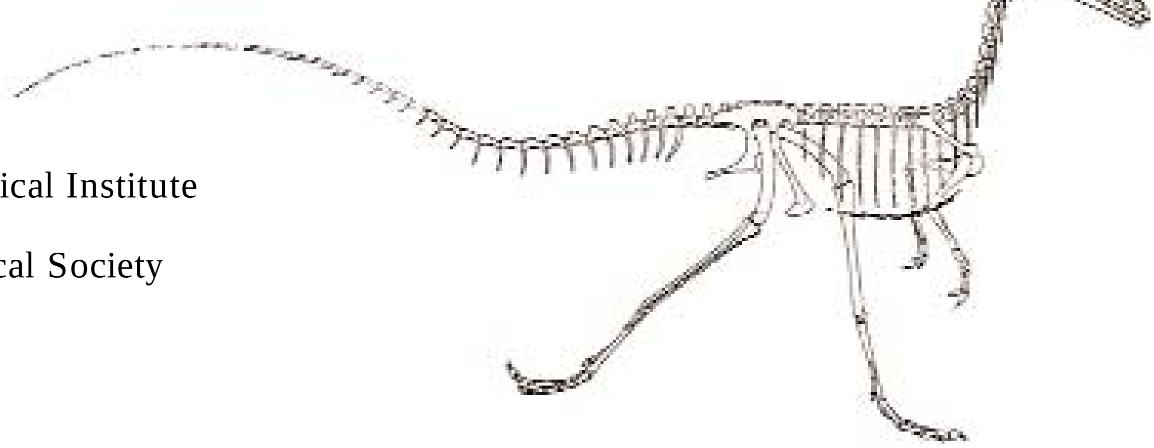

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About the Authors

John Pojeta, Jr. has been an active paleontologist since 1957. He is a Scientist Emeritus with the U.S. Geological Survey (USGS) and Research Associate with the Department of Paleobiology, Smithsonian Institution. He earned his B.S. degree at Capital University, Bexley, OH, majoring in biology and chemistry and earned his M.S. and Ph.D. degrees from the University of Cincinnati, majoring in geology and paleontology. In 1963, he joined the USGS, Branch of Paleontology and Stratigraphy, where he spent his career. His research has centered on early Paleozoic mollusks, and has taken him to many American states, Antarctica, Australia, Canada, China, Czech Republic, Senegal, Sweden, United Kingdom, and elsewhere. He has been Secretary and President of The Paleontological Society; President of the Paleontological Research Institution; Chief, Branch of Paleontology and Stratigraphy, USGS; and a member of the National Academy of Sciences Committee on Paleontological Collecting.

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Trilobite
(Ordovician)

Credits

Front cover — Adapted from "Fossils Through Time," a U.S. Geological Survey poster and photographic collage of life on Earth over the past 600 million years.

Inside Cover and title page — Ammonite fossil (G. James), Modern coral reef (J. Pojeta, Jr.), Ferns (Adobe)

Page ii-iii — Trilobite (M.L. Pojeta, photo: G. James), Fossils (J. Pojeta, Jr.)

Page iv-v — Ammonite, fossil fern (G. James)

Page vi — Geologic Time Scale (De Atley), Adapted from various sources

Page 1— Ammonite (G. James)

Pages 2-3 — *Chesapecten* fossils (adapted From Ward and Blackwelder, 1975**;** Bryce Canyon (M. Miller)

Pages 4-5 — Trilobite, brachiopod (J. Pojeta, photo: G. James), *Tyranosaurus rex* skull (Smithsonian Institution); Jurassic Dinosaur Footprints (modified from Haubold, 1971), Devonian and Ordovician trilobites (adapted from Moore, 1959)

Pages 6-7 — Charles Darwin (1875 portrait), Silurian and Devonian fishes (modified from Fenton and Fenton, 1958), Eocene fish fossil (G. James), Jurassic/Cretaceous fishes (modified from Romer, 1966)

Pages 8-9 — Early Jurassic mammal skeleton (modified from Jenkins and Parrington,1976), Diversification diagram (modified from Novacek, 1994)

Pages 10-11 — Shark's tooth, Fossil seed fern, Petrified wood (G. James)

Pages 12-13 — Hubble image, Earthrise over moon (NASA), Trilobite (J. Pojeta, photo: G. James)

Pages 14-15 — Ammonite (G. James), Block diagram (Springer/De Atley), Stratigraphic ranges table (modified from Edwards and Pojeta, 1994)

Pages 16-17 — Half-life diagram (modified from Bushee and others, 2000), Ordovician limestone and shale (J. Pojeta)

Page 19 — Forelimb comparison (modified from Daeschler and Shubin, 1998)

Pages 20-21 — Comparison of bird and dinosaur skeletons and limbs (modified from Ostrom, 1975 and 1994; Diagram comparing skulls of reptiles to mammals (modified from Savage and Long, 1986)

Pages 22-23 — Reconstruction of the "walking whale that swims" (modified from Thewissen and others, 1996), Sequoia National Park, California (Digital Vision)

Pages 24-25 — Brachiopod (G. James), Dragonfly and Amphibian Fossils (Hemera)

Page 26 — Nautilus (G. James)

Back Cover — Grand Canyon, Arizona (Digital Vision)

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Foreword

Evolution is one of the fundamental underlying concepts of modern science. This powerful theory explains such phenomena as the history of life preserved in the fossil record; the genetic, molecular, and physical similarities and differences among organisms; and the geographic distribution of organisms today and in the past. Indeed, evolution forms the foundation of modern biology and paleontology and is well documented by evidence from a variety of scientific disciplines.

Evolution is also one of the most misunderstood and controversial concepts in the eyes of the general public. This situation is unfortunate, because the controversy surrounding evolution is unnecessary. Resistance to evolution stems in part from misunderstanding science and how it is distinct from religion. Science and religion provide different ways of knowing the Earth and universe. Science proceeds by testing hypotheses and thus is restricted to natural, testable explanations. By definition, science is unable to confirm or deny the existence or work of a Creator; such questions are beyond the realm of science. As a scientific concept, evolution therefore can make no reference to a Creator. Many people of faith, including scientists, find no conflict between evolution and their religion; in fact, many religious denominations have issued statements supporting evolution. Science and religion need not conflict.

Numerous lines of evidence show that life has changed through time. Evolution is the best scientific explanation for this change. This booklet describes a small portion of the evidence for this change, especially as documented by the fossil record, and outlines the processes involved in evolution. Many fascinating questions remain concerning the history of life and the process through which it has developed. As we continue to learn about life on Earth, the theory of evolution will itself evolve. That is the strength, adventure, and excitement of doing science!

Patricia H. Kelley
Paleontological Society President, 2001-2002

Marcus E. Milling
AGI Executive Director

Geologic Time Scale

						Boundaries . Million Years Ago
Phanerozoic	Cenozoic	**Quaternary** Modern humans		Holocene		0.01
				Pleistocene		2
		Tertiary Mammals diversify; early hominids	Neogene	Pliocene		5
				Miocene		23
			Paleogene	Oligocene		34
				Eocene		55
				Paleocene		65
	Mesozoic	**Cretaceous**			Flowering plants common; major extinction including dinosaurs & ammonoids	144
		Jurassic			Early birds & mammals; abundant dinosaurs	206
		Triassic			Abundant coniferous trees, first dinosaurs; first mammals	250
	Paleozoic	**Permian**			Mass extinction of many marine animals including trilobites	290
		Carboniferous Fern forests; insects; first reptiles; crinoids; sharks; large primitive trees	Pennsylvanian			314
			Mississippian			360
		Devonian			Early tetrapods, ammonoids, & trees	409
		Silurian			Early land plants & animals	439
		Ordovician			Early Fish	500
		Cambrian			Abundant marine invertebrates; trilobites dominant	540
"Precambrian"		**Proterozoic**			Single-celled and, later, multi-celled, soft-bodied organisms; first invertebrates	2,500
		Archean			Oldest fossils; bacteria & other single-celled organisms	
					Oldest known fossils	3,800

Although these dates have an accuracy range of about +/– 1%, boundary dates continue to change as geoscientists examine more rocks and refine dating methods.

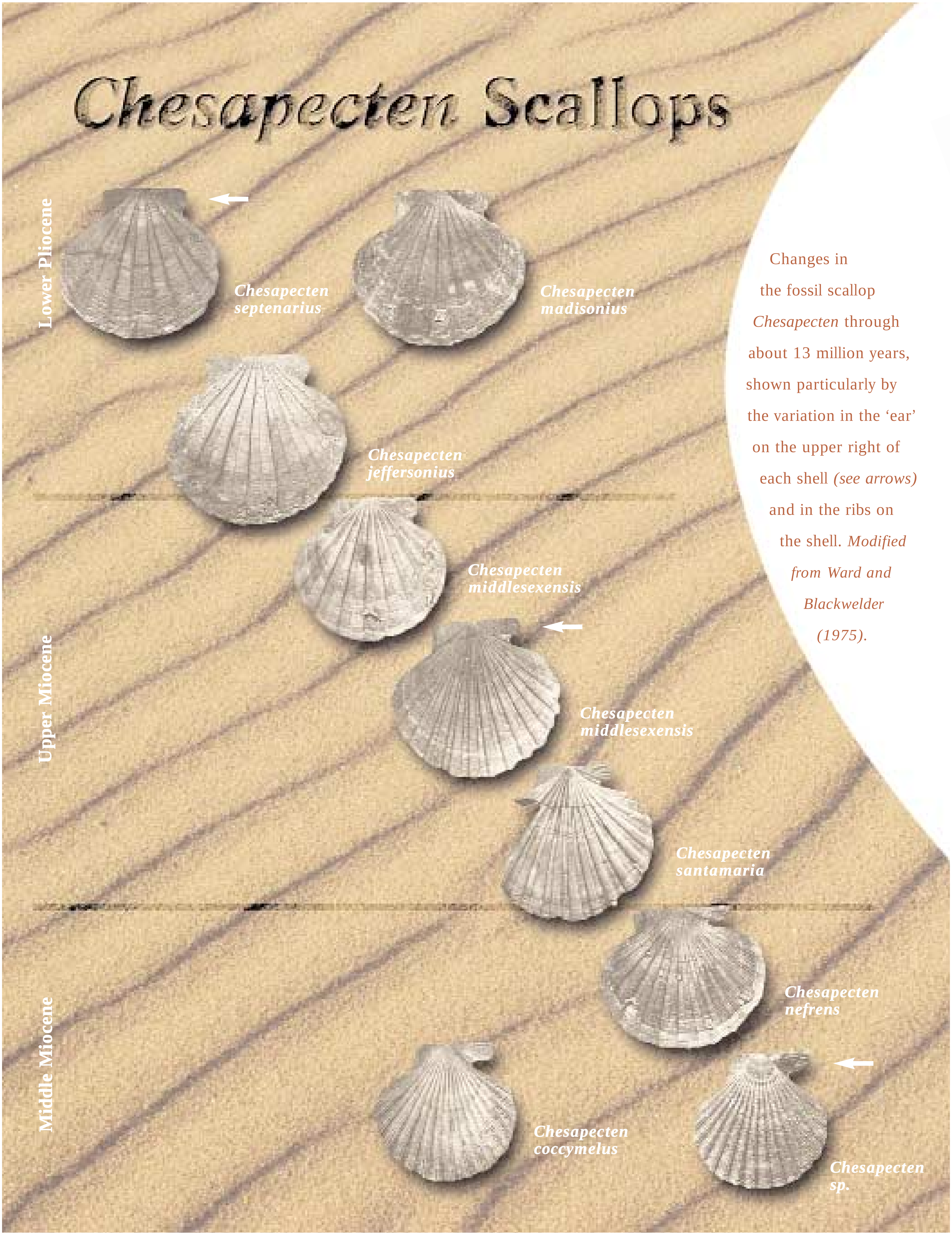
Tyrannosaurus no longer stalks its prey across North America. There are no pterosaurs sailing majestically overhead. Trilobites no longer crawl on the sea floors of Earth. Today, other predators roam in search of a meal. Birds soar the skies, and crabs scuttle across the ocean bed. Life on Earth has changed through time. It has evolved. Change through time is a widely accepted meaning of the word evolution. We speak of the evolution of the English language, the evolution of the automobile, or the evolution of politics in the United States. In natural history, biological or organic evolution means change in populations of living organisms on planet Earth through time.

Charles Darwin defined biological evolution as "descent with modification," that is, change in organisms in succeeding generations. Another way of saying this is, "species of organisms originate as modified descendants of other species" *(Hurry, 1993)*. Biological evolution is the derivation of new species from previously existing ones over time.

Evolution is the central unifying concept of natural history; it is the foundation of all of modern paleontology and biology. This booklet presents a non-technical introduction to the subject of evolution. Here you will find straightforward definitions of important terms as well as discussions of complex ideas.

This brief introduction to the rich and fascinating history of the theory of evolution cannot present in detail the vast body of evidence that has led to the current understanding of evolutionary processes. Our aim is to provide a sense of the history, strength, and power of this important scientific theory. We hope that this booklet will help you sense the wonder and excitement that paleontologists and other students of evolutionary science feel when they contemplate the long and intricate history of life on Earth.

Chesapecten Scallops



Changes in the fossil scallop *Chesapecten* through about 13 million years, shown particularly by the variation in the 'ear' on the upper right of each shell *(see arrows)* and in the ribs on the shell. *Modified from Ward and Blackwelder (1975).*

The Fossil Record

Fossils provide the dimension of time to the study of life

For at least 300 years, scientists have been gathering the evidence for evolutionary change. Much of this vast database is observational, and the evidence came to light with the study of fossils *(paleontology)* and the rock record *(geology)*. This essay focuses on the evidence about evolution from the fossil record.

Documentation of ancestor-descendant relationships among organisms also comes from the fields of biogeography, taxonomy, anatomy, embryology and, most recently, genetics — particularly DNA analysis. Information from these fields can be found in the materials listed in the "Suggested Readings."

The fossil record remains first and foremost among the databases that document changes in past life on Earth. Fossils provide the dimension of time to the study of life. Some of the most basic observations about fossils and the rock record were made long before Darwin formulated his theory of "descent with modification." The fossil record clearly shows changes in life through almost any sequence of sedimentary rock layers. Successive rock layers contain different groups or assemblages of fossil species.

Sedimentary rocks are, by far, the most common rocks at Earth's surface. They are formed mostly from particles of older rocks that have been broken apart by water, ice, and wind. The particles of gravel, sand, and mud, which are collectively called sediment, settle in layers at the bottoms of rivers, lakes, and oceans. Shells and other limy materials may accumulate in the oceans. As the sediments accumulate they bury shells, bones, leaves, pollen, and other bits and pieces of living things. With the passing of time, the layers of sediments are compacted by the weight of overlying sediments and cemented together to become the sedimentary rocks called limestone, shale, sandstone, and conglomerate. The buried plant and animal remains become fossils within the sedimentary layers.

Trilobite
(Cambrian)

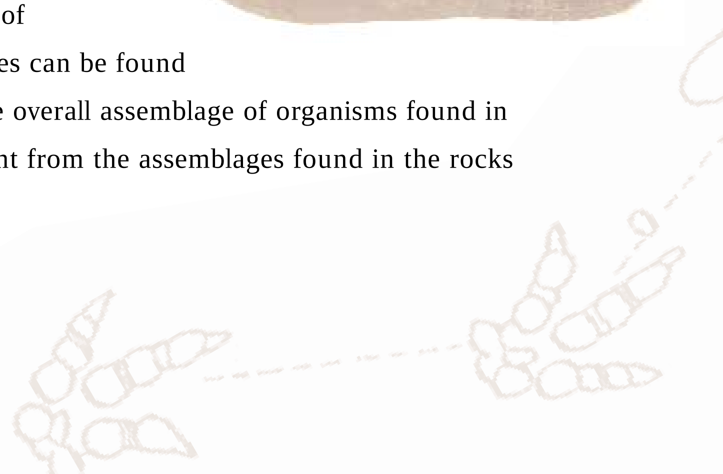
Change Through Time

The geological time-period terms Cambrian, Ordovician, ...,Jurassic,..., Cretaceous, and on through the Quaternary, define successive changes in species of animals and plants through time on Earth. Thus, Ordovician trilobites differ from Devonian trilobites, Silurian and Devonian fish differ from Jurassic and Cretaceous fish, Mesozoic mammals differ from Cenozoic mammals, and so forth. In addition to changes occurring in many different species found in different geological time intervals, whole groups of organisms that were once abundant and diverse, such as trilobites, can become extinct.

Brachiopod
(Devonian)

The boundaries between the great blocks of geologic time called Eras are defined by major changes in the types of fossils found in the rocks deposited in those Eras: Paleozoic means "ancient animals," Mesozoic means "middle animals," and Cenozoic means "recent animals." Trilobites and shelled animals called brachiopods are common and typical Paleozoic fossils. Dinosaurs, certain large marine reptiles, such as ichthyosaurs and mosasaurs, and the flying reptiles called pterosaurs are found only in Mesozoic rocks. Fossils of mammals, clams, snails, and bony fishes are typical of Cenozoic fossil assemblages. Some species can be found on both sides of a time boundary; however, the overall assemblage of organisms found in the rocks of a given age is recognizably different from the assemblages found in the rocks above and below.

Allosaurus
(Jurassic)

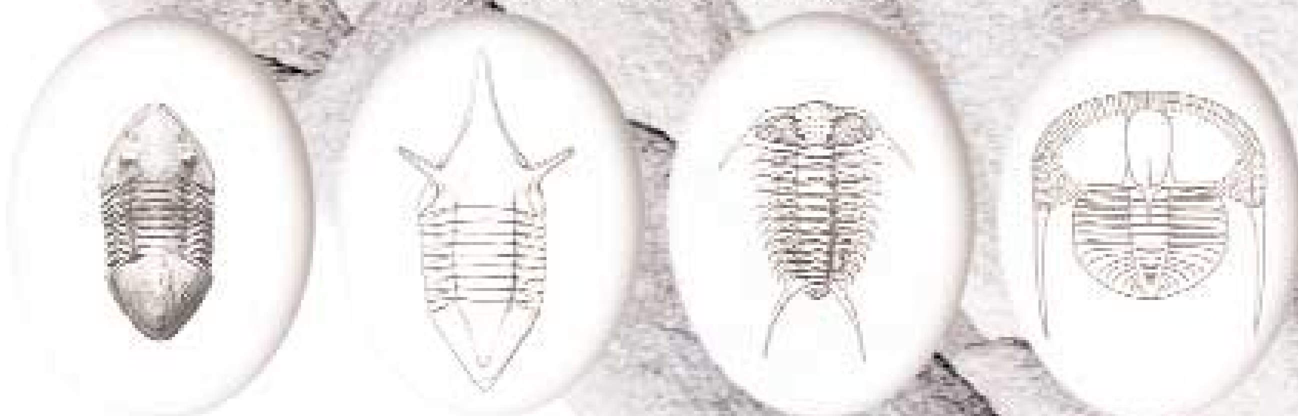


Devonian Trilobites

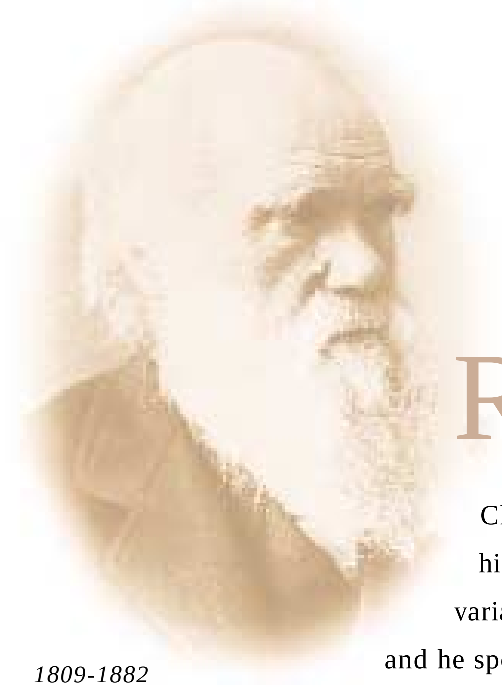
409-360 Million Years Ago

Ordovician Trilobites

500-439 Million Years Ago



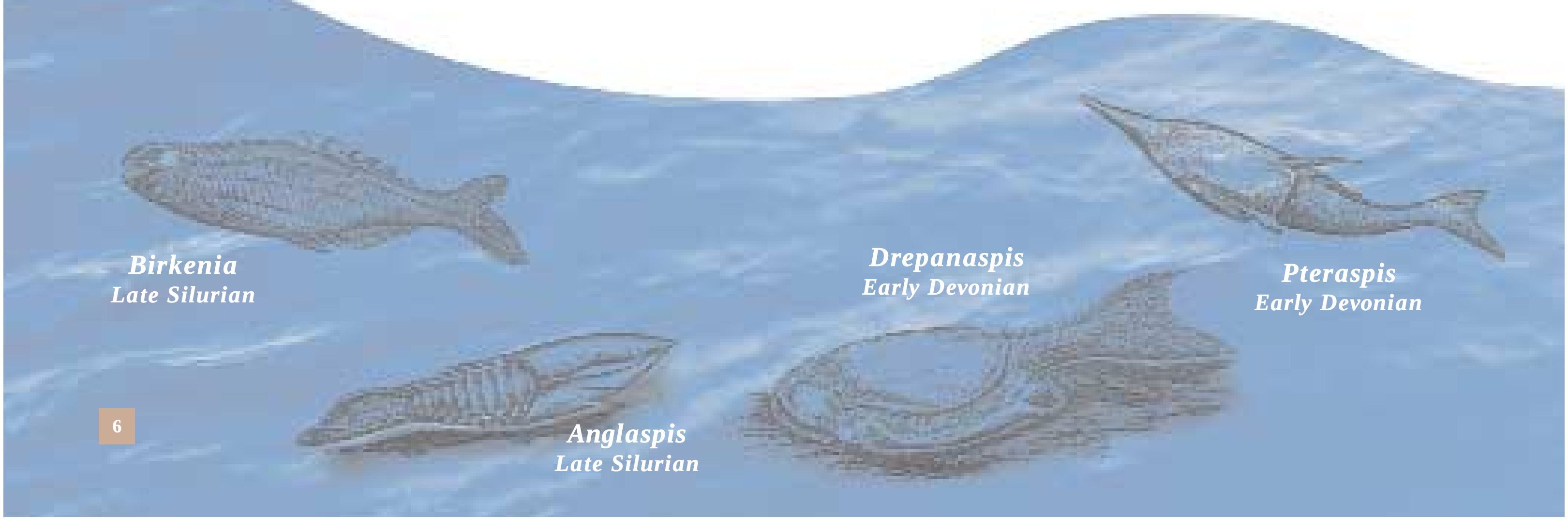
Four species of Devonian trilobites (upper row) compared with four species of Ordovician trilobites (lower row). Size varies from 1 inch (25 mm) to 4 inches (100 mm). *Modified from Moore (1959).*



1809-1882

Darwin's Revolutionary Theory

Charles Darwin used information from several disciplines in developing his theory of evolution. He was particularly impressed by the amount of variation that occurs within living species, especially in domestic animals, and he spent a great deal of time studying breeding programs. Even in Darwin's day, the human effort in breeding variants of domestic animals had resulted in many breeds of dogs, cats, horses, sheep, and cattle. As an example, consider the tremendous variation in domestic dogs. The Chihuahua and the Saint Bernard are about as different in size, shape, hair length, and other features as one could imagine; yet both breeds are domestic dogs with the scientific name *Canis familiaris*. The differences between them were produced by human-engineered selective breeding programs. Artificial selection is the term for what we do when we choose plants and animals with desirable features and breed them to produce or enhance these features in their offspring. As different as they look, Chihuahuas and Saint Bernards ... and Poodles, Pomeranians, Pekinese...all domestic dogs share the same gene pool. This shared gene pool means that all dogs have the ability to interbreed, and this is why all domestic dogs are placed in one species. The common gene pool of dogs also allows for the great variation we see in "man's best friend." A standard definition of species in animals is the ability to interbreed and produce fertile offspring.



Darwin gathered data and honed his theory for 20 years before publishing his well-known book in 1859, *The Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races in the Struggle for Life*. Darwin and his fellow naturalist Alfred Wallace independently came to the conclusion that geologically older species of life gave rise to geologically younger and different species through the process of natural selection.

Darwin's theory of evolution can be summarized in four statements.

1. Variation exists among individuals within species. Anyone who looks at their friends and relatives, or their pets, can see variation. Breeders of animals and plants use these diverse characteristics to establish new varieties of dogs, cats, pigeons, wheat, cotton, corn, and other domesticated organisms. Scientists who name and classify plants and animals are acutely aware of variation in natural populations. For example, the level of resistance to insecticides varies among individuals within species of insects. This variation enables some individuals to survive application of insecticides and produce offspring that inherit this resistance to these insecticides.

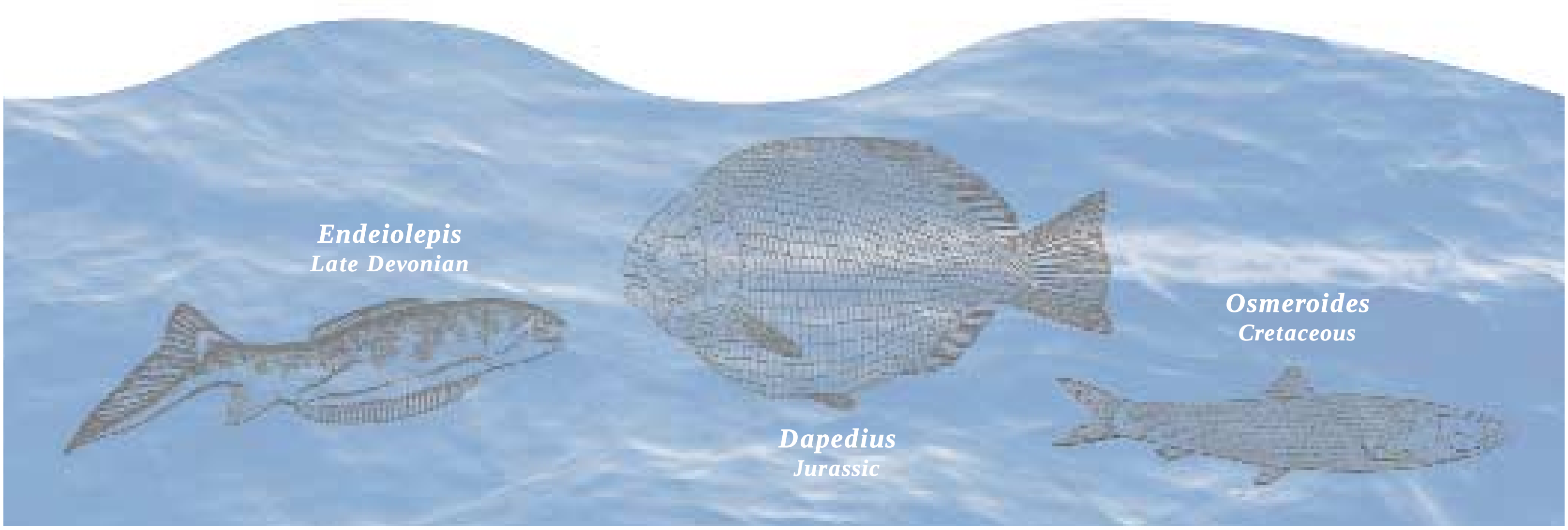
Fish Fossil (Eocene)

2. Organisms produce more offspring than the environment can support. All living things produce more individuals than can survive to maturity. Think of the thousands of acorns that one mature oak tree produces every year. A female salmon produces about 28,000,000 eggs when spawning. One oyster can

Charles Darwin was born in Shrewsbury, England. He began studying medicine at Edinburgh University at age 16, but his interests changed. Ultimately he went to Cambridge University and prepared to become a clergyman. After receiving his degree, Darwin accepted an invitation to serve as an unpaid naturalist on the H.M.S. Beagle, which departed on a five-year scientific expedition to the Pacific coast of South America on December 31, 1831.

The research resulting from this voyage formed the basis of Darwin's book, *The Origin of Species by Means of Natural Selection* (1859), in which he outlined his theory of evolution, challenging the contemporary beliefs about the creation of life on earth.

Fish diagram was modified from Fenton and Fenton (1958) and Romer (1966).

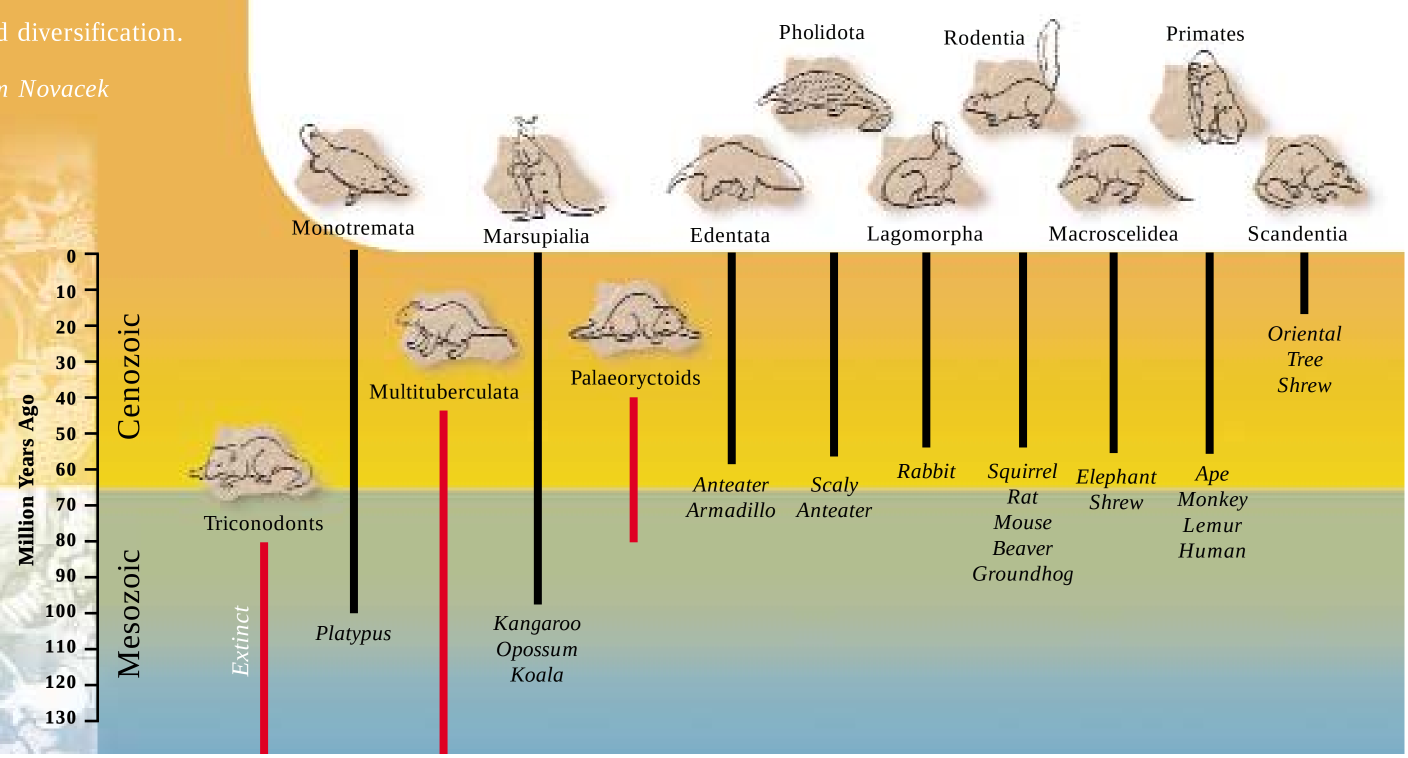


produce 114,000,000 eggs in a single spawning. Darwin calculated that in elephants, which are among the slowest breeding land mammals, if all of the potential young of a single female survived and reproduced at the same rate, after 750 years the descendants of this single mother could number 19,000,000! Clearly, if all of these seeds, eggs, and young survived to become adults who also reproduced, the world would soon be overrun with oak trees, salmon, oysters, and elephants.

Early Jurassic mammal
Modified from Jenkins and Parrington (1976).

3. Competition exists among individuals. Regardless of the rate of reproduction in a species, all of the young do not survive to become reproducing adults. This fact indicates that large numbers of offspring somehow are eliminated from the population. Some certainly die by accident. But most of them succumb to competition with other individuals. The most intense competition may be among individuals of the same species who compete for nearly identical environmental requirements. Competition may be as simple as a race to get a rabbit — the first fox there gets lunch; the others go hungry. Competition may involve obtaining a choice nesting site, or being able to find the last available hiding hole when a bigger fish comes looking for dinner. Those individuals who catch the rabbit or find the hiding hole survive to pass on their genes to the next generation.

Late Triassic and Jurassic mammals were small. Most were about the size of a mouse; a few attained domestic cat size. Most were insect eaters or omnivores; a few were probably herbivores. By Cretaceous time, mammals the size of opossums occur in the fossil record; these existed with mouse-sized animals that were the ancestors of living marsupials and placentals. In early Cenozoic time, mammals underwent a tremendous radiation and diversification. *Modified from Novacek (1994).*



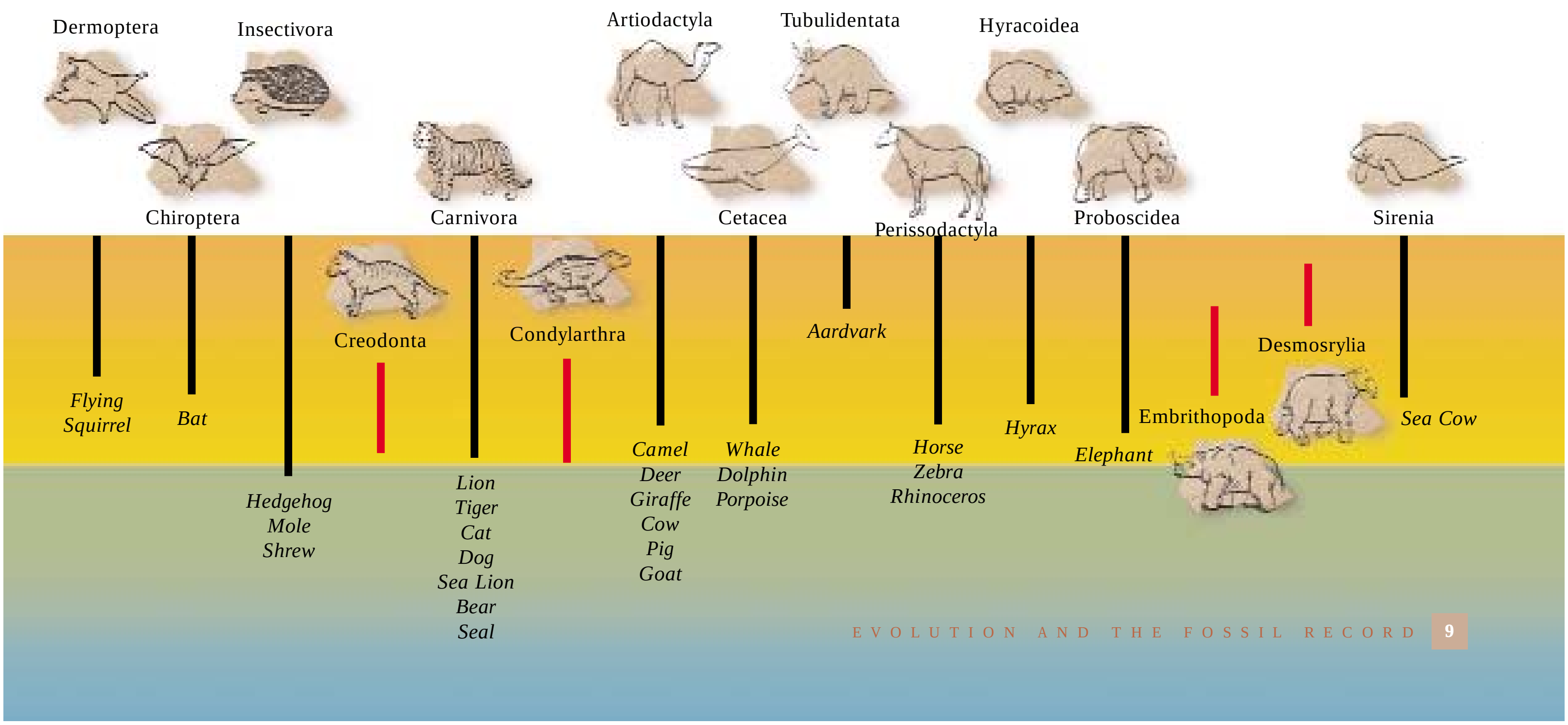
4. The organisms whose variations best fit them to the environment are the ones who are most likely to survive, reproduce, and pass those desirable variations on to the next generation.

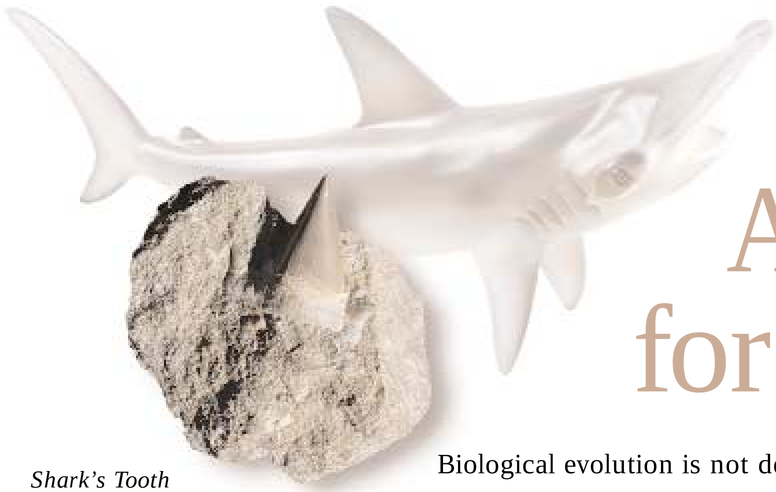
Many of the natural variations we observe in species do not seem to be either particularly helpful or particularly harmful to an individual in its struggle for survival. Hair and eye color may be such neutral variations in human beings. Some variations certainly lower the chances of survival, such as hemophilia in mammals, albinism in many wild animals, or an unusually thin shell in clams living where there are numerous hungry snails.

Some variations are helpful. For example, any variation that increases an antelope's speed may help it elude predators. Any variation that increases water retention in a desert plant will favor survival of that plant to reach maturity. Those animals and plants that survive to maturity and are able to reproduce become the parents of the next generation, passing on the genes for the successful variation.

Darwin called the process by which favorable variations are passed from generation to generation natural selection. He made many important observations on the relationship of individual variation to survival. During his stay in the Galapagos Islands, Darwin noted that the populations of tortoises on each island had physical features so distinctive that people could often tell from which island an animal came simply by looking at it.

We commonly hear natural selection referred to as "survival of the fittest." This popular phrase has a very specific biological meaning. "Fittest" means that organisms must not only survive to adulthood, they must actually reproduce. If they do not reproduce, their genes are not passed on to the next generation. Evolution occurs only when advantageous genetic variations are passed along and become represented with increasing frequency in succeeding generations.





Shark's Tooth
(Paleocene)

A Mechanism for Change

Biological evolution is not debated in the scientific community — organisms become new species through modification over time. "No biologist today would think of submitting a paper entitled 'New evidence for evolution;' it simply has not been an issue for a century" *(Futuyma, 1986)*. Precisely how and at what rates descent with modification occurs are areas of intense research. For example, much work is under way testing the significance of natural selection as the main driving force of evolution. Non-Darwinian explanations such as genetic drift have been explored as additional mechanisms that explain some evolutionary changes. Darwin proposed that change occurs slowly over long periods of geologic time. In contrast, a more recent hypothesis called punctuated equilibrium proposes that much change occurs rapidly in small isolated populations over relatively short periods of geologic time.

Modern Fern

Fossil Seed Fern
(Pennsylvanian)

In Darwin's time, the nature of inheritance and the cause of variation were very poorly understood. The scientific understanding of heredity began with the work of Gregor Mendel in the 1860s in Brno, Czech Republic. This understanding accelerated throughout the 20th century and now includes knowledge of chromosomes, genes, and DNA with its double helix.

Evolution could not occur without genetic variation. The ultimate source of variation can now be understood as changes or mutations in the sequence of the building blocks of the genetic material carried on the chromosomes in eggs and sperm. Many of these changes occur spontaneously during the process of creating copies of the genetic code for each egg or sperm. For example, the wrong molecule may become attached to the newly formed strand of DNA, or the strand may break and a portion can be turned around. Certain forms of radiation and chemical toxins can also cause mutations in the DNA.

Because the sequence of building blocks in DNA is the genetic foundation for the development of an individual's features or characteristics, changes in the sequence can lead to a change in the appearance or functioning of an individual with that mutation.

Although some changes may prove to be harmful or fatal, other changes produce variations that convey a survival advantage to the organism. It is these variations, when passed on, that give advantages to the next generation.

The Nature of Species

Individuals change throughout their lifetimes; they grow, receive injuries, color their hair, or pierce their eyebrows. These changes are not evolutionary, because they cannot be inherited by the next generation. The changes are lost when the individual possessing them dies. Individuals do not evolve, only populations evolve. Species evolve over successive generations as their local populations interbreed and change. The biological definition of a species embodies this concept: a species is a group of naturally occurring populations that can interbreed and produce offspring that can interbreed. This point is very important: species always consist of changing and interbreeding populations. There never was a first ‘saber-toothed cat,’ ‘first mastodon,’ or ‘first dinosaur.’ Instead, there was a first population of interbreeding individuals that we call ‘saber-toothed cats,’ or ‘mastodons,’ or ‘dinosaurs.’ At any given time in the past, members of populations of a species were capable of interbreeding. It is only with ‘20/20 hindsight,’ the perspective of time, that we designate the breaks between ancestor and descendant species at a particular point.

Although we can often test the biological definition of species directly when studying populations of living organisms, we cannot do the same with fossils. No matter how long we watch, no two fossils will ever breed. Therefore, we must look for other ways to determine relatedness among fossil organisms. Because genetically similar organisms produce similar physical features, paleontologists can use the bones, shells, and other preserved body parts to help us recognize species in the fossil record.

Fossil Wood
(Pleistocene)

The Nature of Theory

In the middle of the 19th century, Darwin presented the world with a scientific explanation for the data that naturalists had been accumulating for hundreds of years — the theory of evolution. The term theory does not refer to a mere idea or guess. Scientific theories provide interpretations of natural phenomena and processes so that they are understandable in terms of human experience. In science, as opposed to common usage, the term theory is applied only to an interpretation or explanation that is well-substantiated by evidence. Useful theories incorporate a broad spectrum of the information available at the time the theory is proposed. Facts, inferences, natural laws, and appropriate well-tested hypotheses are all part of the construction of a strong theory. Thus, a theory is very different from a belief, guess, speculation, or opinion.

Scientific theories are continually modified as we learn more about the universe and Earth. Let's look at three examples.

➢ In 18th century science, combustion was explained by a complex theory having to do with the supposed presence of an undetectable substance called phlogiston. Then Joseph Priestley discovered oxygen and Antoine Lavoisier showed that fire was not a material substance or element, it was the combining of a substance with oxygen. The phlogiston theory was abandoned.

➢ In the 20th century, the theory of continental drift was a step in the direction of recognizing that continents change their geographic positions through time. Continental drift was succeeded by the much more comprehensive theory of plate tectonics, which provided a mechanism for movement of continents, opening and closing of ocean basins, and formation of mountains.

The term theory does not refer to a mere idea or guess

➢ People once thought that diseases were caused by evil spirits, ill humors, or curses. The germ theory showed that many diseases are caused by microbes. In turn, the germ theory of disease has been modified as we have learned that diseases can be caused by things other than germs, such as dietary deficiencies and genetic factors.

Notice that while a particular theory may be discredited or modified, still-valid observational and experimental data, as well as our knowledge of natural laws, are not abandoned; they are incorporated in a new or revised theory.

We have tested some observations so thoroughly that we accept them as facts. For example, we consider it a fact that the sun appears in the eastern sky each morning or that an object released from the top of a building will fall to Earth. Some explanations are so strongly supported by facts, and describe so well some aspect of the behavior of the natural world, that they are treated as scientific laws. Good examples of these include the laws of thermodynamics, which govern the mechanical action or relations of heat; or the laws of gravitation, which cover the interactions between objects with mass.

We continue every day to learn more about the world and the universe in which we live. Thus, scientific theory is always subject to reaffirmation, reinterpretation, alteration, or abandonment as more information accumulates. This is the self-correcting nature of science; dogma does not survive long in the face of continuous scrutiny of every new idea and bit of data. When scientists do not understand how some aspect of our universe operates, they do not assume an unknowable supernatural cause. They continue to look for answers that are testable within the realm controlled by natural laws as we understand them at any given moment. It may be years or centuries before scientists unravel a particularly difficult problem, but the search for answers never stops. This quest for understanding is the wonder and excitement of science!

Trilobite (Ordovician)

Paleontology, Geology, and Evolution

Paleontologists generally come much too late to find anything but skeletons. However, they find something denied to the biologist — the time element. The crowning achievement of paleontology has been the demonstration, from the history of life, of the validity of the evolutionary theory *(paraphrased from Kurtén, 1953).*

Ammonite
(Cretaceous)

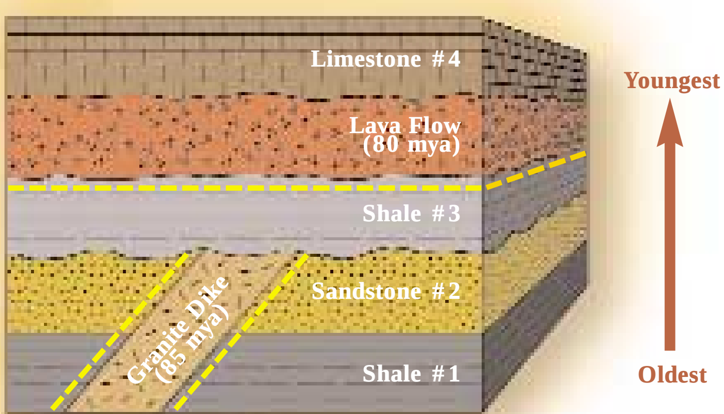
In Darwin's day, the fossil record was poorly known, but this is no longer true. A major focus for geologists is establishing the times of origin of the rock formations in the crust of Earth — the science of geochronology. For paleontologists, it is important to know which rock formations were formed at the same time and thus can be correlated, which rocks were formed at different times, and to put the formations into a time sequence from oldest to youngest in any area under study. Fossils are key to establishing the sequence of the ages of layered sedimentary rocks, and they are the direct proof of the changes that have occurred in living organisms through time on our planet.

In the mid-1600s, about 200 years before Darwin published his theory of evolution, the Danish scientist Nicholas Steno found that it was possible to establish the order in which layered rocks were deposited. He recognized that particles of sand, mud, and gravel settle from a fluid according to their relative weight. Slight changes in particle size, composition, or transporting agent result in the formation of layers in the rocks; these layers are also called beds or strata. Layering, or bedding, is the most obvious feature of sedimentary rocks. The study of layered (sedimentary) rocks is called stratigraphy.

Sedimentary rocks are formed particle by particle and bed by bed, and the layers are stacked one on another. Thus, in any sequence of undisturbed layered rocks, a given bed must be older than any bed on top of it. This Principle of Superposition is fundamental to understanding the age of rocks; at any one place it indicates the relative ages of the rock layers and of the fossils they contain. Because rock types such as sandstone, limestone, and shale are formed repeatedly through time, it is usually not possible to use rock types alone to determine the time in which rock formations were formed, or to correlate them to other areas. To determine the age of most

Testing the Superposition Principle

How old are layers 3 and 4?



Zones of Contact Metamorphism

The oldest rocks, layers 1,2, and 3, were deposited in succession, and they contain fossils that establish their relative age as Late Cretaceous. The granite dike cutting through the shale (#1) and sandstone (#2) must be younger as it shows contact metamorphism with those rocks. Scientists verify this observation by using isotopic methods to determine the age of the dike in years (85 mya). Since the dike is younger than the shale and sandstone deposits, they must be older than 85 mya.

The lava flow on top of layer 3 has been dated isotopically at 80 mya. Therefore, we can deduce that layer 3 and its fossils must have been deposited between 80 and 85 mya. Contact metamorphism occurred when the hot lava flowed onto layer 3, but there is none between the lava flow and the limestone (#4). Why? The lava (80 mya) had cooled and solidified before the limestone was deposited, and so layer 4 must be younger than 80 mya.

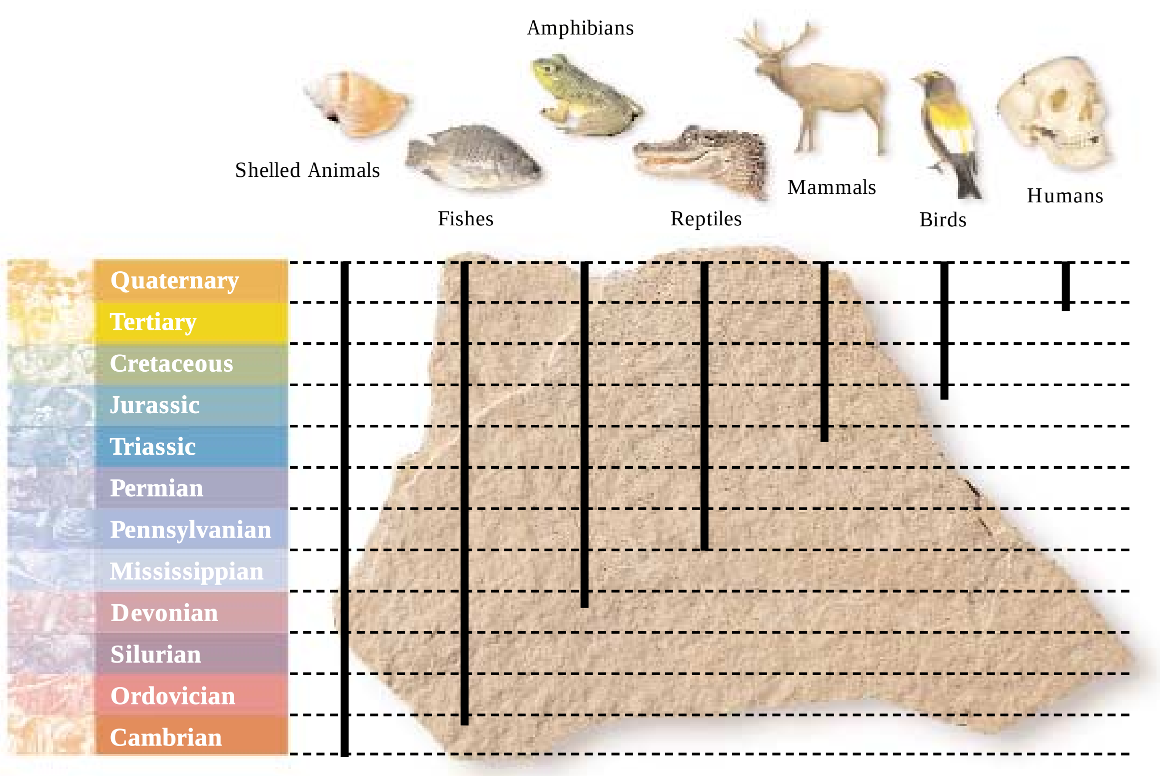
sedimentary rocks, scientists study the fossils they contain.

In the late 18th and early 19th centuries, English geologists and French paleontologists discovered that the age of rocks could be determined and correlated by their contained fossils. Rocks of the same age contain the same, or very similar, fossil species, even when the rock units extend over a large area or the exposures are not continuous. They also noted that there was a distinct, observable succession of fossils from older to younger rocks that did not repeat itself. These geoscientists were the first to use fossils to correlate the time of formation of the rocks in which the fossils occur. Three concepts are important in the study and use of fossils: (1) Fossils are the remains of once living organisms; (2) The vast majority of fossils are the remains of the hardparts of extinct organisms; they belong to species no longer living anywhere on Earth; (3) The kinds of fossils found in rocks of different ages differ because life on Earth has changed through time.

If we begin at the present and examine older and older layers of rock, we will arrive at a level where no human fossils are found. If we continue backward in time, we successively come to layers where no fossils of birds are present, no mammals, no reptiles, no four-footed animals, no fishes, no shells, and no members of the animal kingdom. These concepts are summarized in the general principle called the Law of Fossil Succession. The kinds of animals and plants found as fossils change through time. When we find the same kinds of fossils in rocks in different places, we know the rocks are of the same age.

Principle of Superposition —

In any sequence of undisturbed layered rocks, a given bed must be older than any bed on top of it.



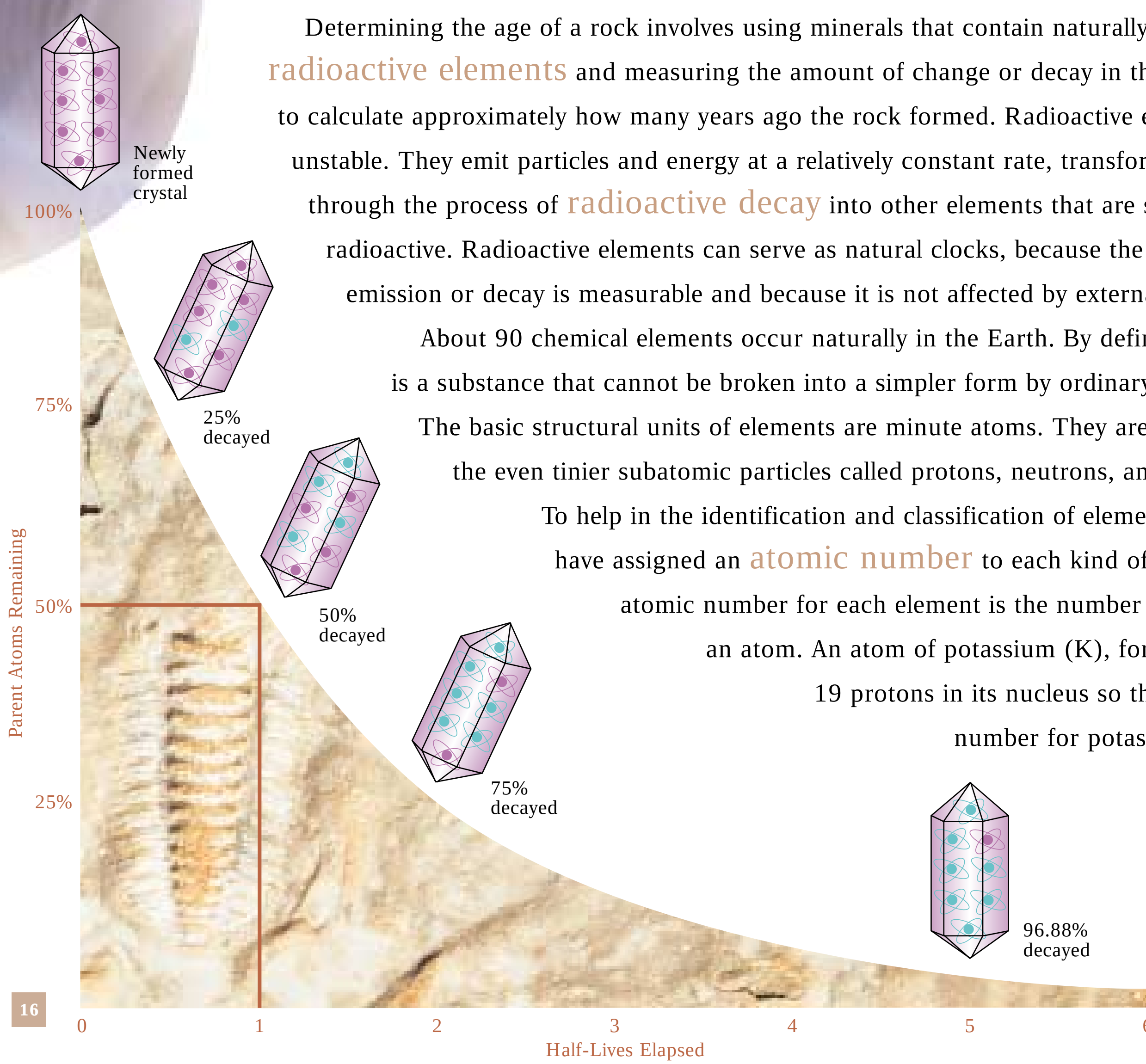
Stratigraphic ranges and origins of some major groups of animals. *Modified from Edwards and Pojeta (1994).*

Dating the Fossil Record

The study of the sequence of occurrence of fossils in rocks, biostratigraphy, reveals the relative time order in which organisms lived. Although this relative time scale indicates that one layer of rock is younger or older than another, it does not pinpoint the age of a fossil or rock in years. The discovery of radioactivity late in the 19th century enabled scientists to develop techniques for accurately determining the ages of fossils, rocks, and events in Earth's history in the distant past. For example, through isotopic dating we've learned that Cambrian fossils are about 540-500 million years old, that the oldest known fossils are found in rocks that are about 3.8 billion years old, and that planet Earth is about 4.6 billion years old.

Determining the age of a rock involves using minerals that contain naturally-occurring radioactive elements and measuring the amount of change or decay in those elements to calculate approximately how many years ago the rock formed. Radioactive elements are unstable. They emit particles and energy at a relatively constant rate, transforming themselves through the process of radioactive decay into other elements that are stable — not radioactive. Radioactive elements can serve as natural clocks, because the rate of emission or decay is measurable and because it is not affected by external factors.

About 90 chemical elements occur naturally in the Earth. By definition an element is a substance that cannot be broken into a simpler form by ordinary chemical means. The basic structural units of elements are minute atoms. They are made up of the even tinier subatomic particles called protons, neutrons, and electrons. To help in the identification and classification of elements, scientists have assigned an atomic number to each kind of atom. The atomic number for each element is the number of protons in an atom. An atom of potassium (K), for example, has 19 protons in its nucleus so the atomic number for potassium is 19.



Modified from Bushee and others (2000).

Although all atoms of a given element contain the same number of protons, they do not contain the same number of neutrons. Each kind of atom has also been assigned a **mass number.** That number, which is equal to the number of protons and neutrons in the nucleus, identifies the various forms or **isotopes** of an element. The isotopes of a given element have similar or very closely related chemical properties but their atomic mass differs.

Potassium (atomic number 19) has several isotopes. Its radioactive isotope potassium-40 has 19 protons and 21 neutrons in the nucleus (19 protons + 21 neutrons = mass number 40). Atoms of its stable isotopes potassium-39 and potassium-41 contain 19 protons plus 20 and 22 neutrons respectively.

In this outcrop of Ordovician-age limestone and shale near Lexington, KY, the oldest layer is on the bottom and the youngest on the top, illustrating the Principle of Superposition. The rocks were deposited one layer at a time "from the bottom up" starting about 450 mya.

Radioactive isotopes are useful in dating geological materials, because they convert or decay at a constant, and therefore measurable, rate. An unstable radioactive isotope, which is the 'parent' of one chemical element, naturally decays to form a stable nonradioactive isotope, or 'daughter,' of another element by emitting particles such as protons from the nucleus. The decay from parent to daughter happens at a constant rate called the **half-life.** The half-life of a radioactive isotope is the length of time it takes for exactly one-half of the parent atoms to decay to daughter atoms. No naturally occurring physical or chemical conditions on Earth can appreciably change the decay rate of radioactive isotopes. Precise laboratory measurements of the number of remaining atoms of the parent and the number of atoms of the daughter result in a ratio that is used to compute the age of a fossil or rock in years.

Age determinations using radioactive isotopes have reached the point where they are subject to very small errors of measurement, now usually less than 1%. For example,

Isotopic Age Dating

Method	Parent/Daughter Isotopes	Half-Lives	Materials Dated	Age Dating Range
Carbon (C)/Nitrogen (N)	C-14/N-14	5,730 yrs.	Shells, limestone, organic materials	100-50,000 yrs.
Potassium (K)/Argon (Ar)	K-40/Ar-40	1.3 billion yrs.	Biotite, whole volcanic rock	100,000-4.5 billion yrs.
Rubidium (Rb)/Strontium (Sr)	Rb-87/Sr-87	47 billion yrs.	Micas	10 million-4.5 billion+ yrs.
Uranium (U)/Lead (Pb)	U-238/Pb-206	4.5 billion yrs.	Zircon	10 million-4.5 billion+ yrs.
Uranium (U)/Lead (Pb)	U-235/Pb-207	710 million yrs.	Zircon	10 million-4.5 billion+ yrs.

minerals from a volcanic ash bed in southern Saskatchewan, Canada, have been dated by three independent isotopic methods (Baadsgaard, et al., 1993). The potassium/argon method gave an age of 72.5 plus or minus 0.2 million years ago (mya), a possible error of 0.27%; the uranium/lead method gave an age of 72.4 plus or minus 0.4 mya, a possible error of 0.55%; and the rubidium/strontium method gave an age of 72.54 plus or minus 0.18 mya, a possible error of 0.25%. The possible errors in these measurements are well under 1%. For comparison, 1% of an hour is 36 seconds. For most scientific investigations an error of less than 1% is insignificant.

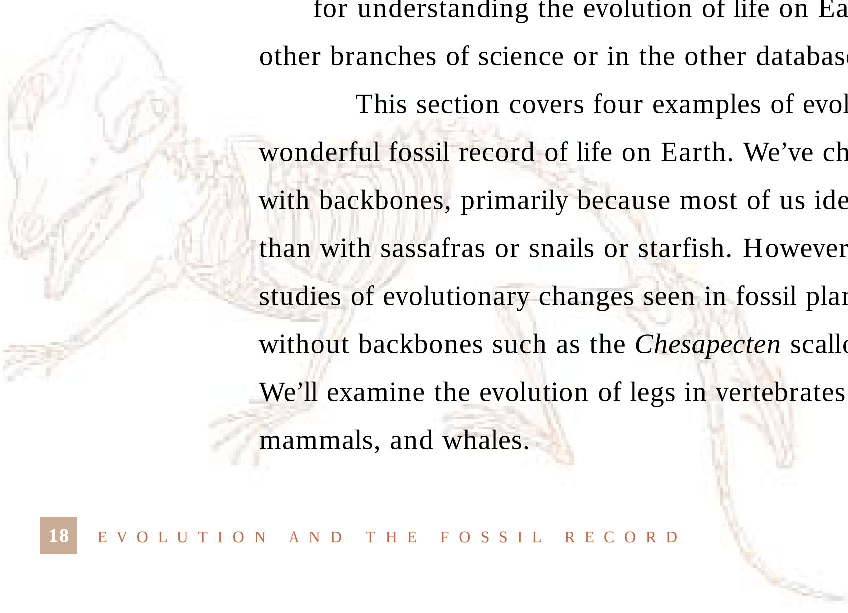
We humans created the classification scheme for life on Earth, and we choose where to draw the boundaries

As we have learned more, and as our instrumentation has improved, geoscientists have reevaluated the ages obtained from the rocks. These refinements have resulted in an unmistakable trend of smaller and smaller revisions of the radiometric time scale. This trend will continue as we collect and analyze more samples.

Isotopic dating techniques are used to measure the time when a particular mineral within a rock was formed. To allow assignment of numeric ages to the biologically based components of the geologic time scale, such as Cambrian...Permian...Cretaceous... Quaternary, a mineral that can be dated radiometrically must be found together with rocks that can be assigned relative ages because of the contained fossils. A classic, real-life example of using K-40/Ar-40 to date Upper Cretaceous rocks and fossils is described in Gill and Cobban (1973).

Examples of Evolution

The fossil record contains many well-documented examples of the transition from one species into another, as well as the origin of new physical features. Evidence from the fossil record is unique, because it provides a time perspective for understanding the evolution of life on Earth. This perspective is not available from other branches of science or in the other databases that support the study of evolution.



This section covers four examples of evolution from the incredibly rich and wonderful fossil record of life on Earth. We've chosen examples of vertebrates, animals with backbones, primarily because most of us identify more easily with this group rather than with sassafras or snails or starfish. However, we could have chosen any of many studies of evolutionary changes seen in fossil plants, invertebrates — animals without backbones such as the *Chesapecten* scallops (above), or single-celled organisms. We'll examine the evolution of legs in vertebrates as well as the evolution of birds, mammals, and whales.

Lobe-finned Fish
(Late Devonian-about 370 mya)

Amphibian-like Tetrapod
(Late Devonian-about 364 mya)

Comparison of homologous bones of the forelimbs (pectoral appendages or arms) of a lobe-finned fish from central Pennsylvania (left) with an amphibian-like tetrapod from Greenland (right). Both are right limbs seen from the underside. H = upper arm bone or humerus; U and r = forearm bones or ulna and radius; u and i = wrist bones or ulnare and intermedium. The hand and finger bones are dark. *Modified from Daeschler and Shubin (1998).*

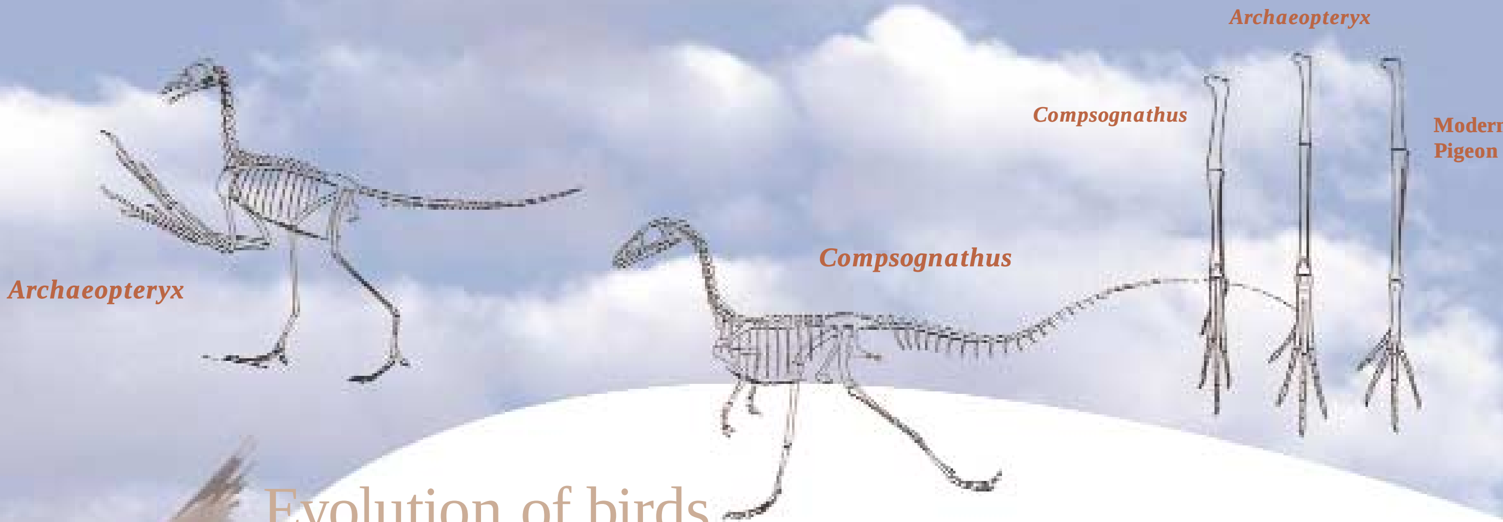
Evolution of vertebrate legs

The possession of legs defines a group of vertebrate animals called tetrapods — as distinct from vertebrate animals whose appendages are fins, the fishes. In most fishes, the thin bony supports of the fins are arranged like the rays of a fan; hence these fishes are called 'ray-finned' fish. Trout, perch, and bass are examples of living ray-fins.

Certain fishes are called 'lobe-finned,' because of the stout, bony supports in their appendages. Lobe-finned fish first appear in the fossil record in early Late Devonian time, about 377 mya. The bony supports of some lobe-finned fishes are organized much like the bones in the forelimbs and hind limbs of tetrapods: a single upper bone, two lower bones, and many little bones that are the precursors of wrist and ankle bones, hand and foot bones, and bones of the fingers and toes that are first known in Late Devonian amphibian-like animals from about 364 mya. These animals were the first tetrapods. Many similarities also exist in the skull bones and other parts of the skeleton between Devonian lobe-finned fishes and amphibian-like tetrapods. In fact, in certain fossils the resemblances are so close that the definition of which are fish and which are tetrapods is hotly debated.

In 1998, a lobe-finned fish was described from Upper Devonian rocks from about 370 mya in central Pennsylvania (Daeschler and Shubin, 1998). This fish has bones in its forelimb arranged in a pattern nearly identical to that of some Late Devonian amphibian-like tetrapods. The pattern includes a single upper-arm bone (humerus), two forearm bones (radius and ulna), and many little bones connected by joints to the forearm bones in the positions of wrist and finger bones. However, the finger-like bones look like unjointed fin rays, rather than the truly jointed finger bones of tetrapods. Should the animal be called a fish or a tetrapod? It's hard to say. On the basis of the finger bones, it could be classified as a fish, whereas, on the basis of the large limb bones, the animal could be classified as a tetrapod.

Remember that we humans created the classification scheme for life on Earth, and we choose where to draw the boundaries. When dealing with transitional forms of life this is not an easy task!



Evolution of birds

Most paleontologists regard birds as the direct descendants of certain dinosaurs — as opposed to descendants of some other group of reptiles. Paleontologists and zoologists have long accepted that birds and reptiles are related. The two groups share many common traits including many skeletal features, the laying of shelled eggs, and the possession of scales, although in birds, scales are limited to the legs. Among modern birds, the embryos even have rudimentary fingers on their wings. In one modern bird, the South American hoatzin, *Opisthocomus hoazin*, the wings of the juvenile have large moveable claws on the first and second digits. The young bird uses these claws to grasp branches.

The descent of birds from dinosaurs was first proposed in the late 1860s by Thomas Henry Huxley, who was a famous supporter of Darwin and his ideas. Evidence from fossils for the reptile-bird link came in 1861 with the discovery of the first nearly complete skeleton of *Archaeopteryx lithographica* in Upper Jurassic limestones about 150 million years old near Solenhofen, Germany. The skeleton of *Archaeopteryx* is clearly dinosaurian. It has a long bony tail, three claws on each wing, and a mouth full of teeth. However, this animal had one thing never before seen in a reptile — it had feathers, including feathers on the long bony tail. Huxley based his hypothesis of the relationship of birds to dinosaurs on his detailed study of the skeleton of *Archaeopteryx*.

Comparisons of the skeletons of the bird *Archaeopteryx* and the dinosaur *Compsognathus.* Upper right diagrams compare the hindlimbs of *Compsognathus* with *Archaeopteryx* and a modern pigeon. *Modified from Ostrom (1975 and 1994).*

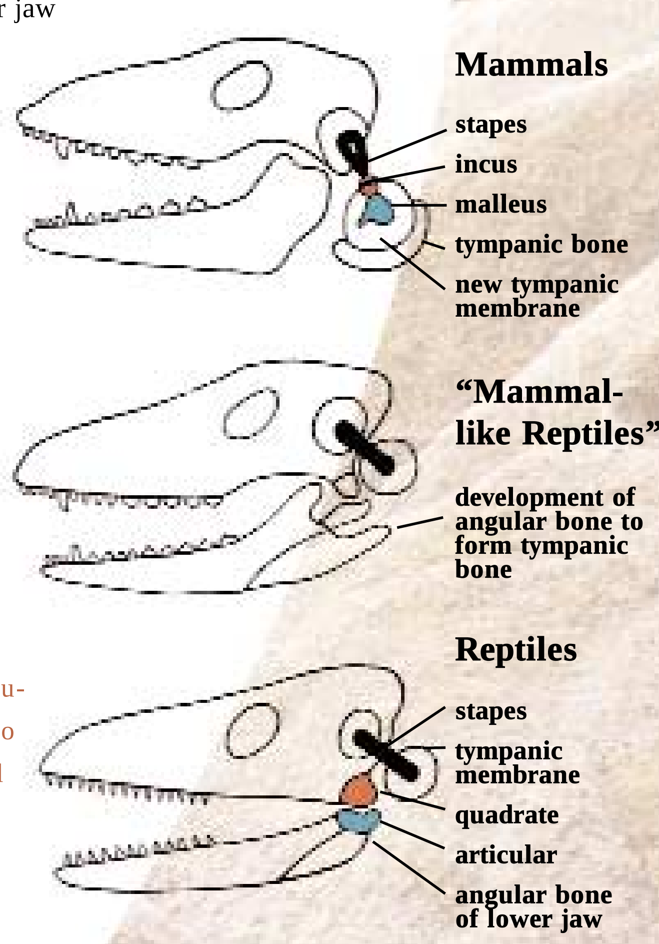
One of the leading scholars of the bird-dinosaur relationship is John Ostrom of Yale University, who has summarized all the details of the skeletal similarities of *Archaeopteryx* with small, bipedal Jurassic dinosaurs such as *Compsognathus*. *Compsognathus* belongs to the group of dinosaurs that includes the well-known *Velociraptor*, of *Jurassic Park* fame, and *Deinonychus*, which Ostrom called the ultimate killing machine. The skeleton of *Archaeopteryx* is so similar to that of *Compsognathus* that some specimens of *Archaeopteryx* were at first incorrectly classified as *Compsognathus*. Ostrom regarded *Archaeopteryx* as being on the direct line of descent of birds from reptiles.

New fossil specimens from Mongolia, China, Spain, Argentina, and Australia have added to our knowledge of the early history of birds, and many paleontologists now reckon that the turkey on our Thanksgiving tables is a descendant of the dinosaurs.

Evolution of mammals

The oldest reptiles having mammal-like features, the synapsids, occur in rocks of Pennsylvanian age formed about 305 mya. However, the first mammals do not appear in the fossil record until Late Triassic time, about 210 mya. Hopson *(1994)* noted, “Of all the great transitions between major structural grades within vertebrates, the transition from basal amniotes [egg-laying tetrapods except amphibians] to basal mammals is represented by the most complete and continuous fossil record.... Structural evolution of particular functional systems has been well investigated, notably the feeding mechanism... and middle ear, and these studies have demonstrated the gradual nature of these major adaptive modifications.”

A widely used definition of mammals is based on the articulation or joining of the lower and upper jaws. In mammals, each half of the lower jaw is a single bone called the dentary; whereas in reptiles, each half of the lower jaw is made up of three bones. The dentary of mammals is joined with the squamosal bone of the skull. This condition evolved between Pennsylvanian and Late Triassic times. Evolution of this jaw articulation can be traced from primitive synapsids (pelycosaurs), to advanced synapsids (therapsids), to cynodonts, to mammals. In mammals, two of the extra lower jaw bones of synapsid reptiles (the quadrate and articular bones) became two of the middle-ear bones, the incus (anvil) and malleus (hammer). Thus, mammals acquired a hearing function as part of the small chain of bones that transmit air vibrations from the ear drum to the inner ear.



Diagrammatic skulls showing the changes in the jaw articulation and the ear region in the evolution from reptile to mammal. In reptiles, the lower jaw is made up of several bones on each side and there is only one ear bone, the stapes, on each side. In mammals, the lower jaw is made up of only one bone on each side and the other jaw bones have taken on new functions in the middle ear. The reptilian articular bone becomes the malleus bone of the middle ear of mammals and the quadrate bone of the reptilian jaw becomes the incus bone of the middle ear of mammals. The angular bone is lost. *Modified from Savage and Long (1986).*

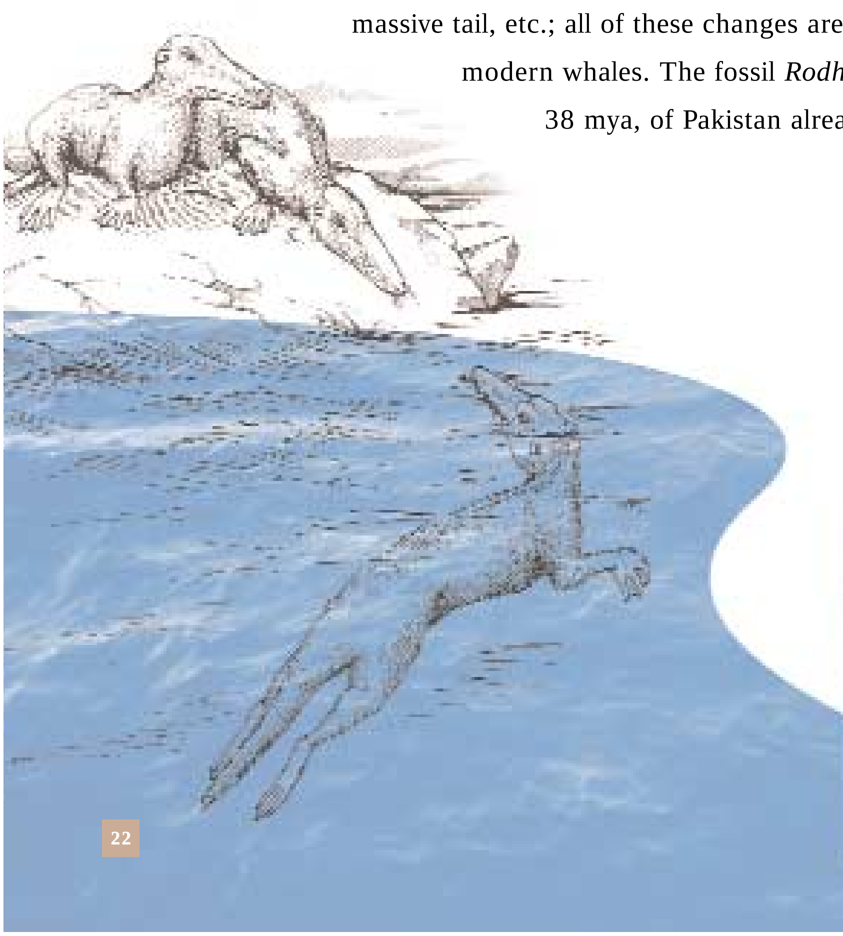
Evolution of whales

During the 1990s our understanding of whale evolution made a quantum jump. In 1997, Gingerich and Uhen noted that whales (cetaceans) "... have a fossil record that provides remarkably complete evidence of one of life's great evolutionary adaptive radiations: transformation of a land mammal ancestor into a diversity of descendant sea creatures."

The trail of whale evolution begins in Paleocene time, about 60 mya, with a group of even-toed, hoofed, trotting, scavenging carnivorous mammals called mesonychians. The first whales (pakicetids) are known from lower Eocene rocks, that formed about 51 mya; the pakicetids are so similar to mesonychians that some were misidentified as belonging to that group. However, the teeth of pakicetids are more like those of whales from middle Eocene rocks, about 45 mya, than they are like the teeth of mesonychians. Pakicetids are found in nonmarine rocks and it is not clear how aquatic they were.

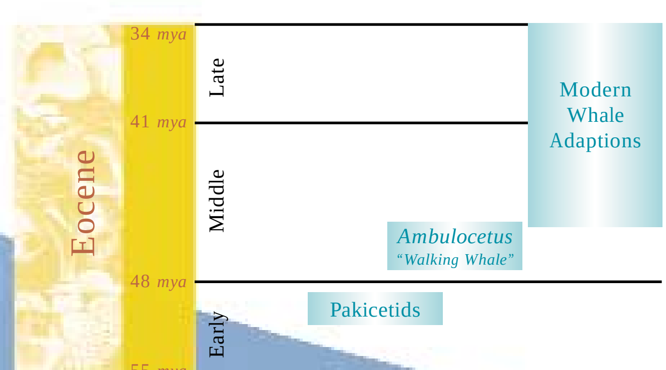
In 1994, *Ambulocetus natans*, whose name means "walking whale that swims," was described from middle Eocene rocks of Pakistan. This species provides fossil evidence of the origin of aquatic locomotion in whales. *Ambulocetus* preserves large forelimbs and hind limbs with large hands and feet, and the toes have hooves as in mesonychians. *Ambulocetus* is regarded as having webbing between the toes and it could walk on land as well as swim; thus, it lived both in and out of the water.

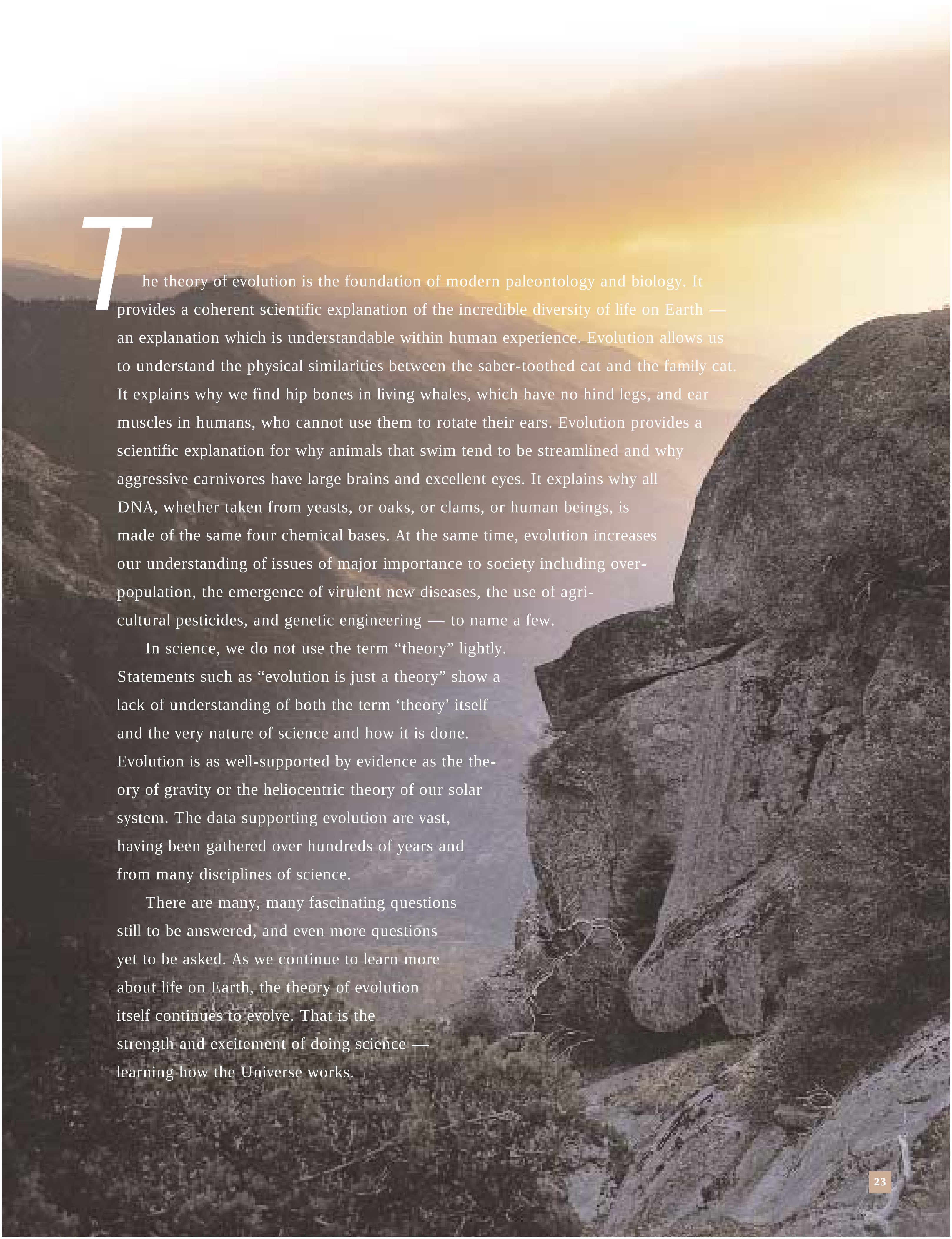
From late Eocene time onward, evolution in whales shows reduction of the hind-limbs, modification of the forelimbs and hands into flippers for steering, development of a massive tail, etc.; all of these changes are modifications for the powerful swimming of modern whales. The fossil *Rodhocetus* from the upper Eocene rocks, about 38 mya, of Pakistan already shows some of these modifications.



Reconstruction of *Ambulocetus natans*, the "walking whale that swims." *Modified from Thewissen and others (1996).*

Succession of Eocene Whale Fossils





The theory of evolution is the foundation of modern paleontology and biology. It provides a coherent scientific explanation of the incredible diversity of life on Earth — an explanation which is understandable within human experience. Evolution allows us to understand the physical similarities between the saber-toothed cat and the family cat. It explains why we find hip bones in living whales, which have no hind legs, and ear muscles in humans, who cannot use them to rotate their ears. Evolution provides a scientific explanation for why animals that swim tend to be streamlined and why aggressive carnivores have large brains and excellent eyes. It explains why all DNA, whether taken from yeasts, or oaks, or clams, or human beings, is made of the same four chemical bases. At the same time, evolution increases our understanding of issues of major importance to society including overpopulation, the emergence of virulent new diseases, the use of agricultural pesticides, and genetic engineering — to name a few.

In science, we do not use the term "theory" lightly. Statements such as "evolution is just a theory" show a lack of understanding of both the term 'theory' itself and the very nature of science and how it is done. Evolution is as well-supported by evidence as the theory of gravity or the heliocentric theory of our solar system. The data supporting evolution are vast, having been gathered over hundreds of years and from many disciplines of science.

There are many, many fascinating questions still to be answered, and even more questions yet to be asked. As we continue to learn more about life on Earth, the theory of evolution itself continues to evolve. That is the strength and excitement of doing science — learning how the Universe works.

Glossary

Fossil Dragonfly
(Jurassic)

appendage A body part that extends outward from the torso of an animal, such as arms, legs, wings, fins or the antennae of an insect.

articulated Body parts held together by a joint, which is often moveable.

artificial selection The process whereby humans choose animals or plants with desirable characteristics and breed them to continue or enhance the desirable features in succeeding generations. Compare with *natural selection*.

assemblage A group of organisms found together at the same place and/or time.

biogeography The study of the geographic distribution of organisms.

biostratigraphy The science that deals with the distribution of fossils in the rock record and organizes strata into units on the basis of their contained fossils.

biota All living organisms in an area under study; the flora, fauna, microbes, etc. considered as a whole.

Brachiopod
(Devonian)

bipedal Used to define animals that walk on two legs, such as birds.

brachiopods A group of marine animals that have a shell with two halves and superficially resemble clams. They are more common in Paleozoic rocks than in younger rocks.

contact metamorphism Reconstitution of rocks that takes place at or near their contact with a body of molten igneous rocks, such as a dike, and that is related to its intrusion.

dogma A doctrine that is laid down as true and beyond dispute.

fitness The quality of having characteristics and/or behaviors that make an organism well-suited to surviving in its environment; biological fitness means the production of viable offspring.

fact In science, an observation or explanation that has been repeatedly tested and is accepted as true.

gene pool The sum total of all genetic information in a specified group of organisms; usually applied to a population or a species.

genetic drift Gradual change over time in the genetic composition of a continuing population that seems to be unrelated to the environmental benefits or detriment of the genes involved.

geochronology The science of dating and determining the time sequence of events in the history of Earth.

half-life The time it takes for 50% of the original amount of a radioactive isotope (the parent) to break down (decay) to another element (the daughter element).

heliocentric theory The theory that holds that the sun is the center of our solar system.

hypothesis A tentative scientifically testable explanation provisionally adopted to explain some aspect or behavior of the natural world.

invertebrate Used to characterize animals without backbones.

isotope One or more varieties of an element having the same number of protons in the nucleus, but differing from one another in the number of neutrons in the nucleus.

Late When used with the name of a geological Period (or any named subdivision of a Period), 'Late' denotes time; specifically, the last (youngest) portion of the specified time unit. Compare with *Upper.*

law A repeatedly tested and reaffirmed general statement of how some aspect of the natural universe behaves under a given set of circumstances.

mutation A change in the sequence of genetic material in DNA.

mya Abbreviation for million years ago.

natural selection The process by which favorable variations are naturally passed from generation to generation; involves elimination by the environment of less-fit organisms before they reproduce. Compare with *artificial selection.*

radioactivity The emission of energetic particles and/or radiation from the nucleus of an atom during radioactive decay.

rudimentary In biology, features of an organism which do not develop to a useable stage in one species, but which closely related species may possess in fully functional form.

sedimentary rock Rock formed from particles of preexisting rocks (for example, sandstone and shale) through the life activities of organisms (for example, coal and many limestones, which are often composed of shells and shell fragments), or by direct precipitation from water (for example, table salt).

strata Layers, specifically, sedimentary rock layers. Singular: stratum.

stratigraphy Study of the relative ages of sedimentary (layered) rocks.

superposition The order in which sedimentary rocks are accumulated in beds one above another, the highest bed being the youngest.

taxonomy The science that deals with the identification, naming, and classification of organisms.

tetrapod A vertebrate animal with four jointed limbs; amphibians, reptiles, birds, and mammals are tetrapods.

theory A well-established testable explanation of some aspect of the natural world; the framework within which new hypotheses are formulated and against which new data are evaluated.

Upper When used with the name of a geological Period or any named subdivision of a Period, 'Upper' indicates the rocks that were formed in the last (youngest) portion of the time unit. Compare with *Late.*

vertebrate A term applied to animals that have a backbone.

Fossil Amphibian
(Permian)

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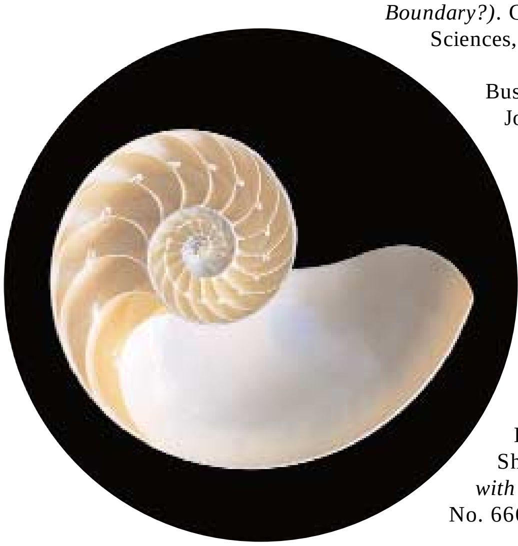

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EVOLUTION
and the Fossil Record

John Pojeta, Jr. Dale A. Springer

Numerous lines of evidence show that life has changed through time. Evolution is the best scientific explanation for this change. This booklet describes a small portion of the evidence for this change, especially as documented by the fossil record, and outlines the processes involved in evolution. Many fascinating questions remain concerning the history of life and the process through which it has developed. As we continue to learn about life on Earth, the theory of evolution will itself evolve. That is the strength, adventure, and excitement of doing science!

— *From the Foreword*

ISBN 0-922152-57-8

American Geological Institute The Paleontological Society

1999 GEOLOGIC TIME SCALE

CENOZOIC

Period		Epoch		Age	Picks (Ma)
QUATERNARY		HOLOCENE			0.01
		PLEISTOCENE		CALABRIAN	1.8
TERTIARY	NEOGENE	PLIOCENE	L	PIACENZIAN	3.6
			E	ZANCLEAN	5.3
		MIOCENE	L	MESSINIAN	7.1
				TORTONIAN	11.2
			M	SERRAVALLIAN	14.8
				LANGHIAN	16.4
			E	BURDIGALIAN	20.5
				AQUITANIAN	23.8
	PALEOGENE	OLIGOCENE	L	CHATTIAN	28.5
			E	RUPELIAN	33.7
		EOCENE	L	PRIABONIAN	37.0
			M	BARTONIAN	41.3
				LUTETIAN	49.0
			E	YPRESIAN	54.8
		PALEOCENE	L	THANETIAN	57.9
				SELANDIAN	61.0
			E	DANIAN	65.0

MESOZOIC

Period	Epoch		Age	Picks (Ma)	Uncert. (m.y.)
CRETACEOUS	LATE			65	.2
			MAASTRICHTIAN	71.3	1
			CAMPANIAN	83.5	1
			SANTONIAN	85.8	1
			CONIACIAN	89.0	1
			TURONIAN	93.5	4
			CENOMANIAN	99.0	1
	EARLY		ALBIAN	112	2
			APTIAN	121	3
		NEOCOMIAN	BARREMIAN	127	3
			HAUTERIVIAN	132	4
			VALANGINIAN	137	4
			BERRIASIAN	144	5
JURASSIC	LATE		TITHONIAN	151	6
			KIMMERIDGIAN	154	7
			OXFORDIAN	159	7
	MIDDLE		CALLOVIAN	164	8
			BATHONIAN	169	8
			BAJOCIAN	176	8
			AALENIAN	180	8
	EARLY		TOARCIAN	190	8
			PLIENSBACHIAN	195	8
			SINEMURIAN	202	8
			HETTANGIAN	206	8
TRIASSIC	LATE		RHAETIAN	210	8
			NORIAN	221	9
			CARNIAN	227	9
	MIDDLE		LADINIAN	234	9
			ANISIAN	242	9
	EARLY		OLENEKIAN	245	9
			INDUAN	248	10

RAPID POLARITY CHANGES

PALEOZOIC

Period		Epoch	Age		Picks (Ma)
PERMIAN		L			248
			TATARIAN		252
			UFIMIAN-KAZANIAN		256
			KUNGURIAN		260
		E	ARTINSKIAN		269
			SAKMARIAN		282
			ASSELIAN		290
CARBONIFEROUS	PENNSYLVANIAN	L	GZELIAN	S.	296
			KASIMOVIAN		303
			MOSCOVIAN	W.	311
			BASHKIRIAN	N.	323
	MISSISSIPPIAN	E	SERPUKHOVIAN		327
			VISEAN		342
			TOURNAISIAN		354
DEVONIAN		L	FAMENNIAN		364
			FRASNIAN		370
		M	GIVETIAN		380
			EIFELIAN		391
			EMSIAN		400
			PRAGHIAN		412
			LOCKHOVIAN		417
SILURIAN		L	PRIDOLIAN		419
			LUDLOVIAN		423
		E	WENLOCKIAN		428
			LLANDOVERIAN		443
ORDOVICIAN		L	ASHGILLIAN		449
			CARADOCIAN		458
		M	LLANDEILIAN		464
			LLANVIRNIAN		470
		E	ARENIGIAN		485
			TREMADOCIAN		490
CAMBRIAN*		D	SUNWAPTAN*		495
			STEPTOEAN*		500
		C	MARJUMAN*		506
			DELAMARAN*		512
		B	DYERAN*		516
			MONTEZUMAN*		520
		A			543

PRECAMBRIAN

Eon	Era	Bdy. Ages (Ma)
PROTEROZOIC		543
	LATE	900
	MIDDLE	1600
	EARLY	2500
ARCHEAN	LATE	3000
	MIDDLE	3400
	EARLY	3800?

GEOLOGICAL SOCIETY OF AMERICA

*International ages have not been established. These are regional (Laurentian) only. Boundary Picks were based on dating techniques and fossil records as of 1999. Paleomagnetic attributions have errors, Please ignore the paleomagnetic scale.

Sources for nomenclature and ages: Primarily from Gradstein, F., and Ogg, J., 1996, *Episodes*, v. 19, nos. 1 & 2; Gradstein, F., et al., 1995, SEPM Special Pub. 54, p. 95–128; Berggren, W. A., et al., 1995, SEPM Special Pub. 54, p. 129–212; Cambrian and basal Ordovician ages adapted from Landing, E., 1998, *Canadian Journal of Earth Sciences*, v. 35, p. 329–338; and Davidek, K., et al., 1998, *Geological Magazine*, v. 135, p. 305–309. Cambrian age names from Palmer, A. R., 1998, *Canadian Journal of Earth Sciences*, v. 35, p. 323–328.

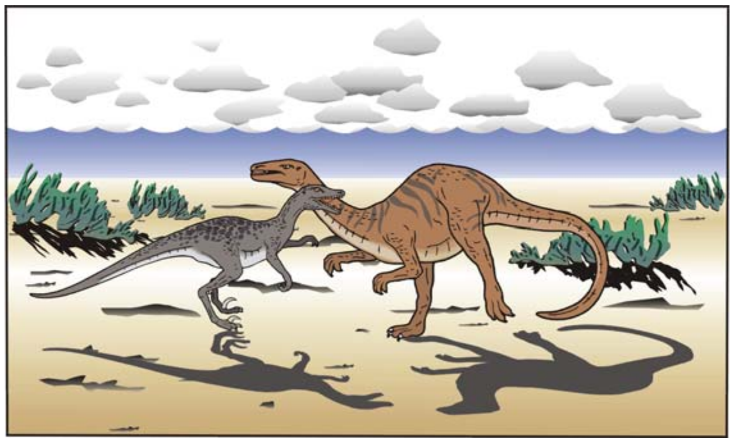
GEOLOGIC TIME SCALE
4500
Formation of the Earth
Hadean
Oldest rocks on Earth
The Acasta Gneiss NWT
4000
Earliest evidence of life
Early
Earliest algal stromatolites
3400
Middle
3000
Archean
Late
2500
Precambrian
Early
1600
Proterozoic
Reverse Time Scale
all intervals are to scale
million of years
0
10
50
100
Middle
900
Late
Earliest soft-bodied animals
Earliest shelled animals
543
Cambrian
First fish
489
Ordovician
443
First land plants
Silurian
418
Devonian
360
First amphibians
Carboniferous
Mississippian
320
First reptiles
Pennsylvanian
300
Mass Extinction
almost 90%of organisms died
Permian
253
Paleozoic
Triassic
First mammals
First dinosaurs
200
Jurassic
142
First birds
Cretaceous
Mesozoic
Phanerozoic
Mass Extinction
extinction of the dinosaurs
65
Tertiary
Cenozoic
Grass
1.7
Earliest humans
Quaternary
Eon
Era
Period
Millions of years ago
© Randolph Corney
Department of Geology
Saint Mary's University
Halifax, Nova Scotia, Canada

HOW FOSSILS FORM

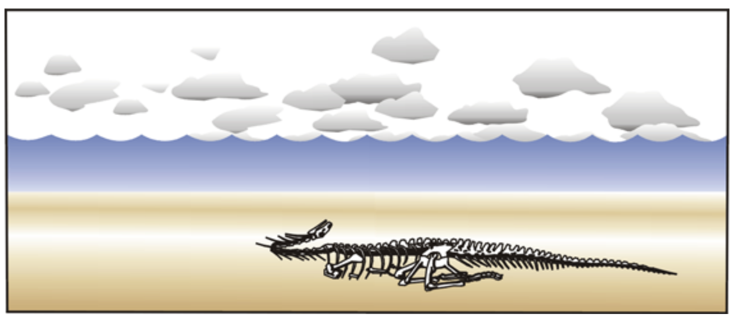
When an animal or plant dies, it eventually disappears. On the surface of the Earth it may be eaten up by scavengers like crows, vultures and coyotes, or by smaller creatures like beetles, maggots and bacteria. What is left will rot away and normally disappears without a trace. It takes special circumstances for animals or plants to be preserved as fossils. It takes extra special circumstances to preserve a fossil well.

Here is a typical case:

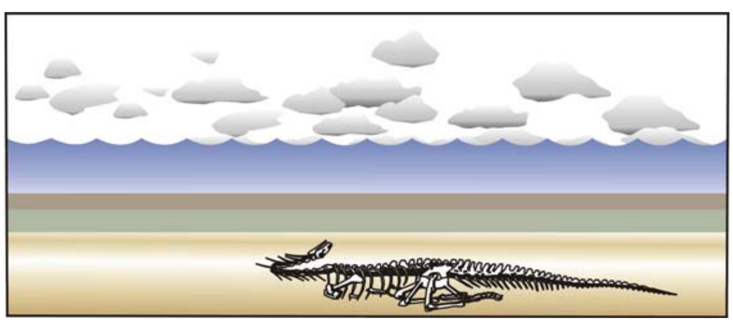
A dinosaur is killed by another alongside a lake. Its body is washed into the water and the remains come to rest on the lake bottom.



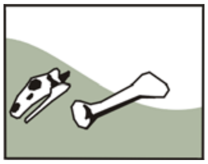
The soft parts of the dinosaur decompose, but the hard parts, like bones and teeth, remain on the lake bottom.



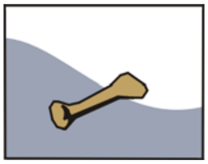
Sediments gradually accumulate on the lake bottom. The layers of mud and silt begin to exclude oxygen and decomposition slows down. As time passes and more sediment accumulates, the bones and teeth are trapped under the layers as fossils.



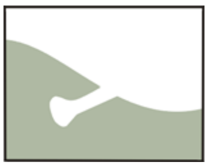
At this stage four different things can happen to the bones and teeth to turn them into fossils:



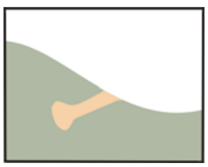
Original remains. The bones and teeth remain unchanged. This is an extremely rare case and requires special conditions.



Petrified fossils. In some cases, the original material of the teeth and bones is replaced by another mineral, typically silica. This preserves the original structure beautifully, but the original materials have been replaced by a mineral.

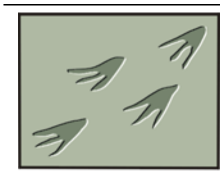


Mould fossils. The bones and teeth rot away slowly, leaving holes in the rock that are the same shape as the original material. These holes are called moulds.



Cast fossils. Once a mould forms, it is common for the mould to be filled in by sediment or other materials. These secondary materials make a fossil that is the exact same shape as the original remains, but made up of different material. This is a cast.

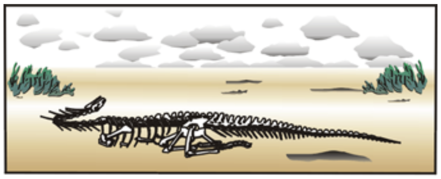
Other kinds of fossils reflect the activities of organisms. These are called **trace fossils.**

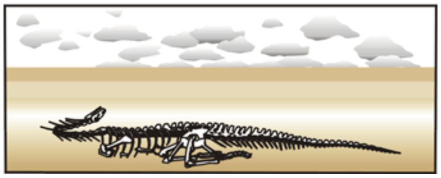


For example, when an animal, such as a dinosaur leaves footprints in mud by the lake, these may get dried out by the sun, filled with sediments and preserved. Similarly, when a worm or snail burrows through the sediment in search of food, the trace of its track may also be preserved.

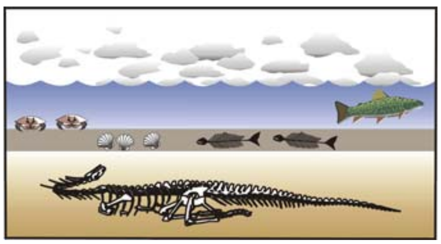
HOW EARTH SCIENTISTS READ THE ROCKS

The following images portray the geological history of one area over a long period of time.

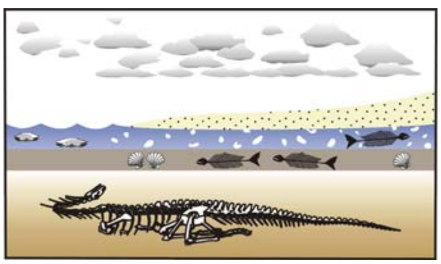




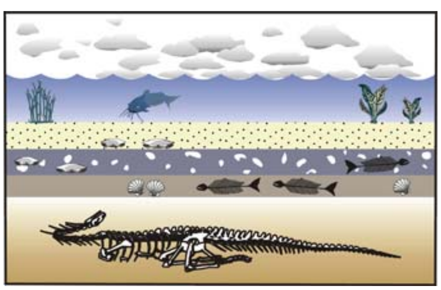
An animal dies in the desert and its remains are left in the sand. The sandstone that forms contains fossils of the bones and teeth of this desert animal.



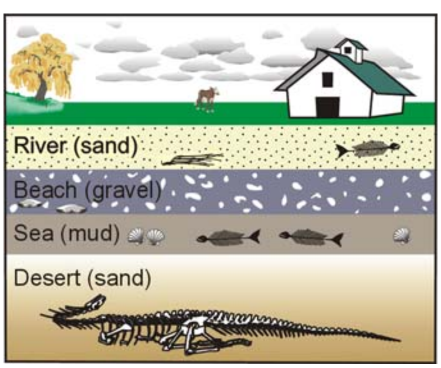
As time passes, the sea spreads over the area, allowing mud to accumulate on the seabed. Sea animals, such as fish and clams, die and their hard parts gradually accumulate on the seabed. Their fossil remains would be found in this mud layer.



Over many years, the sea withdraws from the area, and a beach is formed. It is made up of pebbles, forming a gravel layer. Different creatures that lived along the shoreline, such as crabs, would be preserved as fossils in this gravel layer.



After many more years, the sea has receded far from the area. A river formed, cut into the gravels, and deposited sand as the water ran through the river bed. A variety of freshwater organisms and plants would be found as fossils in this sand layer.



The materials that accumulate during each stage in the geological history of the area - the desert sand, the marine mud, the beach gravel and the freshwater sand – form a series of layers, known as beds. These beds, originally soft sediments, gradually turn to rock as they are compacted by overlying sediments and cemented by minerals deposited from the water seeping between the grains of sediment. Each bed contains a distinct suite of fossils that can help interpret the age and environment when the different sediments were deposited.

FIVE PRINCIPAL APPLICATIONS OF FOSSILS

Telling time . . . . . Biostratigraphy

Paleontological study of fossil assemblages makes possible the dating and comparison of fossiliferous rocks throughout the world. Organisms that are abundant, evolve quickly, have a wide distribution and are relatively tolerant of a range of different environments make the best time indicators. Species that have these characteristics are likely to be used for definition of short intervals of time called zones and they are referred to as index or guide fossils. Many paleontologists, particularly those employed by oil companies and government agencies, are involved in this branch of paleontology which is called *biostratigraphy.*

Understanding ancient environments . . . . . Paleoecology

The appearance and disappearance of different fossils through time tells a story of changing environmental conditions. One of the main objectives in studying sedimentary rocks is the reconstruction of the environment in which the sediments that formed the rocks were deposited. Accurate reconstruction of environments can lead to the discovery of natural resources such as coal, many metals, salt, oil and gas. A study of the environmental requirements of organisms that become fossils provides the most accurate information about the ancient environment in which they lived. Studies of this type are referred to as *paleoecology.*

Understanding the history of life on Earth

Without the study of fossils we would know nothing about the history of life on Earth and the connections of various groups of organisms in the chain of biological evolution. Even though the fossil record is imperfect because organisms have different potential for preservation as fossils (only some are preserved), it is the only record of life on Earth. Detailed studies of fossils are primary components of research on evolution and biodiversity.

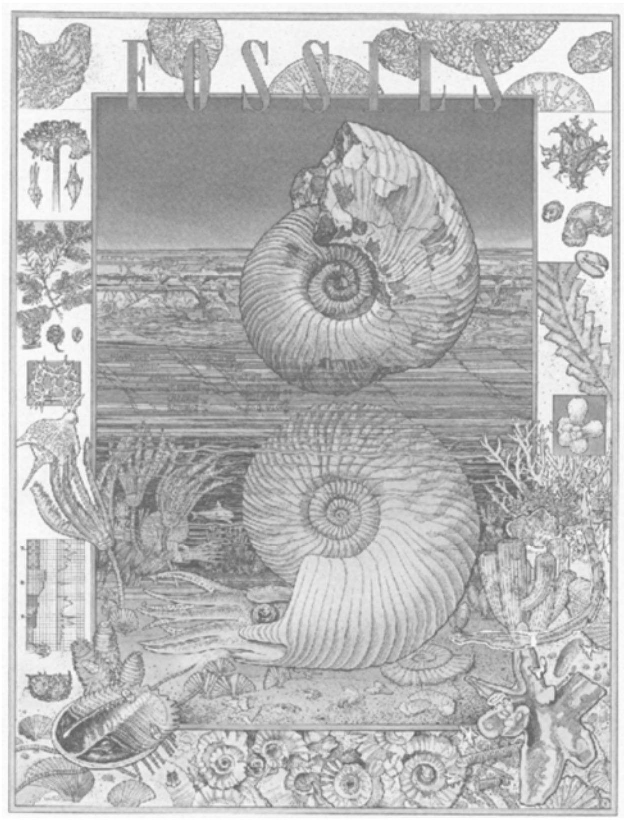
Understanding continental movements . . . . . Paleobiogeography

Unusual patterns in the distribution of fossils were one of the first reasons that scientists began to suspect that the continents had not always been in the same positions as they are today. Now it is well established that continents have moved over the surface of the Earth, and the present-day distribution of fossils is used as one line of evidence to reconstruct the position of continents and oceans in the geological past. Just as the distribution of animals and plants on the Earth today is affected by various environmental conditions, so were the organisms on the ancient Earth. The use of fossils for this purpose is termed *paleobiogeography.*

Understanding the relationships of life to planet Earth . . . . . Paleobiogeochemistry

Knowledge of the history of life provides important information for the understanding of processes that have taken place, and still are taking place, on the Earth's surface. The existence of life on Earth has affected the chemistry of the oceans and atmosphere over the past 3500 million years. The fact that organisms began to secrete shells and skeletons of substances (mainly calcium carbonate, silica and organic compounds) has had, and still has, a significant effect on the distribution of important elements on Earth, especially calcium, carbon, silicon, and oxygen. The appearance of land plants and their continued existence has a profound effect on the composition of the atmosphere. For all these reasons it is important to study the impact of the history of life on the *paleobiogeochemistry* of the Earth.

The Geological Survey of Canada's Fossil Poster



This poster explores the diversity of life on Earth through geological time. The poster illustrates fossils of plants and animals that have inhabited the Earth over the course of its history. The Earth formed more than 4500 million years ago, but the first life, probably bacteria, did not appear until about 3500 million years ago. Since that time, life has evolved on Earth through a process that has given rise to a great variety of plants and animals. Most of these organisms are now extinct and known only from the fossil record. The study of animals and plants that have lived in the past is called *paleontology* and scientists who study fossils are known as *paleontologists.* In order to become a professional paleontologist, a person must study geology and biology, but anyone can have fun collecting and identifying fossils in their own area. Fossils occur in sedimentary rocks which are present in most regions of Canada. To find out what rocks are present in your area consult a geological map or report dealing with your region. Collectors should take care to learn any rules and regulations that apply, to respect the property rights of landowners, and to take safety precautions. Good specimens should be shown to professional paleontologists because they may represent a species new to science or provide other valuable scientific information.

This poster was created by Calgary artist Dennis Budgen in consultation with Godfrey Nowlan and Terry Poulton of the Geological Survey of Canada (GSC) who wrote the text for the booklet.

Posters of Illustrations in "The Land Before Us"

Dennis Budgen was also commissioned to do illustrations for the Royal Tyrrell Museum's book on the geological history of Alberta entitled "The Land Before Us." This series of illustrations is available as a set of seven posters: one is the cover of the book and the others illustrate the development of life on Earth as seen from an Alberta perspective. There are posters illustrating the Precambrian, Early Paleozoic, Late Paleozoic, Early Mesozoic, Late Mesozoic and Cenozoic. These posters are a terrific teaching tool, especially when combined with the information in the book for which they were developed. We highly recommend using the book and posters in your class. These are available in bookstores and the Royal Tyrrell museum.

FOSSILS IN THE CALGARY AREA

Places to find fossils

Some fossils can be found in the Tertiary bedrock around Calgary. Fossil clamshells and plant material are relatively common in the Paskapoo Formation. An excellent example of abundant clamshells can be seen in a block placed for ornamental purposes at the northeast end of the footbridge across the Bow River at Edworthy Park. Many large blocks of sandstone used for ornamental landscaping in the Shawnessy subdivision of southwest Calgary have good plant fossils. Check your neighbourhood, especially if you are located near any of the main river valleys or other areas of bedrock outcrop.

The best place to see lots of fossils is to go to the Royal Tyrrell Museum of Palaeontology in Drumheller. This is one of the best paleontological museums in the world. The Tyrrell also maintains an interpretive centre at Dinosaur Provincial Park and runs trips through the Alberta Badlands that show the fantastic abundance of fossils in the area.

The river valleys in Calgary also contain lots of different kinds of rocks moved by glaciers and the rivers themselves. It is common to find blocks of limestone with fossils in them. Many other blocks are composed of unfossiliferous quartzite.

Finding fossils

Each fossil is a unique object — the remains or traces of an ancient animal or plant. The location of a fossil is as important as the fossil itself. Fossils, together with associated geological and biological evidence, help paleontologists determine what, where, when and how ancient animals and plants lived and died. Their location also leads paleontologists to determine where other fossils are likely to be found. When improperly handled, a fossil loses much of its scientific value. If you find what you think may be a significant fossil, please contact the Royal Tyrrell Museum of Palaeontology in Drumheller (823-7707) or the Geological Survey of Canada office in Calgary (292-7000). When properly collected and recorded, the knowledge of Alberta’s rich fossils can be shared.

Alberta's Historical Resources Act and Fossil Collection and Ownership

Alberta's Historical Resources Act, which governs fossil collecting, defines two ways of collecting fossils:

- Surface collecting - gathering isolated fossils, which are clearly on the surface of the ground. Surface collecting is permitted on private land with the landowner's permission. You may keep surface finds as a custodian, but ownership resides with the Province of Alberta, making it illegal to sell or take such fossils out of the province without an approved Disposition Certificate.
- Excavating - digging, prying or somehow extracting a fossil buried or embedded in the ground or rock face. Fossils should never be removed from their original stratigraphic position without being properly mapped and dated by a paleontologist.

Excavating fossils requires a permit. Applications on standard forms are processed through the Royal Tyrrell Museum of Paleontology. Procedures outlined in the Province of Alberta's Historical Resources Act must also be followed before any part of the collection can be retained. All applications are reviewed by the Alberta Paleontological Advisory Committee to the Minister of Culture and Multiculturalism.

It is illegal to remove fossils from provincial and federal parks in Alberta.

Paleontological resources are protected by the Historical Resources Act. All fossils collected in Alberta since July 5, 1978, and all fossils still in or on the ground, are owned by the province. The province may transfer ownership of fossils identified by a Control List established in 1987 to private parties. This list allows for responsible trade of certain fossils that are abundant within the province and so have limited research and display value.

Although the law is stringent, please encourage your students to look for fossils in the area. Many of the most significant fossil discoveries have been made by young people. For example, a high school student found the dinosaur egg sites in the Alberta Badlands. Another, more local example, is that of an eight-year-old who found what he thought was a fish tail near his house in Shawnessy. He brought the specimen to the Geological Survey of Canada where it was identified as the leaf of a palm tree. It was the first one to be recorded from the area and had great significance, because the presence of palm fronds means an absence of frost. It changed the general environmental interpretation for the early Tertiary rocks in the area to a warmer regime than was previously believed.

So, encourage responsible examination and collecting.

How Fossils Form and what they tell us about the History of Life

PRESERVATION OF FOSSILS

The fossil record preserves less than 1% of all the species that have ever existed on the Earth. Preservation requires special conditions and is enhanced by:
Presence of hard parts: Soft-bodied organisms such as worms are rarely fossilized, but organisms with shells, bones and teeth are more resistant to stresses of burial and chemical change through time.
Favourable preservation environment; Marine organisms are more likely to be fossilized than terrestrial organisms, as they may be buried quickly before they can be eaten or decomposed. Areas of low oxygen levels (peat bogs, swamps) may also enhance preservation because low oxygen impedes bacterial decomposition.

TYPES OF PRESERVATION

Original Material

Unchanged: Examples are bivalve shells, Pleistocene animals from the La Brea Tar Pits, insects preserved in amber; mammoths "freeze-dried" in glaciers or Arctic permafrost, and mummified ground sloths in dry caves in the American Southwest.
Carbonization**:** Volatile elements (nitrogen, sulphur, oxygen, etc.) are lost, leaving only carbon. This process preserves delicate and soft-bodied worms, jellyfish, insects and leaves. The unique organisms of the Burgess Shale in the Canadian Rockies were preserved by *carbonization*.

Replacement of Primary Material

There are various methods, including:

- Original organic material has been dissolved away by circulating groundwater and is replaced by minerals that precipitate out of solution.
- Carbonate skeletons may be replaced by pyrite, hematite or limonite.
- Shell, bone or wood is often replaced by microcrystalline quartz.

This process can occur on so fine a scale that delicate features of the original plants or animals are retained.

Moulds, Impressions, and Casts

Surface characteristics of an organism can be preserved as an *external mould* or *impression*. An *internal mould* reflects, for example, the internal surface of shell valves. Moulds only preserve surface markings, never the original material that composed the hard parts or the internal structures. When an organism is completely dissolved away, the space that it occupied in the sediment may be filled with other materials such as mud or clay. This forms a *cast* of the organism.

Trace Fossils (Ichnofossils)

The study of trace fossils is called *ichnology*. Trace fossils may be tracks, trails, burrows, footprints, grazing patterns or coprolites (fossilized fecal matter). Trace fossils tell us a great deal about the size, lifestyle and environment of an organism.

IMPORTANCE OF FOSSILS

History and evolution of life

The fossil record is a record of evolutionary change. Paleontology helps us understand catastrophic events such as mass extinctions that mark drastic changes in the history of life.

Geological dating and correlation

The Principle of Fossil Succession states that all organisms eventually become extinct, and they are replaced by newly evolved, related forms in an orderly succession through time.

Certain organisms, called *zonal fossils*, are characteristic to specific geological time periods. As a result, Earth scientists can use the fossil content of a bed to determine its geological age. In addition, rocks in one area can be correlated with those at great distances (even on other continents) because they contain identical fossils .

- In order to qualify as a zonal fossil, the organism should: have existed for only a short period of geologic history,
- have distinctive features that make it easy to recognize,
- be abundant enough that it is well represented in the fossil record,
- have a large geographical distribution.

The study of ancient environments

Each type of organism has specific environmental needs. Fossils in sedimentary rocks give us important information about climates and environments of the past.

Province of British Columbia
Ministry of Energy, Mines and
Petroleum Resources

MINERAL RESOURCES DIVISION
Geological Survey Branch

THE IDENTIFICATION OF COMMON ROCKS

By Eileen Van der Flier-Keller
and William J. McMillan

Revised 1987

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The Identification of Common Rocks

INTRODUCTION

The entire earth's surface is made up of rocks. Although in many places the rocks are covered with river, wind or glacially deposited materials, there are few places in British Columbia where rocks cannot be found. A large number of different rock types exist. The identification of common rocks may, however, be complicated by the fact that certain rock types grade into each other. For example there is every gradation between a shale and a sandstone — including sandy shale and shaly sandstone, and also between granite and gabbro. In addition a single rock type may vary in appearance.

The booklet deals mainly with rock types found in British Columbia and is therefore addressed to British Columbia readers. The rocks of this province are however not unique, and the principles used here can be applied anywhere. The geology of British Columbia is fascinating; it is complex, many processes are at work, and there are a great variety of rocks. Rocks are an integral part of the landscape; being able to identify them can greatly enhance your enjoyment of the natural world.

Before starting to identify rocks it is helpful to know a little about what rocks are, how they are formed, and how they are classified. These topics are dealt with in the next few pages. A brief discussion of the major rock groups — **igneous, sedimentary** and **metamorphic,** and their most common forms — is also included.

Rocks are precisely classified using various properties which are determined by petrologists using microscopes and other complicated and sophisticated equipment . More approximate, "field" terms are used by geologists in the field and this booklet describes ways to look at and **identify rocks in outcrop.** The purpose of this booklet is to aid the non-specialist to easily identify the rocks, using simple techniques which can be applied in the field or at home. The methods used assume little prior knowledge and the **equipment** required is limited to:

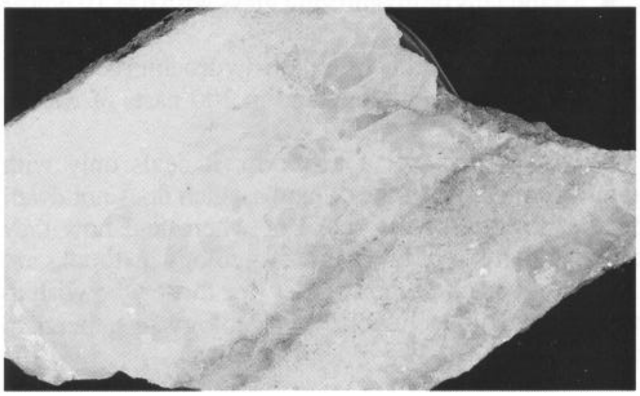
- a rock hammer to break off pieces of rock
- a pocket knife
- a hand lens or magnifying glass with 6 to 10 power magnification
- a dropper bottle of dilute hydrochloric acid (5 parts of concentrated acid in 100 parts of water).

The booklet is not a textbook, it deals only with identifying common rocks, and as such does not dwell on the geology of the rocks or where and how they occur. A number of introductory geology textbooks are listed at the back of the booklet, for those who wish to pursue the study of rocks and geology in general in more detail.

WHAT ARE ROCKS?

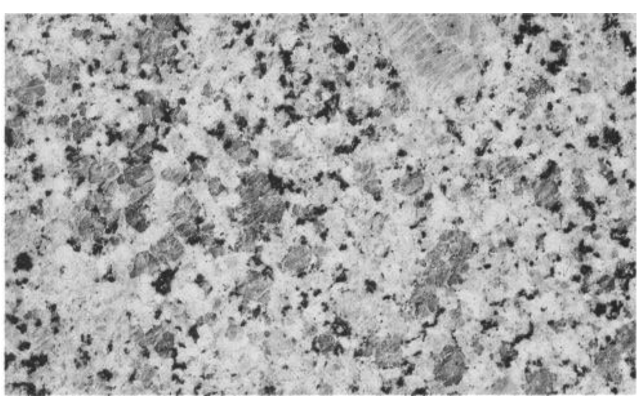
A great variety of definitions have been applied to rocks. For example, engineers may define rocks as materials which must be blasted to make dams, roads and so on, while a builder may define a rock as a hard, resistant building material. Geologists, however, define rocks as **collections or aggregates of mineral grains.** Most rocks fall into this category; however, there are exceptions, such as conglomerate, which is made up of pebbles which are themselves mineral aggregates; obsidian, which is a volcanic glass that cooled so fast that no crystals had time to form; and coal, which is an aggregate of plant material as opposed to mineral matter. A large number of mineral types may be present in a rock, for example quartz, feldspar and muscovite in granite, or the entire rock may be made up of many grains of a single mineral, for example quartz in some sandstones (see Figure 1). Rock generally refers to aggregates of mineral grains that are **coherent**; in other words, the grains stay together and don't disintegrate under normal conditions; thus sand and mud, which disaggregate, are not rocks.

Mineral grains have various shapes and are held together in a rock in a number of ways. Minerals can be rounded or irregular in shape. The **rounded** grains are held together by cement, just as sand grains are cemented together to form sandstone. Irregular or angular shaped grains are **interlocking** and this is how grains in granite or gabbro are held together (see Figure 2). These features are important tools in classifying rocks and assigning them to one of the three major rock groups. As will be discussed following, **sedimentary** rocks are made up of fragments of pre-existing



0 2
cm

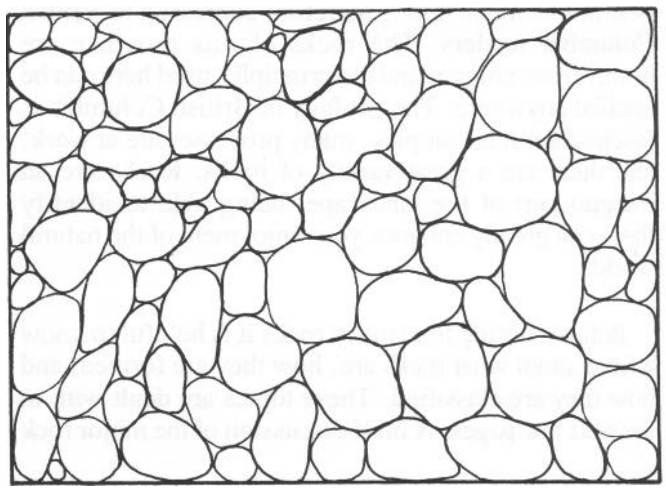
(1A) all the same mineral



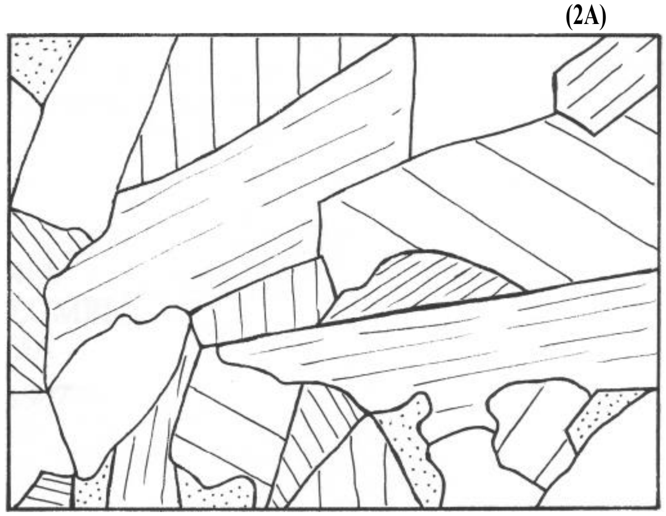
0 2
cm

(1 B) different minerals

Figure 1. Aggregates of minerals: (A) all the same mineral and (B) different minerals.



(2A)



(2B)

Figure 2. Rock held together by (A) cemented and (B) interlocked grains.

rocks which have been weathered and eroded. The rocks which result have rounded grains held together by mineral cements. **Igneous** and **metamorphic** rocks on the other hand crystallized at high temperatures and the minerals are interlocking and irregular.

While rocks consist of aggregates of minerals, **minerals** themselves are made up of **one or a number of chemical elements** with a definite chemical composition. Minerals cannot be broken down into smaller units with different chemical compositions in the way that rocks can. More than two thousand three hundred different types of minerals have been identified, luckily many are rare; the common rocks are made up of a relatively small number of minerals.

Since minerals are the building blocks of rocks, it is important that you learn to identify the most common varieties. Minerals can be distinguished using various physical and/or chemical characteristics, but, since chemistry cannot be determined readily in the field, geologists use the physical attributes of minerals to identify them. These include features such as crystal **form, hardness** (relative to a steel blade or your fingernail), **colour, lustre** and **streak** (the colour when a mineral is ground to a powder). More detailed explanations of these terms and other aspects of mineral identification may be found in the guidebooks listed on the last page of this booklet. Generally the characteristics listed above can only be determined if the mineral grains are visible in a rock. The **identification flowchart (see** Figure 5) distinguishes between **rocks in which the grains are visible and those in which the individual mineral components are too small to identify.**

COMMON ROCK-FORMING MINERALS

A small number of minerals, including olivine, quartz, feldspar, mica, pyroxene and amphibole, are the common rock-forming minerals. Because they are so common, and are used as important **tools in classifying igneous rocks,** descriptions which will help you to identify them are included in this booklet. Except for quartz, all the minerals listed above are actually groups of minerals which have many common characteristics. Instead of trying to separate all the minerals which make up a certain group, they are dealt with here as a single mineral with common characteristics.

Olivine: Olivine, or peridot in the jewelry trade, is yellow-green, translucent and glassy looking. Crystals are uncommon; it usually occurs as rounded grains in igneous rocks or as granular masses. Olivine is almost as hard as quartz; it does not have a well-developed cleavage.

Quartz: Quartz is a glassy looking, transparent or translucent mineral which varies in colour from white and grey to smoky. When there are individual crystals they are generally clear, while in larger masses quartz looks more milky white. Quartz is hard — it can easily scratch a steel knife blade. In the rock, quartz grains are irregular in shape because crystal faces are rare and quartz does not have a cleavage (that is, it does not break on regular flat faces).

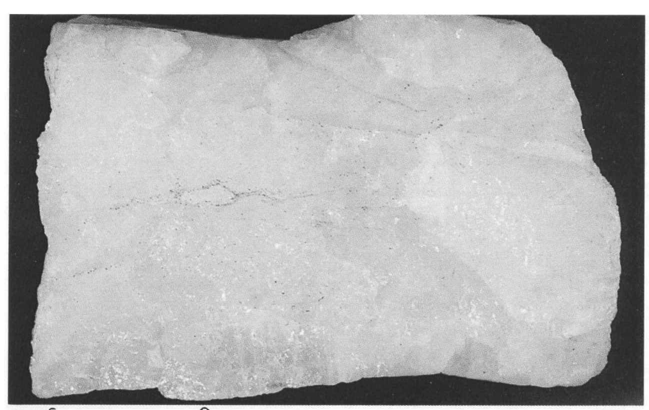
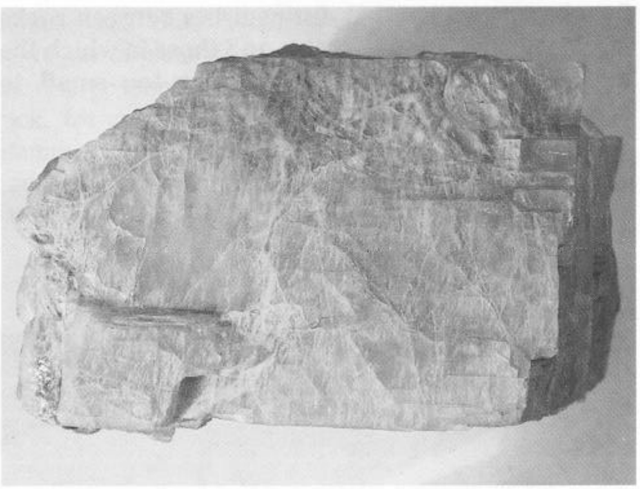


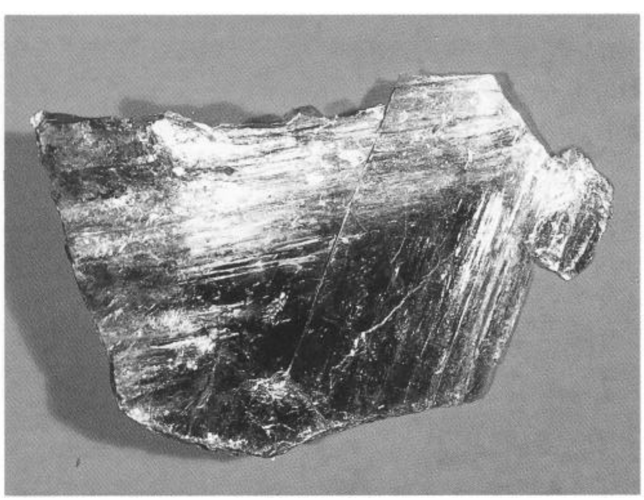
Figure 3. Common rock-forming minerals: (A) quartz, (B) feldspar, (C) mica, (D) pyroxene and (E) amphibole.

Feldspar: Feldspar is the other common, light-coloured rock-forming mineral. Instead of being glassy like quartz, it is generally dull to opaque with a porcelain-like appearance. Colour varies from red, pink and white (orthoclase), to green, grey and white (plagioclase). Feldspar is also hard but can be scratched by quartz. Feldspar in igneous rocks forms well-developed crystals which are roughly rectangular in shape, and they cleave or break along flat faces. The grains, in contrast to quartz, often have straight edges and flat rectangular faces, some of which may meet at right angles.



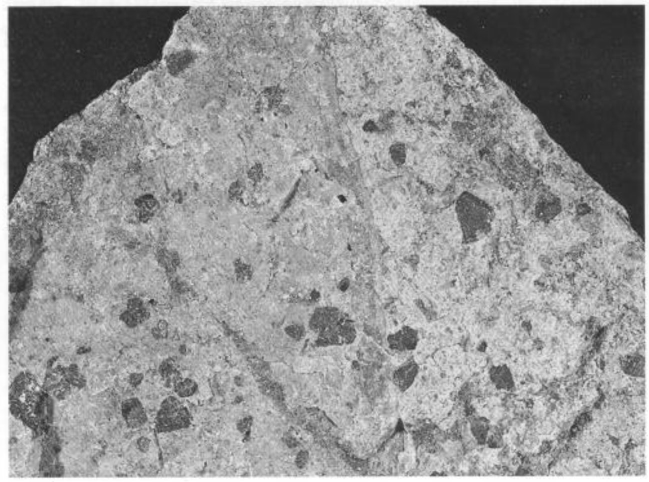
0 2 cm (3B) feldspar

Mica: Mica is easily distinguished by its characteristic of peeling into many thin flat smooth sheets or flakes. This is similar to the cleavage in feldspar except that in the case of mica the cleavage planes are in only one direction and no right angle face joins occur. Mica may be white and pearly — muscovite, or dark and shiny — biotite.



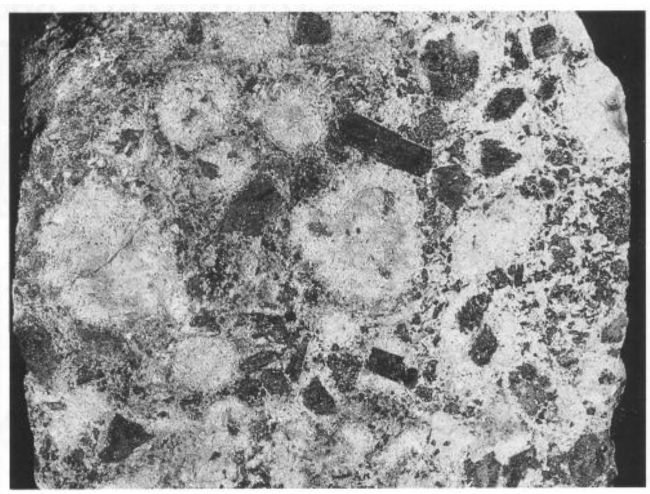
0 2 cm (3C) mica

Pyroxene: The most common pyroxene mineral is augite. Augite is generally dark green to black in colour and forms short, stubby crystals which, if you look at an end-on section, have square or rectangular cross-sections.



0 1 cm (3D) pyroxene

Amphibole: The most common amphibole is hornblende. Hornblende is quite similar to augite in that both are dark minerals, however hornblende crystals are generally longer and thinner and shinier than augite and the mineral cross-sections are diamond shaped.



0 2 cm (3E) amphibole

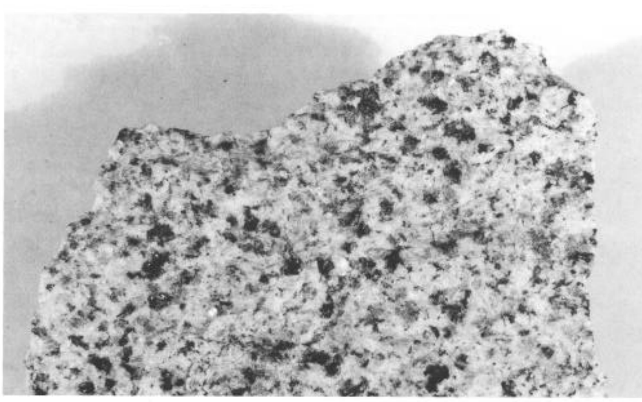
Quartz and feldspar are light-coloured minerals; mica, pyroxene and amphibole are dark coloured. The colour of a rock will be determined by the proportions of light and dark-coloured minerals present. If most of the grains are quartz and feldspar then the overall appearance of the rock will be light, while the opposite will be true if the minerals are mainly mica, pyroxene and amphibole. The colour of a rock with between 25 and 50% dark minerals is intermediate.

ROCK CLASSIFICATION

Rocks are classified or grouped together as igneous, sedimentary and metamorphic according to how they were formed. Rocks form in three main ways: **igneous —** by crystallization of minerals from molten material or magma as it cooled; **sedimentary** --- by accumulation of materials which have been eroded and weathered from pre-existing rocks at the earth's surface; **metamorphi c —** by modification of pre-existing rocks by heat, pressure or the action of chemical solutions.

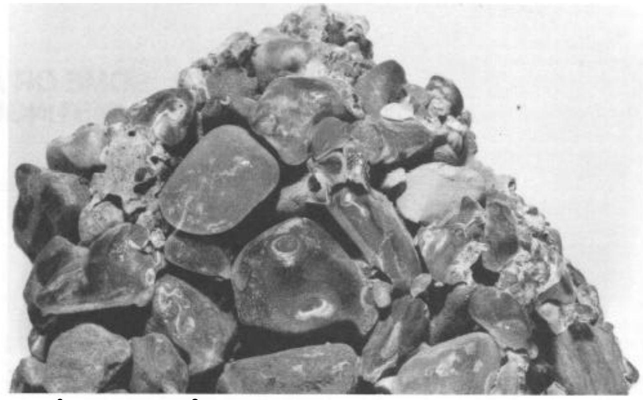
Every rock has characteristics that reflect its process of formation; these are used to determine whether the rock is igneous, sedimentary or metamorphic (see Figure 4). For example, a rock with rounded grains cemented together is sedimentary, while one with a strong banding and orientation of the minerals is metamorphic. Identification of rock types within the three divisions depends on the nature of the mineral grains, including their composition and size and relationship to surrounding grains; the way the rock occurs; how uniform it is; its hardness; how it reacts with acid; its colour; and the way in which it breaks. Before trying to identify a rock, break a piece off with a rock hammer. This will expose a clean, fresh surface. (WARNING — **do not use a carpenter's hammer, they are hardened steel and will chip.)**

When a rock is dirty or covered with lichen many of its characteristics are obscured, preventing you from accurately identifying the rock. Identification of beach pebbles that are smoothed and rounded is not considered here because this booklet deals specifically with fresh surfaces. Many pebbles are relatively easy to identify without breaking, but many are extremely difficult, and breaking usually destroys their interest and charm. As a rule a pebble catches the eye and is picked up because it is an object which shows some special effect of colour or pattern, often due to layering, veining or alteration. Such pebbles are not good examples of common rock types.



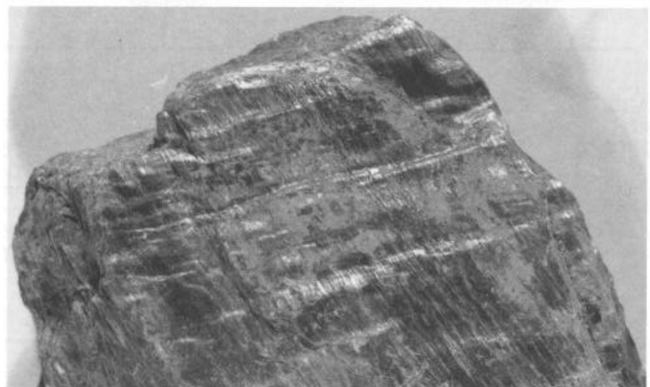
0 2
cm

(4A) igneous



0 2
cm

(4B) sedimentary



0 1
cm

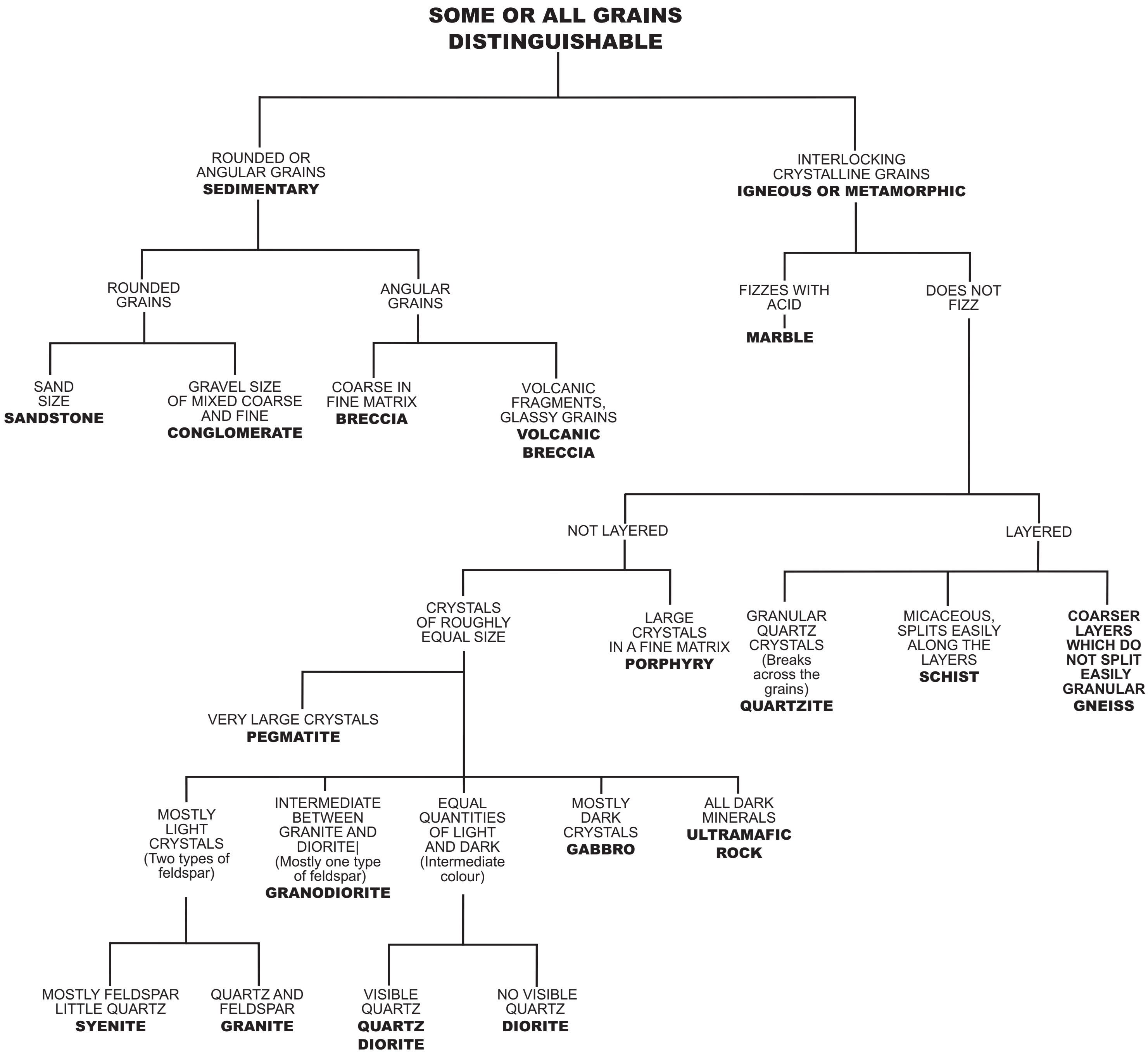
(4C) metamorphic

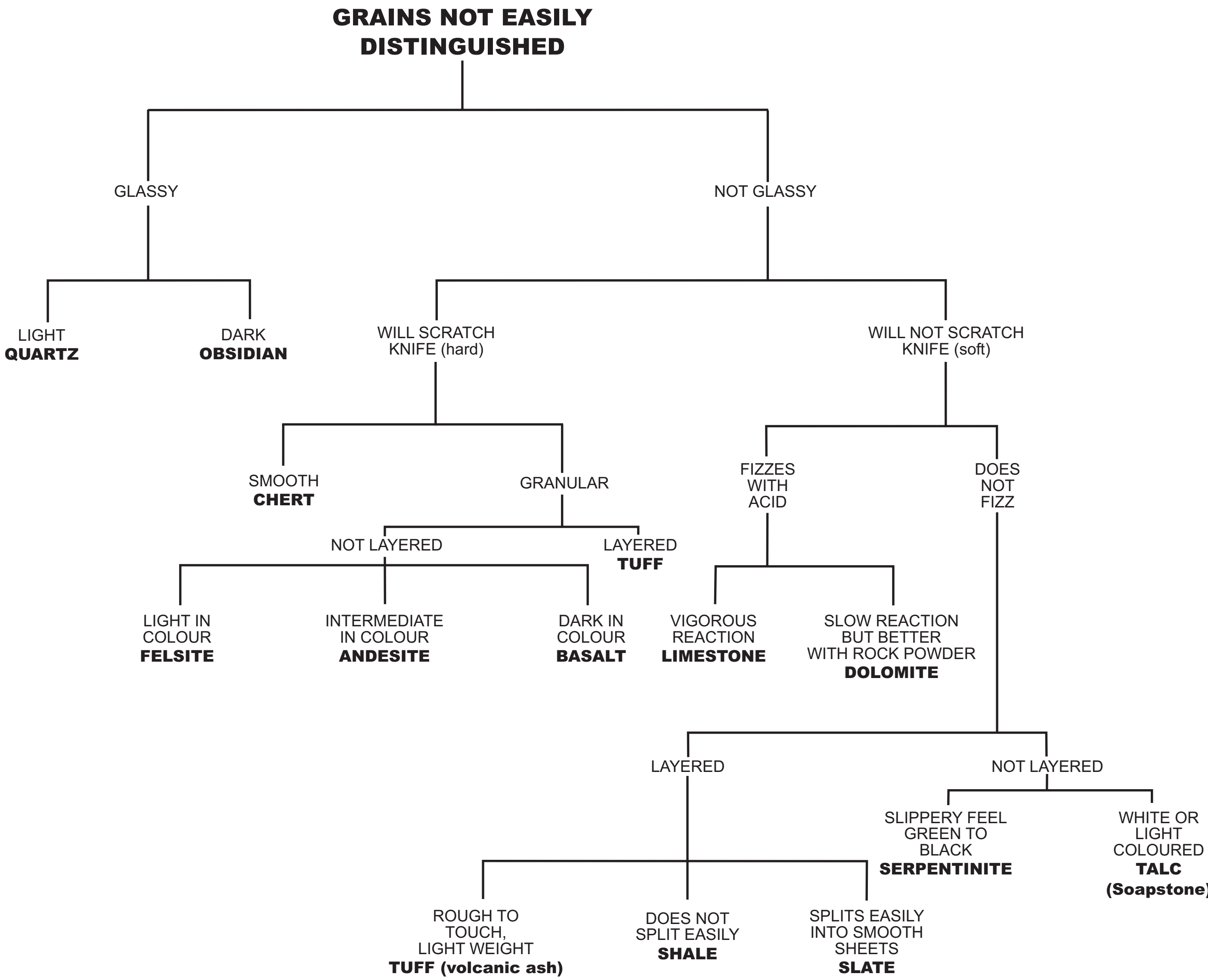
Figure 4. Appearances vary for (A) igneous, (B) sedimentary and (C) metamorphic rocks.

KEY TO USING THE ROCK IDENTIFICATION CHART

To identify a rock which is of interest, first, take a fresh surface and examine it carefully with the naked eye. Starting at the top of the chart, decide whether the grains which make up the rock can be distinguished or not. Where some of the grains can be seen, for example a rock in which there are a number of large grains in a very fine matrix, go to the right side and proceed from there. From here on use a hand lens and, where it is required, a knife or dilute hydrochloric acid (5%). Follow the flow lines downward and at each branching check all the possible options and decide which one most closely fits your specimen. Continue downwards until you come to a rock name. Check the rock description in the igneous, sedimentary and metamorphic sections of the booklet and if the features and the way the rock occurs fit your sample — BRAVO! Otherwise go back to the chart and check for alternative choices at places where you may have been unsure of your observations; rocks vary so don't be surprised or discouraged if this happens.

Figure 5. Rock Identification Chart




GRAINS NOT EASILY DISTINGUISHED
GLASSY
NOT GLASSY
LIGHT
QUARTZ
DARK
OBSIDIAN
WILL SCRATCH KNIFE (hard)
WILL NOT SCRATCH KNIFE (soft)
SMOOTH
CHERT
GRANULAR
NOT LAYERED
LAYERED
TUFF
LIGHT IN COLOUR
FELSITE
INTERMEDIATE IN COLOUR
ANDESITE
DARK IN COLOUR
BASALT
FIZZES WITH ACID
DOES NOT FIZZ
VIGOROUS REACTION
LIMESTONE
SLOW REACTION BUT BETTER WITH ROCK POWDER
DOLOMITE
LAYERED
NOT LAYERED
SLIPPERY FEEL GREEN TO BLACK
SERPENTINITE
WHITE OR LIGHT COLOURED
TALC
(Soapstone)
ROUGH TO TOUCH, LIGHT WEIGHT
TUFF (volcanic ash)
DOES NOT SPLIT EASILY
SHALE
SPLITS EASILY INTO SMOOTH SHEETS
SLATE

Igneous rock forms as molten material, called **magma,** cools and solidifies. As the hot magma rises to the surface and cools the chemical elements within it combine, and minerals begin to crystallize. As cooling continues, crystals get larger and more numerous and begin to interfere with the neighbouring crystals which are also growing; the result is a mass of partially formed and interlocking crystals. If cooling is slow minerals with sharp edges and perfect faces are rare; normally so many form at once that they don't have room to grow in this way.

Magma when it cools deep within the earth cools very slowly, allowing the crystals to grow to be quite large, 3 to 10 millimetres or more. This results in a medium or coarse-grained igneous rock — termed **intrusive or plutonic.** Examples of this type of rock are granite or gabbro. If on the other hand the magma cools close to or at the earth's surface. as for example in the Hawaiian volcanoes, cooling takes place very rapidly allowing little time for crystal growth. This type of igneous rock — **volcanic or extrusive** — will be very fine grained. An example is basalt. In some cases the magma cools so quickly that no crystals grow and volcanic glass results. Another common scenario is where cooling of the magma begins deep inside the earth where a number of quite large crystals grow, then is moved nearer to the surface where it is cooled rapidly. The resulting rock has some large, well-formed crystals sitting within a fine-grained matrix; it is called a porphyry. The large crystals are called phenocrysts.

A large number of igneous rocks exist and they grade from one type into another. **Classification** schemes are usually based on the types and amounts of minerals present (see Figure 6), and the size of the crystals. While the compositional variations of the rock groups are important to petrologists, here we will only introduce you to the basic rock types.

To use this figure, read from the ottom up You can decide what the rock is from the minerals it contains For e ample, if the rock is dark coloured and consists mainly of pyro ene and oli ine, with a out plagioclase, it is a ga ro if it has com ined mica and amphi ole, uart , orthoclase and the rest is pagioclase, it is a granodiorite

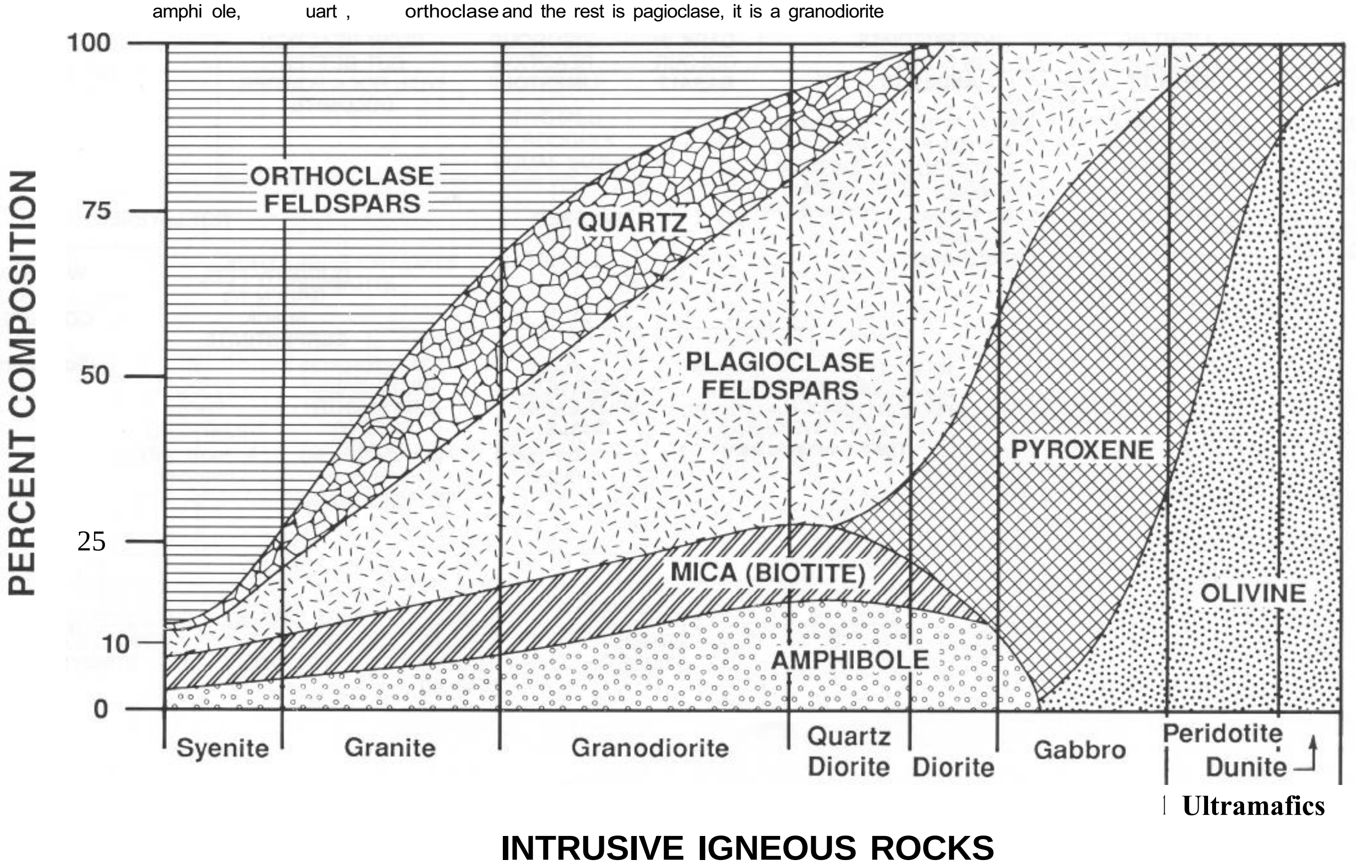


Figure 6. Classification of igneous rocks by mineral composition.

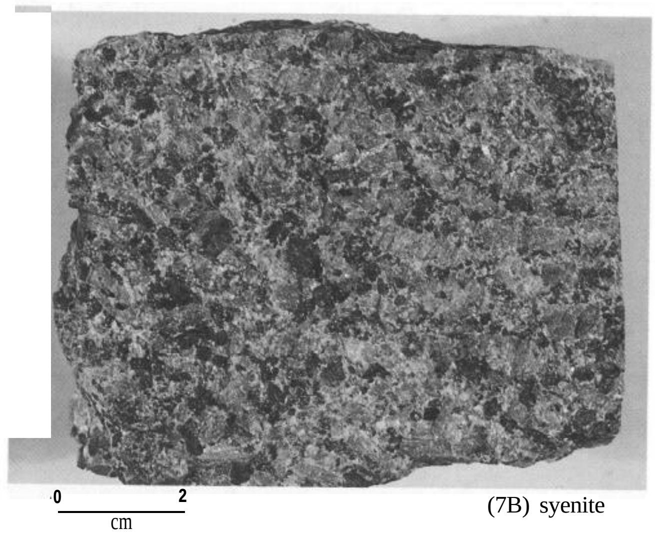
INTRUSIVE OR PLUTONIC ROCKS

Intrusive rocks, because they crystallized at depth, are completely crystalline, generally unlayered, and consist of interlocking crystals that are **medium to coarse grained.** Differing proportions of light and dark minerals result in a colour range from light to dark. These colour variations, and the presence or absence of quartz, are used to distinguish the different kinds of intrusive rocks (see Figures 6 and 7).

Most igneous rocks are of intermediate composition and colour. These intermediate-coloured intrusive rocks form a series which grades between granite on the light-coloured side, through granodiorite, quartz diorite and diorite to gabbro on the dark side.

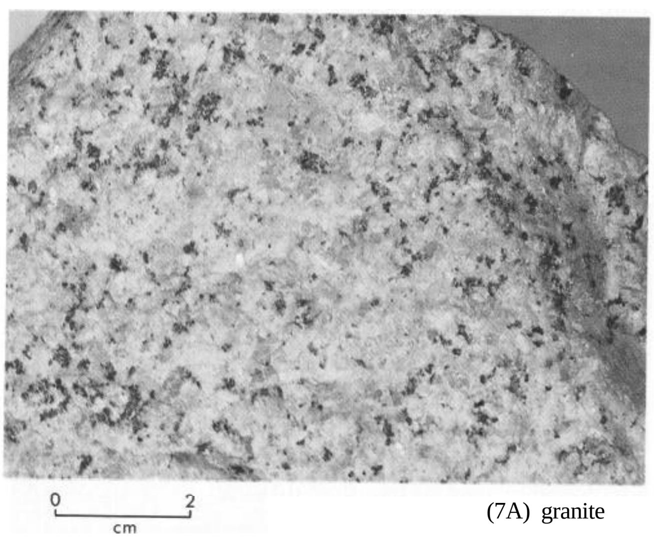
Granite: is a pink or greyish coloured, medium to coarse-grained, evenly granular rock which represents the lightest coloured variety of intrusive rock. The grains are mainly white/pink orthoclase feldspar, with lesser amounts of white/grey plagioclase feldspar, and quartz; small amounts of dark biotite and/or hornblende are mixed in with these light mineral components. In some granites, where the feldspar is red in colour, the rock will appear darker. True granite is not common in British Columbia.

Syenite: is also light coloured. It is similar to granite except that it contains very few or no quartz grains. It is therefore made up predominantly of interlocking feldspar crystals with minor amounts of mica or hornblende. Syenite is rare in British Columbia. If the crystals are very large (more than 2 centimetres), the rock can be called a pegmatite.

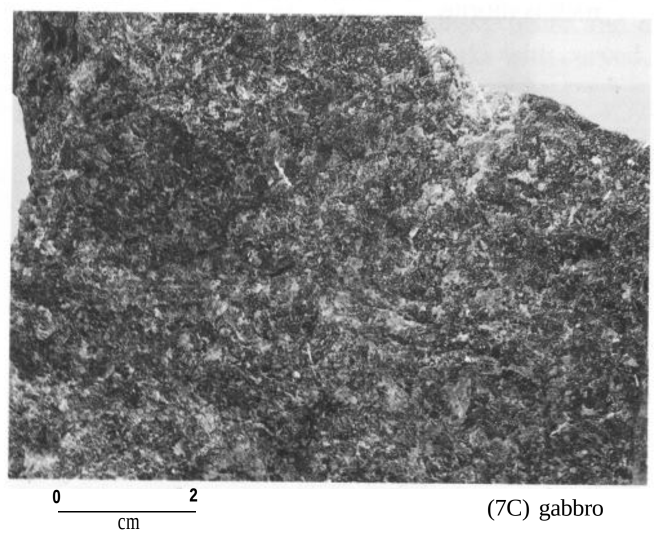


(7B) syenite

Gabbro: is a dark, medium to coarse-grained intrusive rock, containing more than 50% dark crystals and interlocking light crystals. The dark minerals are mainly pyroxene, with minor amounts of hornblende or biotite; the light minerals are usually light grey plagioclase feldspars. Gabbro is not common in British Columbia. If there are NO light crystals at all, the rock is an ultramafic.



(7A) granite

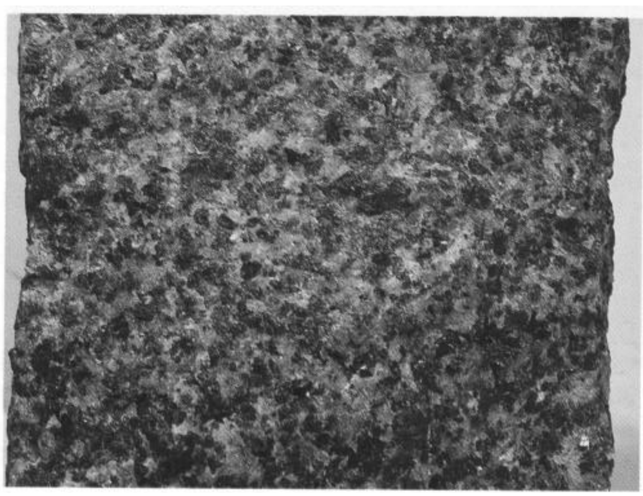


(7C) gabbro

Figure 7. Common slowly cooled igneous rocks of the plutonic or intrusive type are (A) granite, (B) syenite, (C) gabbro, (D) diorite (E) quartz diorite and (F) granodiorite.

Diorite - Quartz Diorite - Granodiorite: These intermediate-coloured intrusive rocks form a series which grades between granodiorite on the light-coloured side, through quartz diorite and **diorite,**

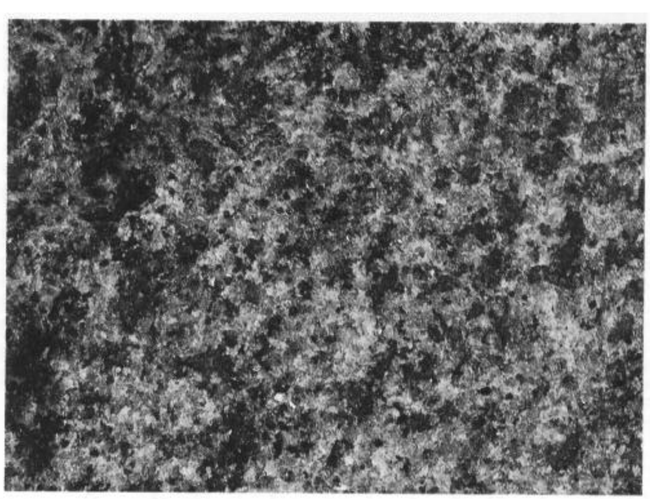
to gabbro on the dark side. The gradation represents an increase in dark minerals, a decrease in quartz, and an increase in the amount of grey plagioclase. The intermediate rocks may be difficult to separate. Only the most common varieties in British Columbia **— quartz diorite and granodiorite —** are discussed here.



0 1 cm

(7D) diorite

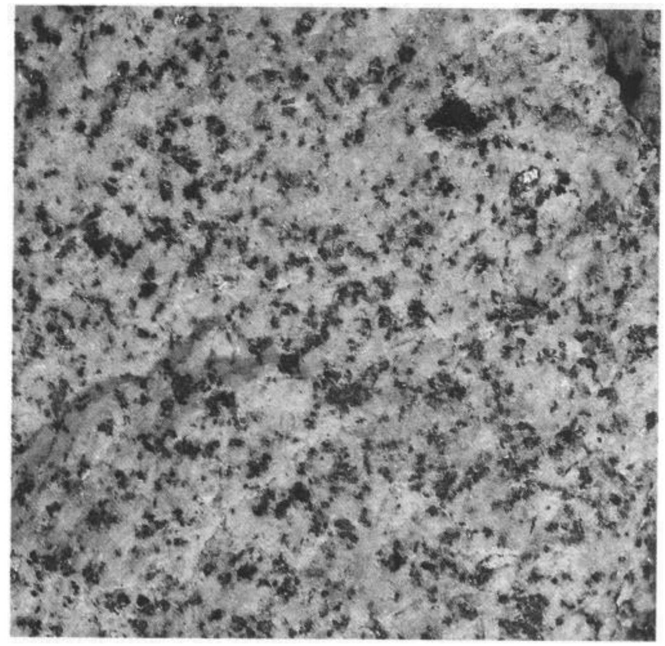
Quartz Diorite: is a medium to dark grey, medium to coarse-grained rock consisting mainly of plagioclase feldspar, some quartz, and abundant dark minerals (roughly a third). If there is no quartz, the rock is diorite.



0 1 cm

(7E) quartz diorite

Granodiorite: falls between granite and quartz diorite; it contains more dark minerals than granite but fewer than quartz diorite. The light-coloured minerals are quartz and feldspar; the feldspar is a mixture of orthoclase and plagioclase.



0 2 cm

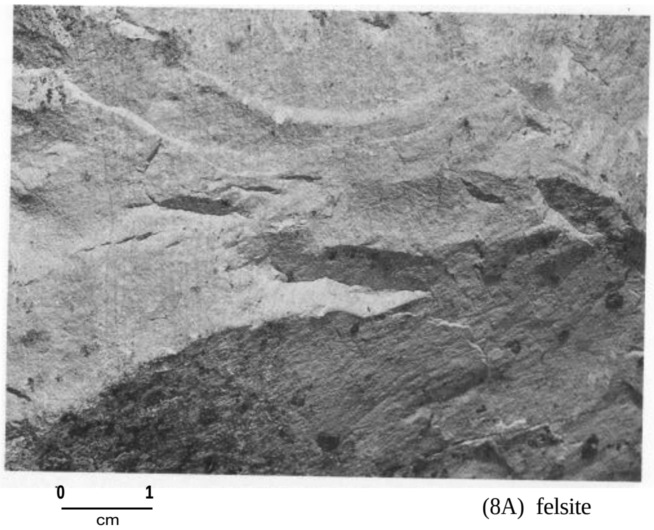
(7F) granodiorite

EXTRUSIVE OR VOLCANIC ROCKS

When magma is erupted from volcanic vents at the earth's surface it cools very rapidly and a **fine-grained** rock results. Although the grains may not be clearly visible, generally the rock will still have a granular texture. Different types of volcanic eruptions give rise to different types of volcanic rocks. If magma pours out onto the surface, a **volcanic lava** with flow structures, phenocrysts, and abundant vesicles (or gas bubble cavities) may result.

If the eruption is forceful, like Mauna Loa in Hawaii, or explosive, like Mount St. Helens, the rock formed may consist of a variety of fragments including glass shards, volcanic bombs, ash and pumice. These deposits are commonly layered and are termed **agglomerates or volcanic breccias.** Volcanic rocks form from the same magma as intrusive igneous rocks. Although the crystals are too small to identify without a microscope, they show the same series of mineral gradations and corresponding colour variations as their medium and coarse-grained counterparts (see Figure 8). Volcanic rocks are often difficult to crack with a hammer and break with a rough fracture surface.

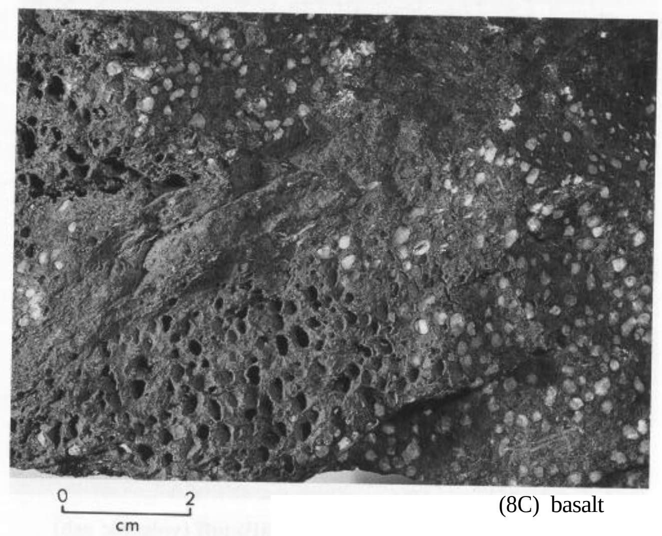
Felsite: is a general term for all light-coloured volcanic rocks. The most common variety, which is the fine-grained or volcanic equivalent of granite, is called rhyolite. Felsites are generally granular, rough to the touch, and in some cases show a series of more or less parallel bands of different colours called flow bands. These may be wavy and swirly and can therefore be distinguished from sedimentary bedding or metamorphic foliation. Felsites are not common in British Columbia.



(8A) felsite

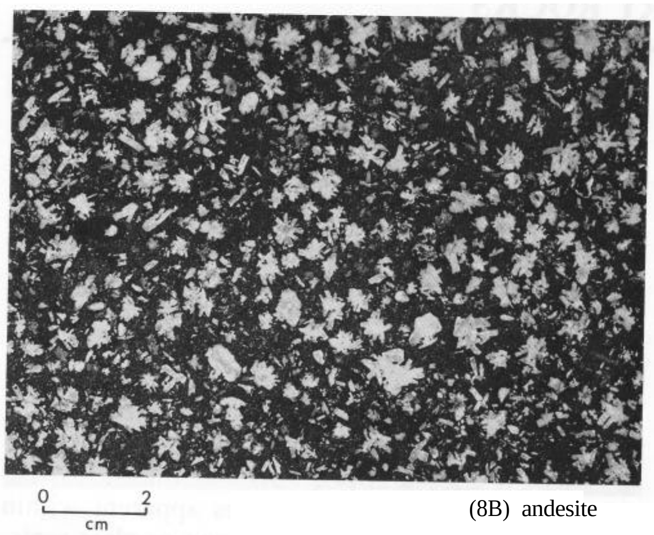
Andesite: is intermediate in composition and colour between felsite and basalt; it is the fine-grained, volcanic equivalent of diorite and is generally a dark grey rock consisting mainly of plagioclase feldspar and abundant dark minerals. Colours range from grey and grey-green to red or pink. Andesites are generally porphyritic, that is, they contain some large crystals floating in a fine-grained matrix. In British Columbia andesites are more common than felsites, but less common than basalt.

Basalt: is a fine-grained, dark-coloured, dense rock which has a dull, granular appearance. Basalt, which is the volcanic equivalent of gabbro, is often porphyritic. Commonly basalt is vesicular, that is, it has holes (vesicles) which were once gas bubbles; later, these holes often fill with mineral matter (amygdules). Basalts which formed by underwater eruptions characteristically develop pillow-like shapes. Basalt is a common rock in British Columbia.

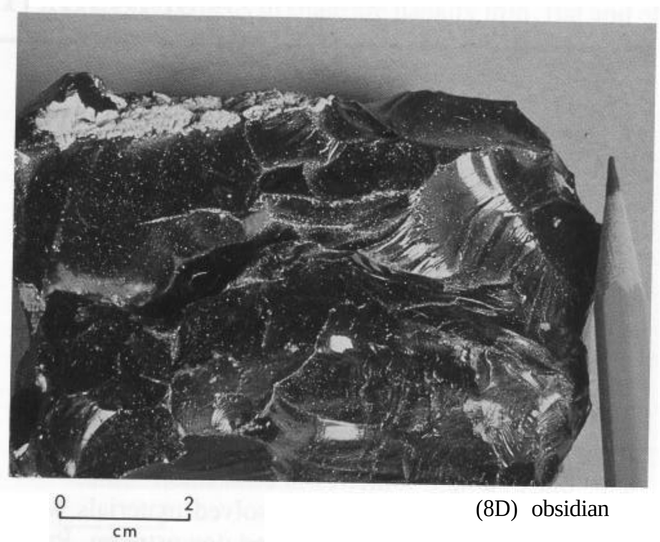


(8C) basalt

Obsidian: is a natural volcanic glass. It is generally dark in colour, with a bright glassy lustre and a conchoidal fracture, that is, it breaks with curved, striated faces like glass. Obsidian is not common in British Columbia.



(8B) andesite

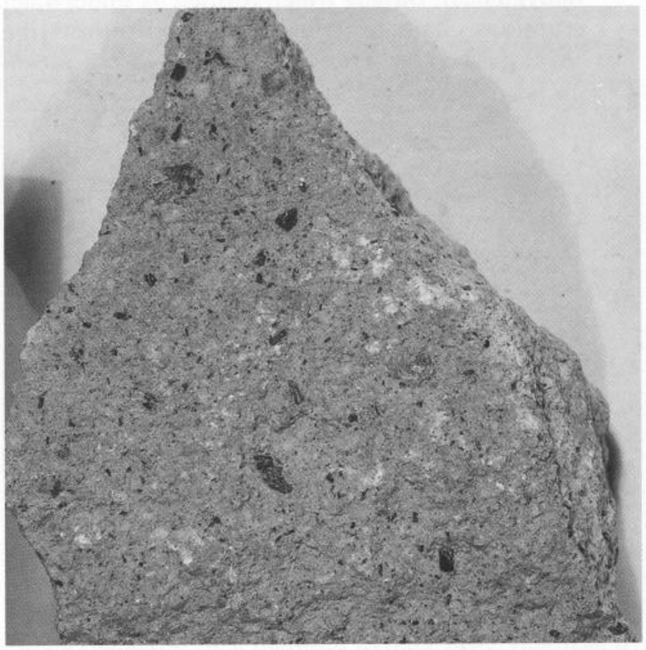


(8D) obsidian

Figure 8. Common quickly cooled igneous rocks of the volcanic or extrusive type are (A) felsite, (B) andesite, (C) basalt, (D) obsidian, (E) volcanic ash (tuff) and (F) volcanic breccia.

Tuff or volcanic ash: contains a variety of small or large angular fragments. Because they were blown out of the volcano and fell through the air, bigger and heavier fragments fell faster and the rocks formed tend to be layered like sedimentary rocks.

Fine-grained accumulations of material are called ash or tuff, and coarser grained deposits, **agglomerates** or **breccias.** The composition of these rocks is variable. Volcanic agglomerates are not very common in British Columbia.



0 cm

(8E) tuff (volcanic ash)

(8F) volcanic breccia

SEDIMENTARY ROCKS

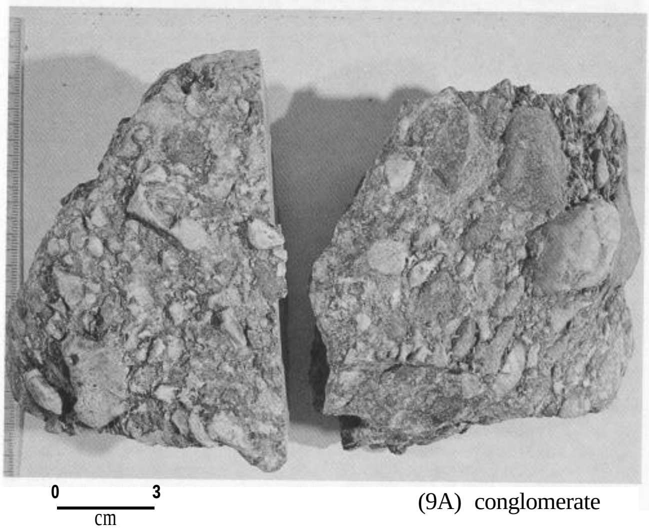
Sedimentary rocks form at the earth's surface by the action of weathering and erosion of pre-existing rocks. Rocks are gradually broken down by physical and chemical means when they are exposed to the atmosphere. Wind-blown particles abrade; rain pounds and the rainwater dissolves some parts; alternate freezing and thawing of water in microcracks break down the surface layer; gravity and weather shift unstable particles down slope and they abrade or break other rocks that they hit. Catastrophic events also occur: earthquakes trigger massive rockslides; floods move huge amounts of materials and undercut their banks; volcanos blast cubic kilometres of rock into rubble.

Broken rocks, grains and dissolved materials wash into rivers and are carried or rolled downstream. Particles are abraded and gradually rounded off as they grind together like pebbles in a lapidary tumbler. When the rivers enter lakes or the ocean, particles are dropped and dissolved materials tend to deposit as fine precipitates of mud or ooze. Particles vary in size from boulders through gravel and sand to silt and mud. Sediment may also be transported by glacial ice or the wind.

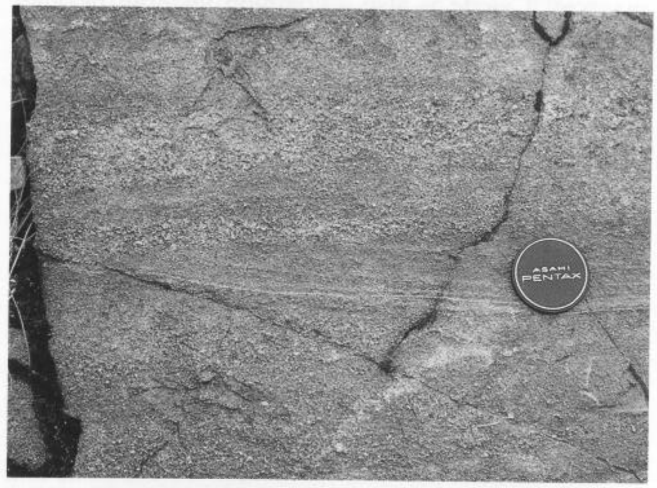
The deposited materials, when other layers of transported sediment are added on top, become compacted and mineral matter precipitates from trapped water and **cements** the grains together forming sedimentary rocks. Because sedimentary rocks are formed by the accumulation of layers of deposited material, they very often have **a layered appearance.** Sedimentary rocks may have various other structures apparent within them, such as ripples, animal burrows or plant roots. Often plants and animal remains drop into and become buried in the accumulating sediment, becoming **fossils.**

Conglomerate: is a cemented-together gravel that consists mostly of rounded rock fragments which are greater than 2 millimetres in size. The spaces between the grains are filled with varying amounts of fine-grained material or cement. Conglomerate, as with most sedimentary rocks, is laid down in layers, however, these layers are often so thick that they are not visible in an isolated outcrop.

Sandstone: consists of rounded sand grains cemented together; it is one of the most common sedimentary rocks. A sandstone may contain obvious layers (bedding) or lines at angles to the layers (cross-bedding), but in some cases the beds are too far apart to see in one exposure, as is the case with conglomerate.



(9A) conglomerate

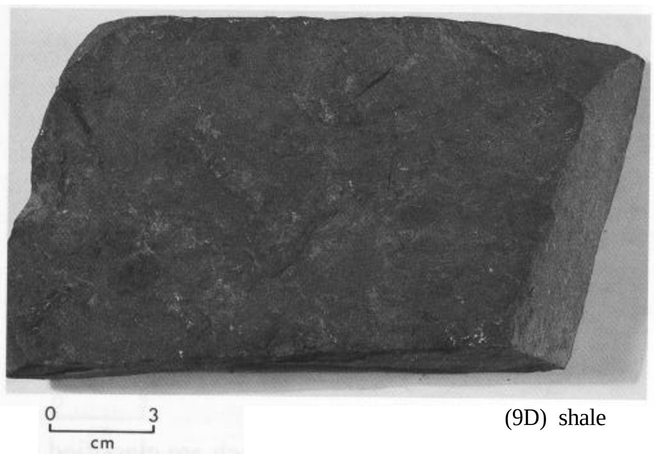


(9C) sandstone

Breccia: is similar to conglomerate in that it consists of coarse-grained fragments surrounded by finer grained material. The fragments in a breccia, however, are sharp and angular, looking as if they were just broken, while those in conglomerates are rounded.

Shale: has the appearance of earthy, hard, mud or clay, which is not surprising since shale is a compacted version of these materials. Shales vary in colour but are generally grey to black or brown. Shale is a soft rock and can easily be scratched with a knife. When hit with a hammer, a mark will remain and the rock breaks into chunks as opposed to sheets (as would be the case for metamorphosed shale — slate). The beds in shale are usually thin, flat and of uniform thickness.

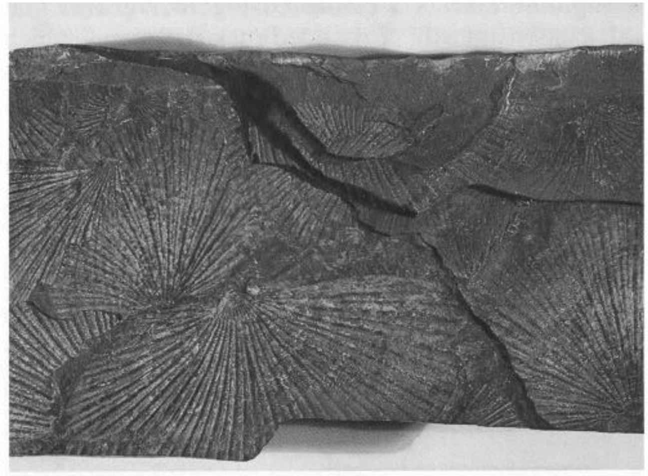
(9B) breccia



(9D) shale

Figure 9. Some common sedimentary rocks are (A) conglomerate, (B) breccia, (C) sandstone, (D) shale, (E) fossiliferous limestone, (F) dolomite and (G)

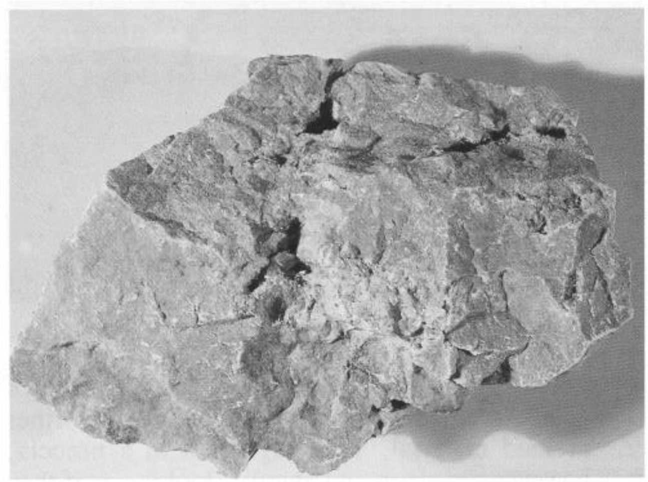
Limestone: is a white, grey or black, fine-grained rock which fizzes **vigorously** when a drop of dilute hydrochloric acid is put on it. It commonly contains fossils, such as shells or other animal remains, and in some cases the fossils may make up most of the rock. When limestone is hit with a hammer it may give off a sulphurous smell. Calcite is the dominant constituent in limestones and it is the material which causes the rock to effervesce in acid. Calcite is also a common material in other sedimentary rocks, where it can occur in fossils or in veins and fracture coatings. For this reason one must be careful when testing for a reaction to acid, and put the drop of acid on a fresh rock surface which does not contain fossils or veins.



0 3 cm

(9E) fossiliferous limestone

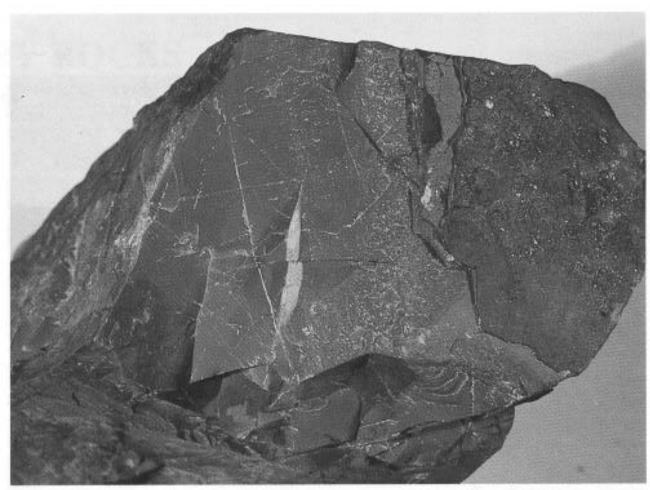
Dolomite: looks very much like limestone except that it is generally tan in colour and fizzes **weakly** if at all when a drop of cold dilute hydrochloric acid is put on it. If dolomite is ground to a powder or hot acid is applied, it will fizz strongly. Limestone and dolomite also weather differently: weathered dolomite often becomes brown or reddish and rough and finely angular; limestone, on the other hand, weathers smooth and light grey or white.



0 3 cm

(9F) dolomite

Chert: is a hard, compact, dense, brittle rock which generally varies in colour from white, through light grey to dark grey. The appearance is waxy and smooth; quartz, with which chert might be confused, is glassy. When struck with a hammer, chert breaks with a conchoidal fracture, like broken glass, or shatters into splinters. These properties result because chert consists of very fine-grained silica. Chert occurs as nodules or irregular bands in limestone, or as thin beds or ribbon-shaped layers separated by thin films of shale.



0 2 cm

(9G) chert

NOTE: For sedimentary rocks, which are classified mainly on the basis of grain size, all **gradations** between each category are found. This means that you may encounter a sandy conglomerate or a muddy sandstone. Gradations should be kept in mind when classifying these rocks.

METAMORPHIC ROCKS

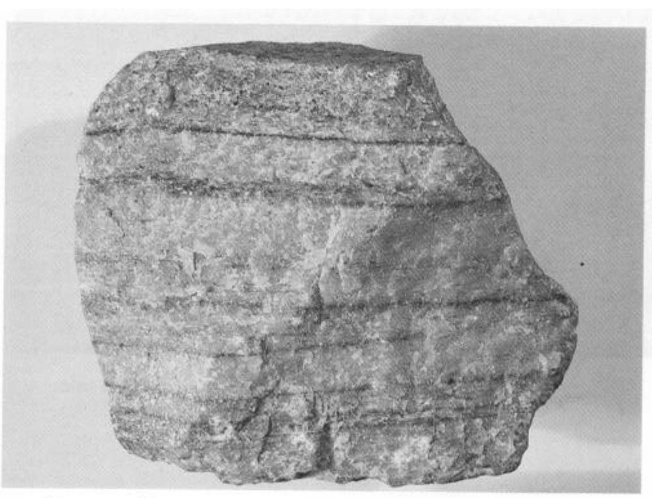
Metamorphic rocks (see Figure 10) form when pre-existing rocks are subjected either to **elevated temperatures or pressures,** or to the actions of chemically active solutions. One or more of the following changes take place:

a) the rock recrystallizes to form a coarser grained rock

b) new minerals form overgrowths on the original minerals

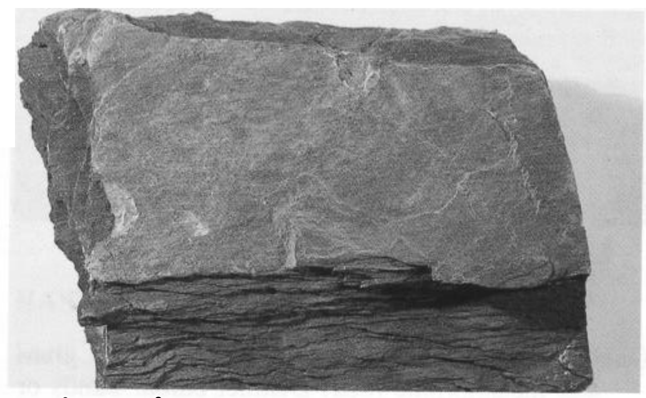
c) a foliation or strong banding develops, along which the rock splits into sheets, bands or flakes. Foliation is caused by the orientation of flattish or elongate minerals on a planar surface.

Quartzite: is metamorphosed quartz sandstone. It is a very hard, sugary textured rock that consists of interlocking quartz grains. The original quartz sand grains are also enclosed in and bound together by quartz cement. This makes the rock hard; when hammered, it breaks across the grains and cement as opposed to around the grains as is the case in sandstones. Freshly broken faces have a glassy appearance. Quartzite is generally light in colour but impurities such as mica are common and any gradation between quartzite and schist, which is described following, may occur. Quartzite may retain some of the original bedding of the sandstone.



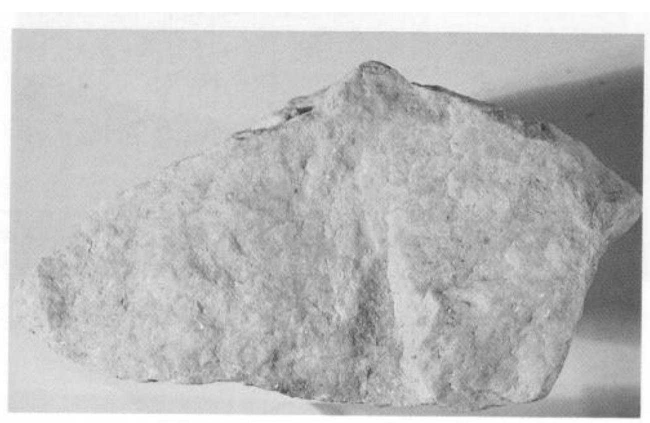
(10A) quartzite

Slate: is the metamorphic product of shale. Slate is a fine-grained brittle rock which splits readily into thin smooth-faced layers or sheets. Slates are generally dark grey, green or black in colour, but may also be red or brown. Individual grains cannot be distinguished with the naked eye. The term argillite refers to rocks with characteristics intermediate between shale and slate; they are harder than shale but do not break into sheets like slate.



(10B) slate

Marble: is limestone or dolomite that has recrystallized due to metamorphism. It is a light-coloured rock and consists of medium to coarse-grained interlocking calcite or dolomite crystals. A marble formed of calcite crystals will fizz with dilute acid and a dolomite marble will fizz if powdered or reacted with hot or concentrated acid. Darker streaks are often present in marble as are calcite veins. Marble scratches easily with a knife.



(10C) marble

Figure 10. Common metamorphic rocks include (A) quartzite, (B) slate, (C) marble, (D) schist, (E) gneiss, (F) serpentinite crossed by an asbestos vein and (G) talc.

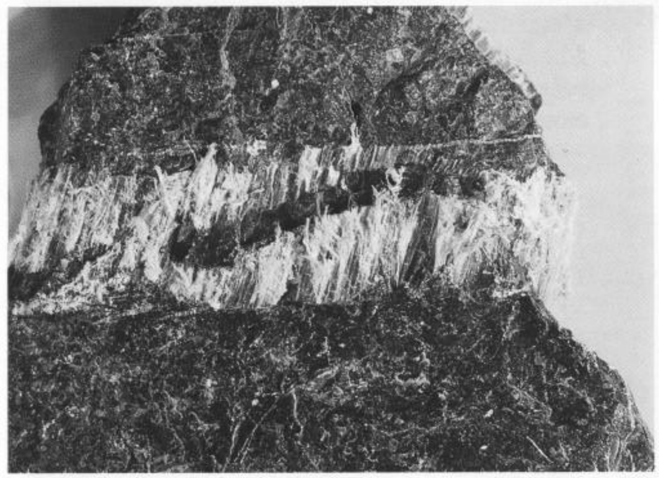
Schist: is a metamorphic rock which is intermediate between slate and gneiss. The rock has layers consisting of aligned mica or mica-like minerals which give the rock a glistening appearance. It splits readily along these layers and the broken faces usually consist of wavy or lens-shaped slabs or flakes rather than thin sheets.

0 2 cm (10D) schist

Gneiss: is a medium to coarse-grained, banded, granular metamorphic rock. Distinct colour bands or streaks are produced by the alternation of layers of light and dark-coloured minerals. The layers do not split readily and when broken are not smooth. Gneiss may form from diorite, granite, shale, sandstone, schist or other rocks.

0 2 cm (10E) gneiss

Serpentinite: is an oily looking green to black fine-grained rock that can be scratched easily with a knife. In many places it is highly sheared and breaks into scaly fragments with smooth shiny faces and a slippery feel. At thin edges the fragments tend to be translucent. Serpentinite is composed of the mineral serpentine. Soapstone is a rock composed of the mineral talc and can be mistaken for serpentine. Soapstone, however, is usually light green to grey in colour and soft enough to be scratched with the fingernail.



0 2 cm serpentinite crossed by an asbestos vein

0 2 cm (10G) talc

ADDITIONAL READING

BOOKS AND PAMPHLETS OF INTEREST

Field Guide Identification Booklets (1986 prices quoted):

The Larousse Guide to Minerals, Rocks and Fossils, W.R. Hamilton, A.R. Woolley and A.C. Bishop, ***Larousse and Co. Inc., New*** York. $13.95

Rocks and Minerals, Zim, Shaffer and Perlman, A Golden Nature Guide, ***Simon and Schuster,*** New York. **$4.95**

A Field Guide to Rocks and Minerals, F.H. Pough, ***Houghton Mifflin Co.,*** Boston. $18.95

The Autobon Society Field Guide to North American Rocks and Minerals, ***Knopf. $19.50***

Simon and Schusters' Guide to Rocks and Minerals, ***Simon and Schuster. $18.50***

GOVERNMENT PUBLICATIONS

B.C. Geological Highway Map, Province of British Columbia, ***B.C. Ministry of Energy Mines and Petroleum Resources —*** available through the Geological Association of Canada, Vancouver. $4.50

An Introduction to Prospecting, ***B.C. Ministry of Energy, Mines and Petroleum Resources,*** Paper 1986-4. Available from the Ministry, Publications Section, 552 Michigan Street, Victoria, B.C. $10.00

* Geology and Canada, ***Geological Survey of Canada*** Publication. Free.

* Rock and Mineral Collecting in British Columbia, S. Learning, ***Geological Survey of Canada*** Paper 72-53. $2.75

* Rocks: Minerals: Fossils: and Gemstones, ***Geological Survey of Canada*** Publication. Free.

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* Available from Information Canada, Ottawa, KlA 0S9 or the Geological Survey of Canada, 601 Booth Street, Ottawa, KlA 0E8.

BASIC GEOLOGY TEXTBOOKS

Earth, F. Press and R. Siever, ***W.H. Freeman and Co., 1986. $46.15***

Principles of Geology, J. Gillully, A.C. Waters and A.O. Woodford, ***W.H. Freeman and Co., 1974. $U.S. 30.95***

Physical Geology, C.C. Plummer and D. McGeary, ***W.M.C. Brown Publishers. $27.70***

Essentials of Geology, F.K. Lutgers and E.J. Tarbuch, ***Merrill Publishing, 1986.*** $U.S. 18.95

Queen's Printer for British Columbia
Victoria, 1987

MINERAL IDENTIFICATION

Minerals are naturally occurring, non-living substances found in the Earth. There are over 2000 different minerals, but only a few are commonly found in the crust. Each mineral has a characteristic chemical composition that determines its overall appearance in much the same way as DNA determines how we look. There are a number of characteristic properties that can be used to identify any mineral specimen.

Mineral Properties

Colour and Streak

Most minerals have a characteristic colour but this alone is not a good way to identify all mineral specimens. Some minerals such as quartz can occur in a rainbow of colours including clear, purple (amethyst), rose or even black, depending on minute chemical impurities.


Streak Plate

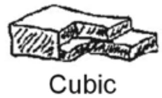

Crushed Mineral

Streak is a much more accurate way of identifying minerals correctly. When a hand specimen of a mineral is scratched across a piece of unglazed tile, it will leave a streak of powdered mineral on the tile (most retail tile outlets will give these to teachers for free). Streak has a particular colour in different minerals. You can get a similar effect by taking a small piece of mineral and crushing it with a hammer (make sure to wear safety goggles). The powdered pieces will have the same colour as the streak on the tile. Some minerals have white streaks, which are difficult to distinguish from one another. Certain minerals, however, have very characteristic streak colours. For these minerals, streak is an important identification test. They include galena (grey-black), pyrite (green-black) and hematite (red-brown).

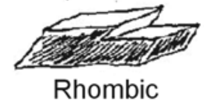
Cleavage

Cleavage describes the way a mineral breaks, and it can be very characteristic of certain specimens. The most common types of cleavage are flaky (as in mica), step-like (as in feldspar), cubic (as in halite, pyrite and galena), and rhombic (as in calcite). These are shown below. Some minerals have no cleavage, but they break in characteristic patterns (*fracture*). Quartz has conchoidal fracture, which is exactly like thick window glass that has been chipped.


Flaky


Cubic


Step-like


Rhombic

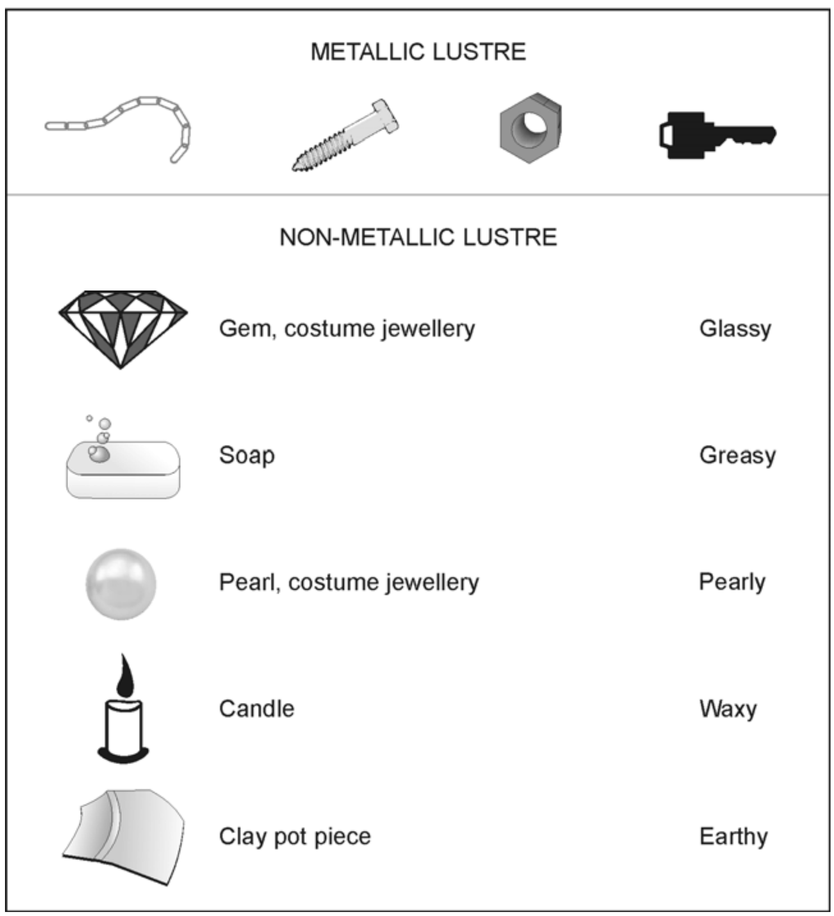
Readily available classroom materials can be used to demonstrate cleavage. For example, fridge magnets stuck together illustrate flaky cleavage. Stacking cubes put together are a perfect example of cubic cleavage. Diamond-shaped attribute blocks can be built up to show rhombic cleavage.

Lustre

Lustre is the way a mineral appears to reflect light. There are two main categories: metallic and non-metallic. The lustre of non-metallic minerals can be further differentiated into glassy (quartz), greasy (graphite), pearly (feldspar), waxy (talc) or earthy (hematite). Common examples of minerals with metallic lustre are galena and pyrite. It is a good idea to have a sample set of lustres so that students can compare their specimens to it (see chart for examples).

Sources for lustre examples: Bead or craft shops are ideal places to find pearly or glassy lustres. Earthy lustre could be a piece of natural clay pottery. Waxy could be paraffin. Greasy could be a piece of plastic container or soap. Different metallic lustres could be coins, bolts, paper clips, etc.

LUSTRE CHART



Hardness

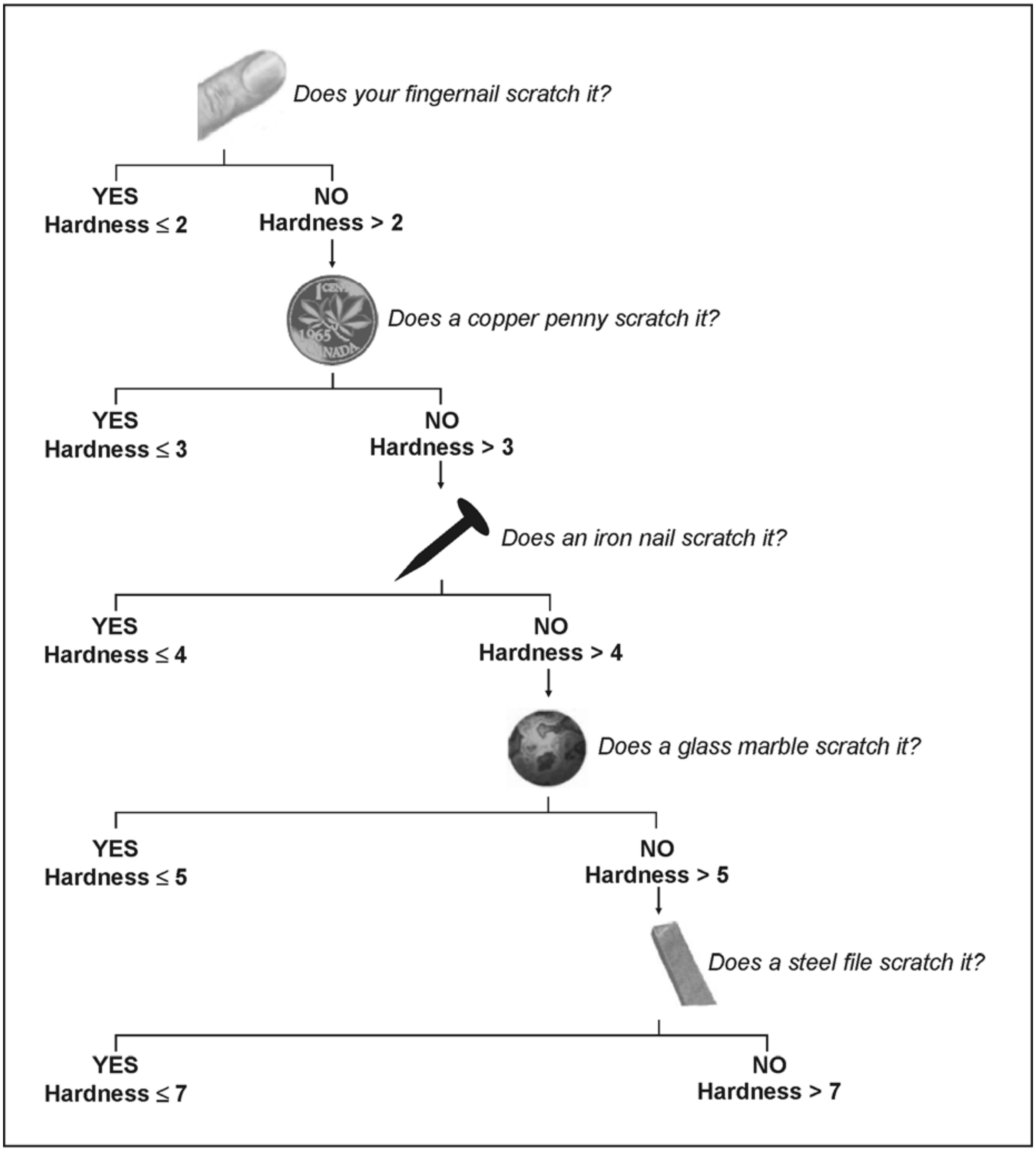
Minerals differ in hardness depending on their atomic structure. In the early 1800s, a German mineralogist named Friedrich Mohs developed a 10-point scale of hardness that is still being used by Earth scientists today. This test is based on the premise that a mineral will scratch itself and any softer object. On the scale from 1 to 10, 1 is the softest and 10 is the hardest. Diamond has a hardness of 10, and is the hardest known material at this time.

The scale below includes hardness, an example of a mineral having that hardness, and a material that you can use to test that hardness. In order to determine the hardness of an unknown mineral, you would first try scratching it with your fingernail. If the mineral did not scratch, go to the next hardness up and try scratching it with a penny, and so until you are successful. The other table is an example of how you might have students work through the hardness test, and order their samples from softest to hardest.

HARDNESS CHART

HARDNESS	MINERAL	TEST MATERIAL
1	Talc	Soft pencil lead
2	Gypsum	Fingernail (2.5)
3	Calcite	Penny (3.5)
4	Fluorite	Iron nail (4.5)
5	Apatite	Glass (5.5)
6	Feldspar	Steel nail
7	Quartz	Steel file
8	Topaz	Sandpaper
9	Corundum	no common equivalent
10	Diamond	no common equivalent

HARDNESS TEST



≤ means less than or equal to
> means greater than

Note: You will not find many minerals with hardness greater than 7. These are more often gem-quality minerals such as topaz, emeralds and diamonds.

Crystal Shape

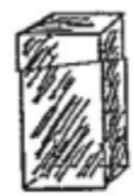
Many minerals have distinctive and beautiful crystal forms. These are visible as flat, clean surfaces on a mineral specimen. There are seven crystal systems but only four are commonly found. These are:

- Cubic (examples - galena, pyrite)
- Hexagonal (example - quartz)
- Tetragonal (example - zircon)
- Rhombic (example - calcite)

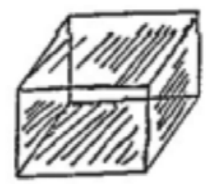
These crystal shapes are pictured below. Students should be able to describe the characteristics and differences of the common crystal systems, and to recognize the similarities between models and crystal shapes that they find. This is a good time to integrate the geometry strand from the math program.

cubic

hexagonal



tetragonal



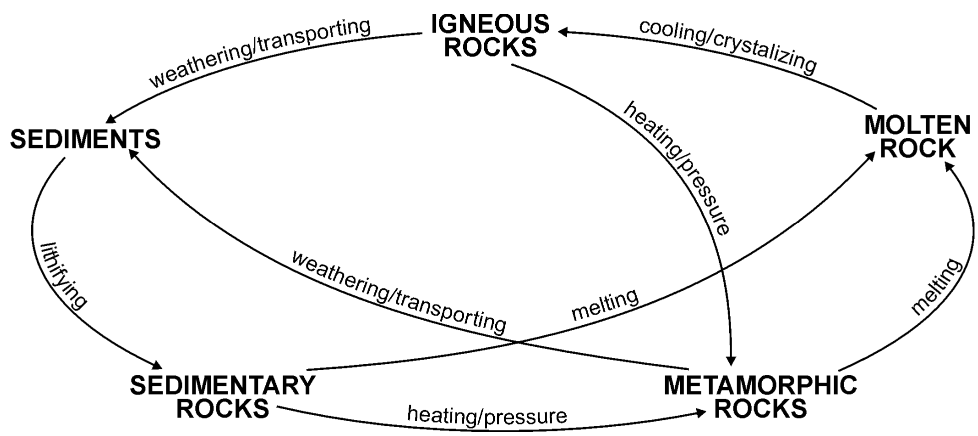
rhombic

THE ROCK CYCLE AND R0CK IDENTIFICATION

When we think of what makes up the Earth, rocks are the first things that come to mind. When we hike in the mountains, walk along a riverbed or sit on a beach, we see the rocks everywhere in our environment. Without realizing it, we automatically classify these rocks in our minds by observing particular features.

Rocks are made up of minerals, but they are not minerals themselves. Rocks usually have more than one mineral within them. The way that mineral grains are arranged in rocks is a good clue to their identification. Rocks can be grouped into three main types based on their origin. These are igneous, sedimentary and metamorphic. Characteristics that are easily observed in rocks, particularly the arrangement of mineral grains, help us classify rocks according to their type.

The Rock Cycle



The rock cycle refers to how rocks are constantly being recycled in much the same way as our garbage and waste is. When rocks break down as a result of erosion, the tiny pieces are carried off and are eventually buried again. If they are buried deeply enough, they will melt into magma, and will eventually become igneous rock. The rock cycle is an essential part of understanding rock classification and identification.

Rock Types

Igneous Rocks

These rocks are formed when melted rock (*magma*) deep inside the Earth cools and hardens. The word “igneous” means “formed by fire”. The principal igneous rock types are:

- GRANITE is the most common igneous rock type. It forms deep within the Earth and is coarse-grained. Usually, it is multicoloured (white, pink, grey, black). Granite is also the most common rock type on Earth, although most of it is buried and hidden from view.
- BASALT is the most common volcanic rock. It forms when lava erupts from volcanoes, cools and hardens quickly. It is usually black and fine-grained, and commonly exhibits flow patterns and evidence of gas bubbles.
- OBSIDIAN is another volcanic rock that cools extremely quickly when it erupts directly into water. It is so fine-grained that it looks like black glass. That is

because the crystals making up the rock cooled so quickly they did not have time to grow.
- PUMICE is a less common volcanic rock, but is very interesting because it is the only rock that floats. It forms when escaping gases cause lava to foam up and harden, making it extremely porous and lightweight.

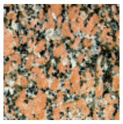
Sedimentary Rocks

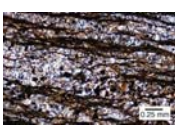
Sedimentary rocks are formed from eroded gravel, sand, mud and carbonaceous material that has been carried long distances by water or wind. These materials settle on the bottom of rivers, lakes and oceans. These loose sediments are deposited in thick piles that are slowly buried and harden as a result of pressure and chemical changes. They become sedimentary rock, of which there are five main types:
- CONGLOMERATE is formed when large, rounded pebbles (quartzite and feldspar) are carried by rivers, deposited, and cemented together by brownish sand or clay.
- SANDSTONE is formed when sand is carried by rivers or by wave action. After the sand is deposited and buried, it becomes hard as the grains get cemented together. Commonly, you see layers of different coloured grains in this rock. It feels much like sandpaper when rubbed.
- SHALE may be made from clay, mud, and/or silt carried by rivers and deposited. It is a soft, smooth rock that may appear layered.
- LIMESTONE is made of calcite from the skeletons and shells of millions of tiny sea creatures that “rain down” from above onto the sea floor. Usually, it is light in colour and may contain fossils. Because it is primarily calcium carbonate, it will fizz in acid (vinegar, lemon juice or dilute muriatic acid).
- COAL is a soft, black and lightweight rock made from ancient decomposed plant material.

Metamorphic Rocks

Metamorphic rocks were originally some other rock type (sedimentary, igneous or other metamorphic). Metamorphic means “changed in form”. When already existing rock is subjected to extreme temperature and pressure as a result of deep burial or mountain building stresses, its original character changes drastically. Mineral grains tend to flatten and become aligned, and new minerals may actually form due to chemical changes. Common types of metamorphic rocks are:
- QUARTZITE is a very hard, light-coloured rock formed when sandstone is subjected to tremendous heat and pressure. It is one of the hardest rocks known, and is completely crystalline, showing no indication of the original sand grains.
- SLATE is a dark-coloured, very fine-grained rock that was originally shale. It splits easily into very thin layers and may contain visible mica flakes. It is very hard and is often used for floor tiles.
- GNEISS (pronounced “nice”) or SCHIST is a medium- to coarse-grained rock that is variable in colour. It forms from shale, slate, sandstone or granite. Irregular or interlocked bands are often visible, and mica is a major component.
- MARBLE is a soft, smooth, variably coloured rock that forms from limestone that has been subjected to extreme heat and pressure. It may have intermixed colour bands. It will fizz in acid because its principal component is still calcium carbonate.

ROCK SPECIMEN INFORMATION SHEET

	ROCK NAME	DESCRIPTION	ORIGIN
IGNEOUS	Granite 	Granite is a combination of light and dark coloured minerals. Light minerals include quartz grains, white or pink feldspar and silvery muscovite. Dark minerals include biotite and hornblende. Granite is a coarse-grained rock with interlocking crystals randomly arranged.	An intrusive igneous rock that forms deep in the Earth's crust from cooling magma. The magma is usually silica (quartz) rich and the slow cooling produces large crystals that are visible without a microscope.
	Basalt 	Dark gray to black, made up of microscopic crystals, very hard, may contain evidence of gas bubbles (vesicular basalt).	Volcanic in origin, formed from magma that erupts from a volcano or a fissure as lava. Because it cools quickly, there was not enough time for grains to become large enough to see.
	Porphyritic Rhyolite 	Usually light coloured (gray, tan, reddish, greenish) with very large crystals scattered throughout a fine-grained matrix. It may show some evidence of gas bubbles or flow lines.	This started out as an intrusive rock as seen by the large crystals (phenocrysts). However, before more crystals could form, the magma was suddenly ejected out of a volcano or fissure so the matrix is microcrystalline and the rock is considered extrusive.
	Obsidian 	Glassy and usually black, although there make be white crystals that look like snowflakes (snowflake obsidian) or red swirls. Glass-like conchoidal fracture which looks like a ridged semicircle.	An extrusive volcanic rock formed by lava that erupts into cold water. It hardens so quickly that crystals have no time to form, thus the glassy texture.
	Pumice 	Very light gray to medium gray with lots of gas bubbles, giving it a sponge-like appearance. It is so lightweight it will float in water.	An extrusive igneous rock that comes from magma containing a great deal of trapped gas. This gas causes an explosive eruption, which results in a volcanic glass filled with air spaces when the magma suddenly cools.
SEDIMENTARY	Conglomerate 	Looks like a mixture of sand and different sizes of rounded pebbles. If the pebbles are angular, it is called breccia.	Sand and pebbles collect on river banks or shorelines. As more sediment piles on top, the underlying layers compact and are cemented by material (usually quartz or calcite) dissolved in water that seeps through them.
	Sandstone 	Can be nearly white to red or brown. Composed of grains that are mainly the same size, but size may vary slightly in layers. Can be fine-, medium- or coarse-grained. This is usually determined by the "feel" of the rock.	Resistant quartz sand grains are produced by weathering of other rocks such as granites. Deposited in a basin such as an ocean or a river, sediments are buried and compacted under the weight, and then cemented.

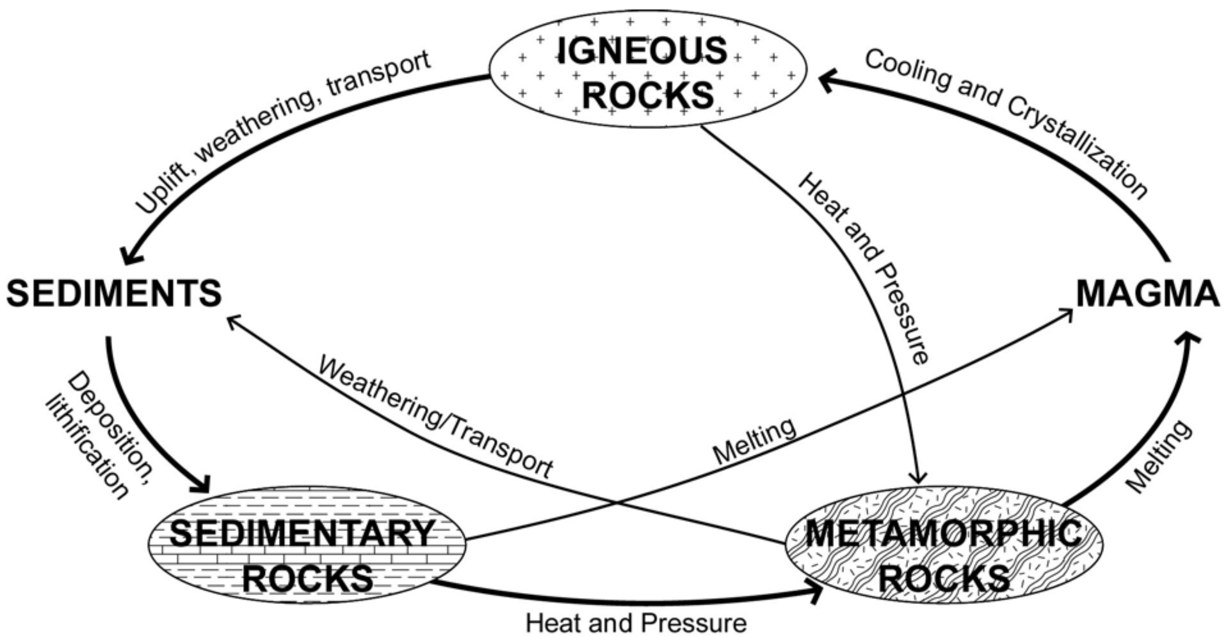
	Mudstone 	Colour may be tan, green, brown, gray, red or black, depending on the source of clay or mud. Massive and structure-less with no layers. It crumbles easily. Smells like wet mud when moistened. A weaker rock than shale.	Mud and clay particles accumulate in a basin such as a deep lake or ocean. If they are not buried deeply enough, they will become a very weak rock that crumbles into powder when weathered.
	Shale 	Colour may be tan, green, brown, gray, red or black. Particles are too small to be seen by the unaided eye but you can usually see evidence of layers. Shale is weak and breaks along layers. When moistened, shale usually smells like wet mud.	When clay sediments settle in deep, quiet water, they accumulate and can become deeply buried. If these layers are buried deeply enough, they will be compressed and converted into a soft rock called shale.
	Fossiliferous Limestone 	White, gray or tan, may be fine- or medium-grained but not crystalline. Fossils are commonly visible. Fizzes in dilute hydrochloric acid. [better to say muriatic acid, as in activities}	Formed in ocean water as a result of coral reefs being buried by mud or by lime mud being deposited on the sea floor. It is the product of calcareous organisms dying and raining down.
	Rock Salt 	Transparent to translucent, colourless to white, massive or cubic crystals, very soft (can be scratched by fingernail). Made up of the mineral halite.	Sometimes stretches of seawater become land-locked because of tectonic or climatic changes. As the water of an enclosed sea area evaporates, the result is a salt lake with a saline content higher than that of the ocean. Further evaporation leaves a large expanse of crystallized salt, which is buried by other sediment to become rock.
METAMORPHIC	Marble 	Usually white but may be streaked with other colours, fine- to coarse-grained crystals, fairly soft, fizzes in dilute hydrochloric acid.	Formed from limestone (parent rock) that has been subjected to extreme temperature and pressure.
	Phyllite 	Commonly silver or greenish. Shiny appearance depending on which direction it is seen from. This characteristic sheen often identifies phyllite. Corrugated appearance to layers. Very fine-grained.	The parent rock for phyllite is slate. As slate becomes more deeply buried underground and pressure and temperature continue to rise, chlorite and mica crystals recrystallize into larger crystals, which reflect light more easily than slate. Transitional between slate and schist.
	Schist 	Layered rock with abundant shiny mica crystals (small, flaky crystals). Layers are usually thin with interlayered mica and quartz. Layers may be somewhat wavy. May be medium- or coarse-grained. Usually split easily along layers of mica.	Schists are usually formed from shales (parent rock). Often sea floor shales that are exposed to tremendous pressure and temperature during tectonic activity such as subduction.

The Rock Cycle

When we think about what makes up Earth, rocks usually come to mind. We see them all around usas we hike in the mountains, walk along a stream or riverbed, visit the beach, or notice attractive building stone.

Rocks are made of minerals and generally have one or more mineral within them. The best indicator of a rock's identification is the way these mineral grains or crystals are arranged in the rock. Rocks are grouped into three types based on their origin: *igneous*, *sedimentary* and *metamorphic*. Characteristics that are easily observed in rocks, especially the arrangement of mineral grains, help us classify rocks.

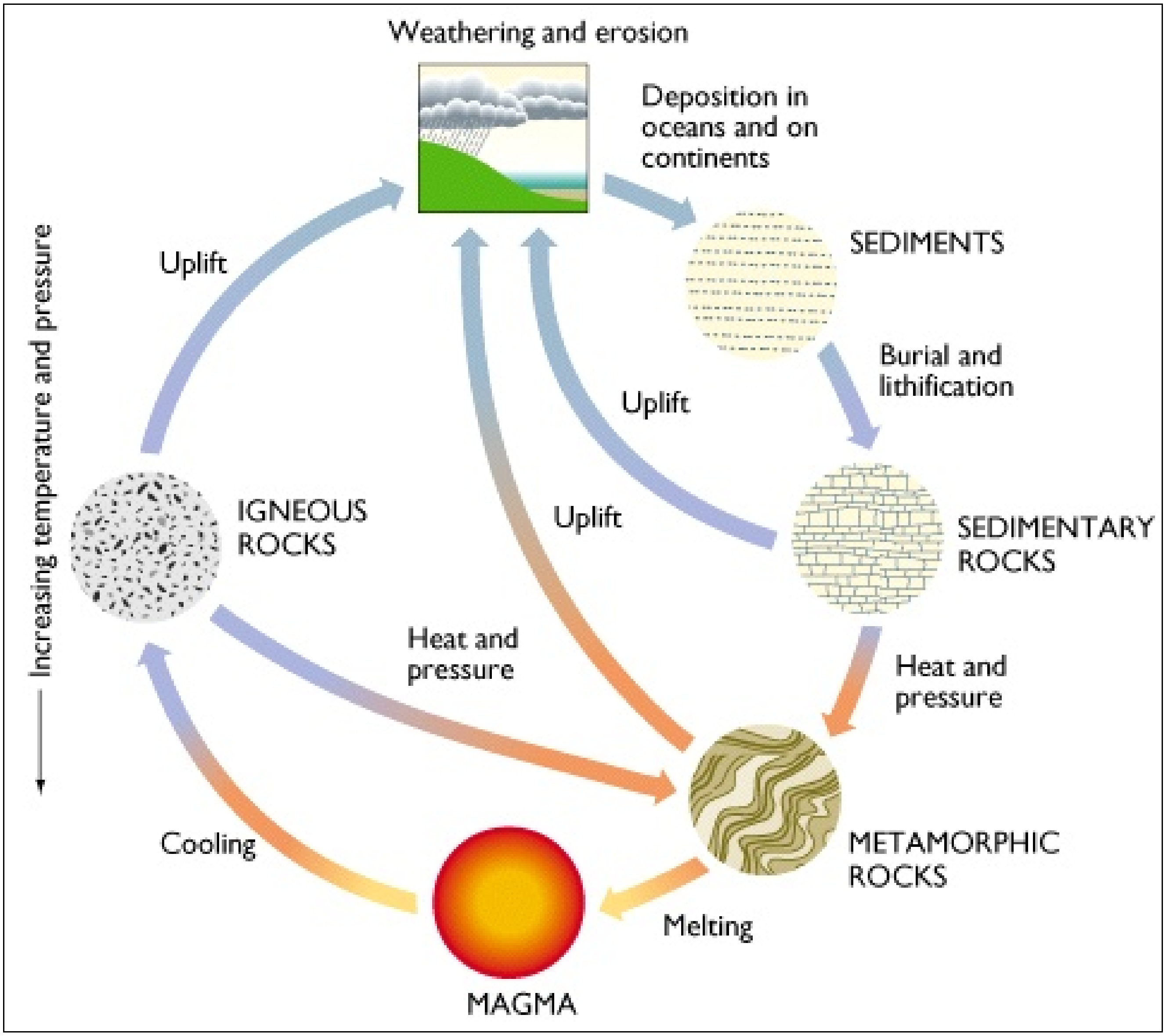
The Rock Cycle



The *rock cycle* describes how rocks pass from one form to another. A more accurate term might be the "Rock Recycle." Throughout geological time, any of the three rock types can be transformed into another in this ongoing cycle. Remember our Earth is dynamic, so the rocks you will hold in your hands today are not final products, but will ultimately transform into other rocks through time. The rock cycle is important for understanding rock classification and identification.

The outside path of the cycle shows us that *magma* (molten rock) forms igneous ("formed by fire") rocks, which then undergo uplift, weathering and transport to form sediments, which are carried away by various processes and deposited elsewhere and lithify into sedimentary ("settling") rocks. If these rocks are buried deeply enough, they transform into metamorphic ("changed") rocks that will melt into magma and be recycled into igneous rocks. The internal pathways show other transformations such as igneous rock becoming buried and transforming into a metamorphic rock.

THE ROCK CYCLE

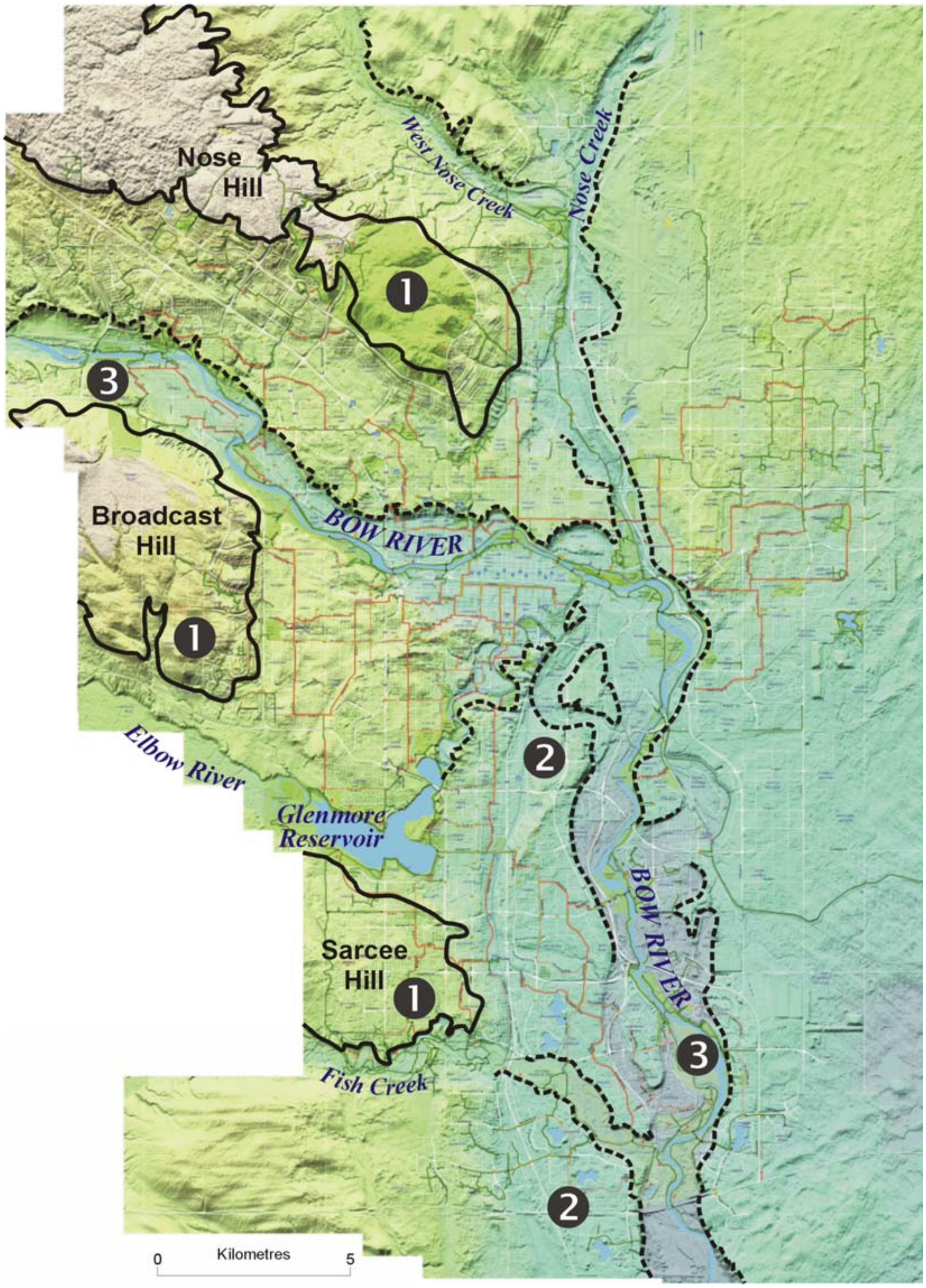


GEOLOGY IN THE CITY OF CALGARY

The City of Calgary was founded at the confluence of the Bow and Elbow rivers near the west edge of the Canadian plains. These plains slope gently northeastward, away from the Rocky Mountains. The undulating topography in the city has a relief of about 175 m. It is mainly the product of erosion by the rivers in Quaternary times (the last 1.6 million years) and generally reflects the underlying bedrock surface.

There are three main levels in the topography of Calgary:

1. The highest level consists of the mostly flat-topped uplands that have a bedrock core and comprise erosional remnants of old river plains. The bedrock is Paskapoo Sandstone of Paleocene age (early Tertiary), about 58-65 million years old. The upland areas are Nose Hill, Broadcast Hill and Sarcee Hill that rise to elevations of 1270 m, about 175 m above the Bow and Elbow river beds.
2. The middle level is an undulating plain that fills the space around and between the hills. The surface at this level is generally glacial till but may also contain river deposits related to streams. In northwest Calgary, this area is covered by hummocky moraine deposited by glaciers.
3. The lowest level consists of the river flood plains, which are in places up to 2 km wide and cut down about 35 m below the middle level. Downtown Calgary is situated on this level.



The map above shows the geography of the City of Calgary with the key topographic levels identified. The solid lines represent escarpments bordering bedrock-cored uplands (level 1, above). The dashed lines indicate distinct rims separating the intermediate topographic level from modern flood plain. Where the dashed lines are missing, the intermediate level slopes gradually down to river level. From Osborn and Rajewicz (1998).

Bedrock Geology

Outcrops of bedrock are rare in the Calgary area. Where they do occur, they generally consist of fine- to medium-grained sandstone and shale of early Tertiary (Paleocene) age. This bedrock was deposited by meandering rivers that were eroding the Rocky Mountains as they were being created during the period of mountain building known as the Laramide Orogeny. These rivers spread enormous amounts of sediment eastwards from the mountains during the Tertiary. The whole unit is about 600 m thick beneath Calgary, and is generally referred to as the Paskapoo Sandstone, although it has also been divided on a finer scale into the lower Paskapoo Formation (with volcanic rock fragments) and an upper Porcupine Hills Formation (with sedimentary rock fragments).

Outcrops occur in several places, notably the Edworthy ravine at Edworthy Park, the Spruce Cliff area downstream along the Bow River, the southwest slope of Nose Hill and the north shore of Glenmore Reservoir. Other less impressive outcrops occur along the Bow River at various places, such as Silver Springs. Locally, plant fossils and fossil clam shells are common within the sandstone. However, most of the bedrock is covered by unconsolidated sediments related to the latter stages of glaciation and associated river and lake deposits of Quaternary age.

The sandstone has been quarried over the years as building stone, most notably, following the devastating fire of November 7, 1886 that destroyed the wooden buildings in downtown Calgary. The old part of our city hall built in 1911 at 800 Macleod Trail East is a fine example of the use of local sandstone.

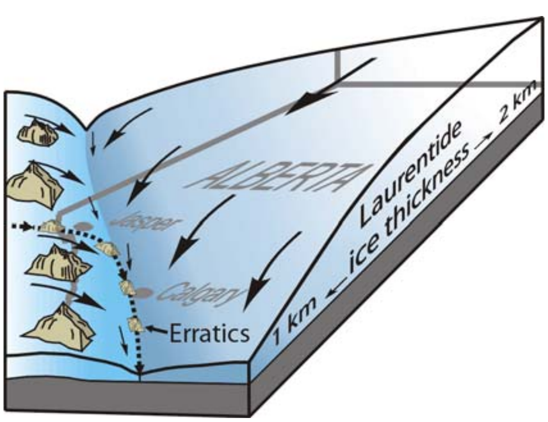
If a hole were drilled beneath Calgary, it would pass through more than 4000 m of sedimentary rocks before striking the crystalline, metamorphic and igneous rocks of the Precambrian.

Deposits of the Glacial Era

The unconsolidated sediments overlying the bedrock in the Calgary area vary greatly in thickness. They average about 10-15 m on the uplands and 0-80 m thick at the intermediate and lower levels. In general, three distinct layers are recognized:

Early to pre-glacial sediments
The lowest level is represented by bodies of gravel that lack any pebbles of crystalline rocks. These are generally thought to predate the main glaciation (because of the lack of pebbles from the Precambrian Shield) and may be of early Pleistocene age (about 1.6 million years old).

Glacial tills and river sediments



The next level is a complex body of tills (unsorted sediment deposited directly beneath glaciers) and deposits laid down by rivers. The story is complicated because the glaciers that deposited these sediments came from different directions. The largest ice sheet (Laurentide Ice) was moving material from the centre of the continent towards the margins. Smaller glaciers in the mountains (the remnants of which we can still see today - for a little while longer, anyway) extended out from the mountains and moved material from there. A third body of ice, the Athabasca Valley ice, has been suggested to have been moving from north to south through the region as well.

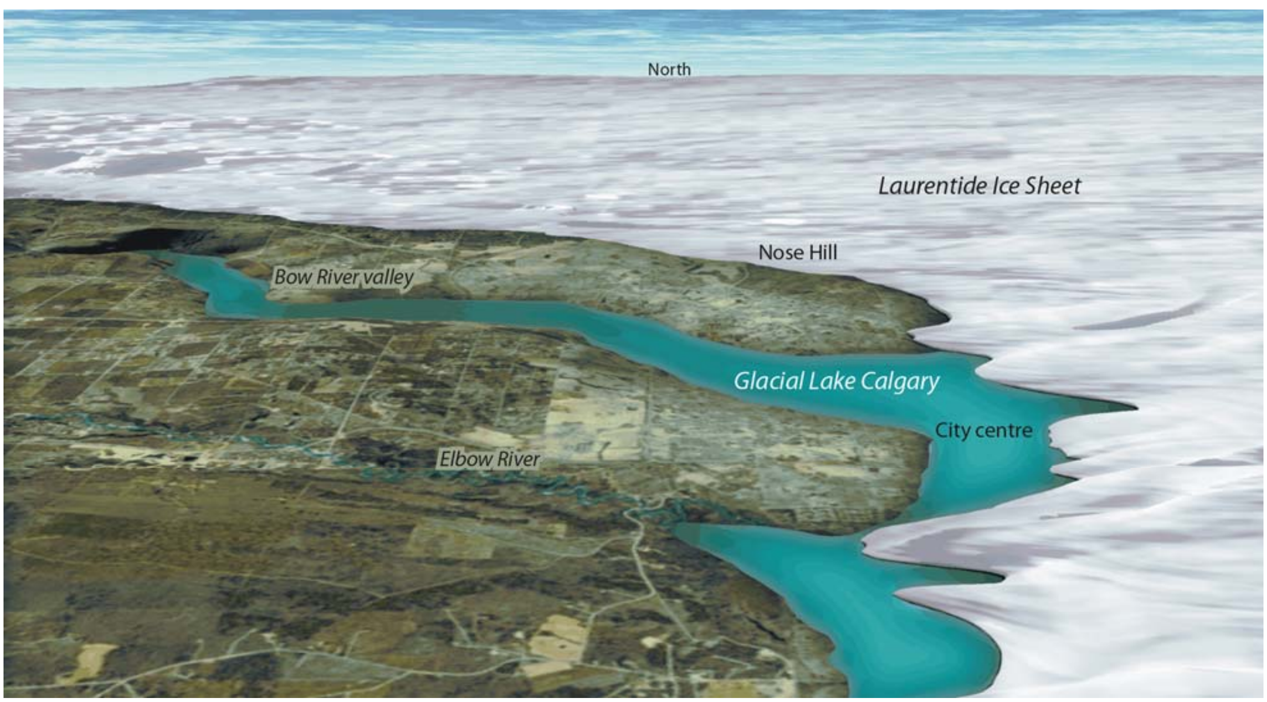
The three operating sanitary landfills in Calgary are based in these glacial deposits. The east Calgary and Shepard landfills are contained in finer-grained sediments, but the Spy Hill operation has many coarse deposits within it. As a result, liquid disposal is not permitted at the Spy Hill facility.

Glacial Lake Calgary Deposits

Finally, in central and northwest Calgary, there are lake deposits associated with an ice-dammed lake called Glacial Lake Calgary. This lake extended up the Bow Valley past the town of Cochrane, and its highest level is reckoned to have been 1220 m. The lake is thought to have existed until about 11 000 years ago.

The lake sediments are mainly silts but also include clay and fine sand. Locally there are pebbles, large blocks and/or lenses of gravel that were presumably rafted into the lake by surface ice. The overall texture of the sediments can change over relatively short distances.

Some of these silts cause significant problems for construction in Calgary and may also cause slope failures following heavy rainfalls. Many central and northwest structures are built on these sediments. However, large buildings like the Foothills Hospital and the University of Calgary facilities are built on piles that transfer the load of the building to the lower stable tills.



This image shows a hypothetical configuration of glacial lakes in the Calgary area. This is the concept of “Glacial Lake Calgary”.

In an excellent paper on the urban geology of Calgary, Osborn and Rajewicz (1998) explain the following incident at the time of construction of Banker's Hall downtown:

"One of the more serious problems caused by the silts to date occurred during the 1987 excavation for the foundation and basement parkade of Bankers Hall, a high-rise office building in downtown Calgary. Many borehole logs for downtown construction projects show bodies of silt, most likely lacustrine, between post-glacial alluvium and underlying till; such bodies, cohesionless and saturated, were encountered several metres below grade during the excavation. Running of silts through lagging boards of the shoring walls caused loss of ground underneath adjacent 9th Avenue, which is the major downtown artery. Silt fans formed in the excavation, a crack appeared in the street, a crane toppled and the shoring wall tilted a small amount. Work was halted while the excavation, and indeed the substructure of the building, was redesigned. Litigation followed the eventual late completion of the building."

The ability of these silts to flow when saturated also causes slope failures in Calgary. Most of these slope failures occur along the bluffs and headlands of the former lake and most move slowly. One can look upon most of these movements as a result of the quest for slope stability following the downcutting by the river, however, some have a decidedly human cause. It is thought that watering of lawns in areas adjacent to river bluffs is the main cause of slope failure, because it elevates the level of the natural water table.

There are several areas with slope stability problems, including the Spruce cliff area (with the very obvious scar of the Wildwood slide), slopes above the Elbow River in the Parkhill area, the slopes separating Crescent Heights from Sunnyside, and perhaps the most prominent at Home Road on the edge of Varsity Estates.

Deposits of the Post-Glacial Era

Volcanic deposits

One interesting deposit that caps much of the glacial sequence is the so-called Mazama tephra. This is the result of a massive volcanic explosion in southern Oregon that occurred about 6850 years ago and laid down a huge area of ash and volcanic debris over northwestern North America.

Formation of our present landscape
Following the glaciation and the release of Glacial Lake Calgary, the local rivers began cutting through the lake sediments and other deposits to form the landscape we know today.

Further reading:

Jackson, L.E. and Wilson, M.C. (Editors) 1987. Geology of the Calgary Area. Canadian Society of Petroleum Geologists.

Osborn, G. and Rajewicz, R. 1998. Urban geology of Calgary. *In* Urban Geology of Canadian Cities, P.F. Karrow and O.L. White (editors), Geological Association of Canada Special Paper42, p. 93-115.

Wilson, M.C. 1983. Once upon a river: Archeology and geology of the Bow River at Calgary, Alberta, Canada. Archeological Survey of Canada, National Museum of Man, Mercury Series, Paper 114, 464 p.

EVIDENCE FOR THE LAYERED STRUCTURE OF THE EARTH

The study of earthquakes is called seismology. It is conducted by studying both natural and artificially produced seismic waves. Natural seismic waves are produced by earthquakes and provide the best evidence for the internal structure of the earth. Artificial seismic waves are produced by the firing of explosives or by using a vibrating machine that produces vibrations of a known frequency.

The devices for recording seismic waves are called seismographs and the seismic information they record is used to study the structure of the Earth. Studies range from looking at the whole Earth to looking only in the thin crustal skin of the Earth, the latter being especially important in the search for oil and gas.

Studies of the whole Earth have produced a picture of its structure from inside to outside. The information comes from measuring the vibrations set off by naturally occurring earthquakes. Just like echoes coming back to you when you shout in a tunnel, the earthquake vibrations bounce back from layers in the Earth. From how long the echo takes to reach the seismograph on the surface we can calculate how far down in the Earth the layers are.

Different Kinds of Waves

Movements within the Earth that cause earthquakes usually happen suddenly because the pressure, which has been building slowly, releases suddenly and catastrophically. The centre of the movement or the point of origin of an earthquake is referred to as the focus, and the point on the surface directly above the focus is called the epicentre.

There are different types of waves produced: P-waves and S-waves move through the Earth; other waves (L-waves) travel at the Earth's surface.

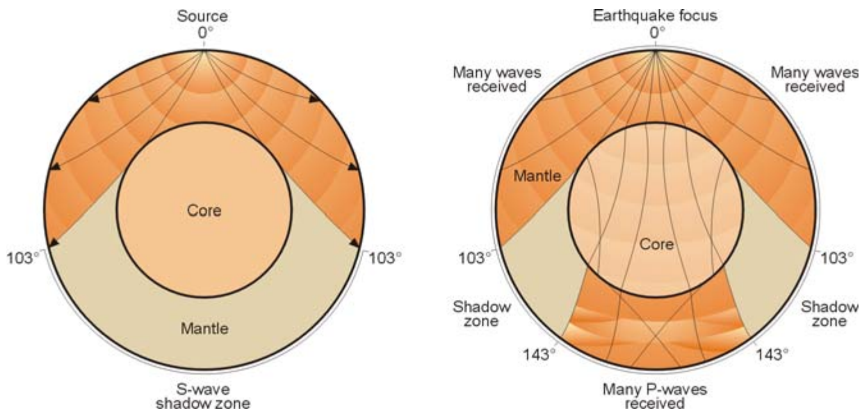
Fast-moving compression waves (P-waves) travel at thousands of kilometres per hour. They are the first to reach the Earth's surface and be recorded by seismographs. P-waves cause particles to move back and forth in the direction of the wave and, therefore, travel through all kinds of matter, including solids, liquids and gases.

Slower moving shear waves (S-waves) arrive later at seismographs. S-waves cause particles to vibrate from side to side at right angles to the direction that the wave is travelling. Because of this action, S-waves do not pass through liquids because molecules in liquid form slide past each other very easily and, therefore, do not transmit the wave.

The last waves to arrive at a seismograph are surface waves (Love waves and Rayleigh waves). These waves travel at the Earth's surface and cause most of the damages that result from earthquakes. Love waves have no vertical component and cause shearing action at the surface. Rayleigh waves produce both vertical and horizontal motions.

Waves and the Layered Structure of the Earth

It is the pattern of reception of P-waves and S-waves at seismographs around the world that has resulted in the knowledge of the layered structure of the Earth's interior. Since S-waves do not pass through liquids, it is possible to postulate that certain layers of the Earth are liquid, while others are solid.



In the first diagram you can see S-waves being deflected by the liquid core, creating a shadow zone in the southern hemisphere with an earthquake source at the North Pole. In the second diagram you can see the P-waves passing through the core directly to the southern hemisphere. The combination of deflection of the S-waves and penetration of the P-waves creates a shadow zone between 103º and 143º. It was this observation that led to an understanding of the layered structure of the Earth.

TOOLS FOR STUDYING EARTH'S INTERIOR

There are many ways of studying the Earth's interior. We can do it remotely by using inferences from geophysical methods, or we can do it directly by collecting rock samples from the Earth's interior.

Geophysical Methods

We have already noted how seismology has assisted us in understanding the overall structure of the Earth, but seismology is also used in much more focussed ways to look at particular parts of the Earth's crust. A commercial application of seismology is used in the search for oil and gas. Exploration companies routinely carry out such seismic surveys. A series of receivers, called geophones, are set out along the ground surface, and then a series of explosions or mechanical vibrations is used to produce waves that are reflected from the underlying rock layers.

The most common modern method of conducting a seismic survey on land uses special trucks to send vibrations of known frequency into the ground and collect the reflections. This method is more environmentally sound than detonating charges. In marine settings, air guns that use compressed air are a more environmentally sound approach than using explosives.

The data from seismic surveys are processed in powerful computers using software that enhances the preferred signals to get as clear an image as possible of the underlying strata. Data from a single line of geophones produces an image of a thin vertical slice of the strata. These days, it is more common for a company to conduct 3-D seismic surveys; that is, collect data from a series of geophone lines and try to create a three-dimensional image of the underlying strata. This is important, because layers significant to exploration commonly thin or thicken or change character, even over relatively short distances.

Excellent images of the sedimentary rocks in the topmost part of the crust are obtained using these methods as the underlying layers are usually clearly shown. Any faulting or folding that may have a strong bearing on the location of hydrocarbon deposits is also usually shown. However, geophysical methods only provide a remote view of the rock layers and are subject to interpretation by Earth scientists. If the exploration team likes what it sees in the seismic survey, the next step is to locate a place to drill so that the information inferred from the seismic survey can be confirmed through actual samples.

Sample Collecting

The principal way to get samples of rock from the Earth's interior is through drilling. A drilling rig is set up at the desired location and a drilling bit, usually equipped with diamonds (the hardest mineral), is rotated in the ground and gradually penetrates through the strata. In a normal drilling situation, small chips of the rocks that the drill passes through are returned to the surface for analysis. These are called cuttings, and Earth scientists study them to learn more about the physical characteristics of the rocks, their chemistry and their age. Significant physical characteristics are the porosity and permeability of the rocks. Porosity is the percentage of the volume of a rock that is occupied by spaces (pores), and this is obviously important for understanding whether the rock is likely to be able to hold fluids. Permeability is the capacity of the rock to transmit fluids.

If the Earth scientist thinks that more detailed knowledge of the properties or relationships of the rock layers is required while drilling the hole, then more continuous rock sampling or coring is carried out. In ideal circumstances these are continuous records of the rock that the drill bit passes through, but there are many factors that conspire to render core collection less than complete. Coring, however, adds considerably to the cost of the well, so it is only undertaken for good reasons.

Cores and cuttings from wells drilled for hydrocarbons are stored in government facilities in Canada, providing a comprehensive record of hundreds of thousands of wells that have been drilled in the past. These databases are often used to plan and execute new exploration programs. The storage and reference facilities for Alberta and the land north of 60 degrees latitude are located in Calgary.

Many different tests can be performed on the rock samples brought to surface during drilling operations. As mentioned previously, they can be studied for physical properties such as porosity and permeability. The details of the rock's structure can also be examined by making a thin section, which is a fragment of rock ground to less than a millimetre in thickness and then mounted between two glass slides. A thin section can be examined using a microscope, and can provide an amazing amount of detail.

Sometimes, samples of rock are processed for microfossils such as the remains of plants (spores and seeds), or the remains of tiny animals such as foraminifera or conodonts. In other cases, it is important to know the total organic carbon (TOC) content of a rock, which is determined by conducting organic geochemistry tests on a rock sample. Rocks with high TOC are important as potential sources of hydrocarbons.

Native stories about Cascadia Subduction Zone earthquakes

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Abstract:

Great earthquakes along the Cascadia Subduction Zone have been taking place for thousands of years. The most recent one (estimated magnitude 9) occurred on January 26, 1700. The exact date was determined from historic records of a tsunami that struck Japan, and confirmed by tree-ring studies of Pacific Northwest coastal trees killed when land level changes plunged their roots into tidal water.

A search of Native American myths, stories and traditions has revealed an abundance of accounts from Washington and Oregon that may be connected to Cascadia Subduction Zone earthquakes. The clearest account is a Quileute story that describes an epic battle along the coast between the Thunderbird and the Whale. During the struggle there is a “shaking, jumping up and trembling of the earth beneath, and a rolling up of the great waters” The story of the Thunderbird and Whale is also the central artistic theme of First Nations peoples on the west coast of Vancouver Island. Variations of the Thunderbird and/or Whale theme are found all along the coast of Washington and Oregon, and these stories often contain descriptions or metaphors consistent with strong ground shaking, permanent land level changes, tsunami, and aftershocks. Understanding these stories as metaphoric descriptions of actual events with profound environmental impacts opens a new window into the interpretation of Native American oral literature. The Native American use of Thunderbird and Whale as a metaphor for subduction zone earthquakes has striking similarities to earthquake myths from Japan and India, and to c. 1700 European scientific ideas on the causes of earthquakes.

THE BIRTH OF BIKING

Did you know that without mining the bicycle would never have been invented? In fact, without mining, none of the everyday products we take for granted would exist. If you look beneath the surface, you'll find that mining has something to do with everything.

ALUMINUM

BROMINE

CALCIUM

CARBON

CEMENT

CHROMIUM

CLAY

GRAVEL

IODINE

MAGNESIUM

MICA

MOLYBDENUM

SAND

STEEL

SULPHUR

TALC

TITANIUM

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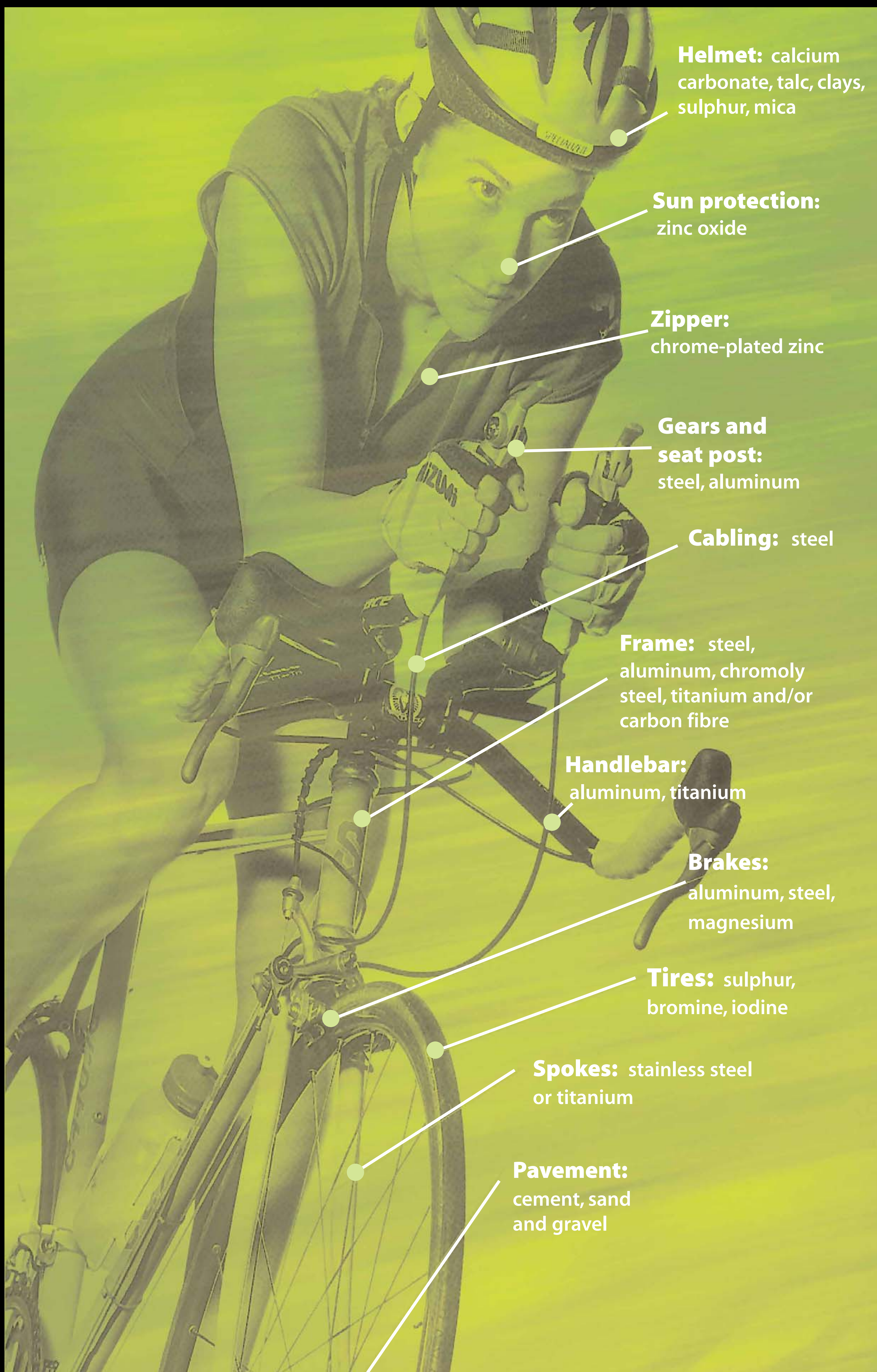

Mining Works for Canada

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THE GENESIS OF CYBERCHAT

Did you know that without mining your computer, telephone, and television wouldn't work? Look beneath the surface. You'll find that mining has something to do with everything.

ALUMINUM
BARIUM
BORON
CADMIUM
CALCIUM
CHROMIUM
CLAY
COBALT
COPPER
FELDSPAR
GERMANIUM
GOLD
INDIUM
LEAD
LIMESTONE
LITHIUM
MICA
NICKEL
PHOSPHOROUS
SILICON
SILVER
SODA ASH
STEEL
STRONTIUM
SULPHUR
TALC
TANTALUM
TIN
TITANIUM
TUNGSTEN
ZINC

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Did you know that without mining the music industry couldn't exist? Mining plays a larger role in our lives than most people realize. In fact, everything harvested, manufactured or transported requires minerals that come from mining. Look beneath the surface. You'll find that mining has something to do with everything.

ALUMINUM

AZURITE

BORAX

BRASS

CARBON

CHROMIUM

COBALT

COPPER

IRON

KAOLIN

MICA

NICKEL

QUARTZ

SILICA

SILVER

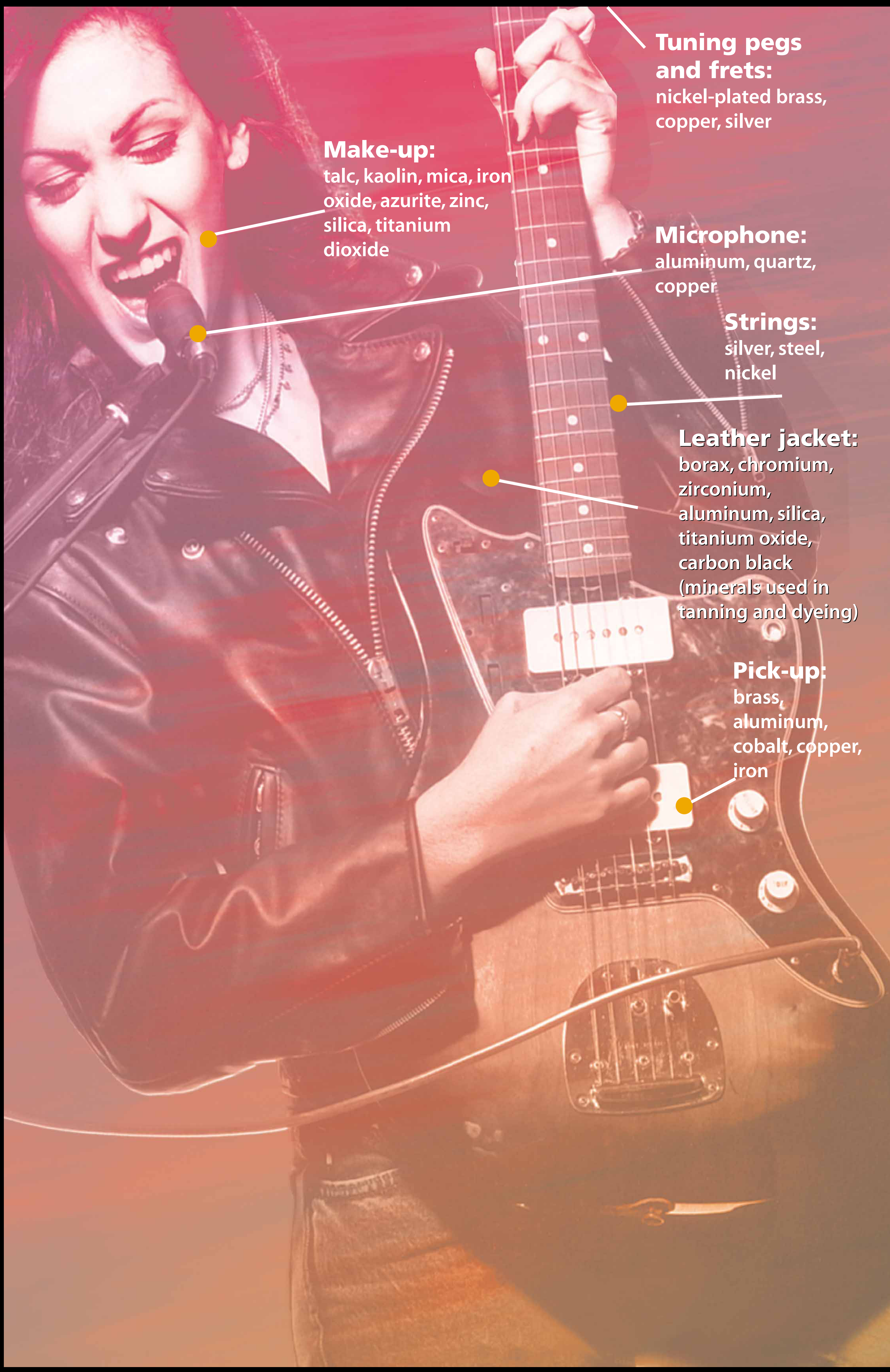
STEEL

TALC

TITANIUM

ZINC

ZIRCONIUM



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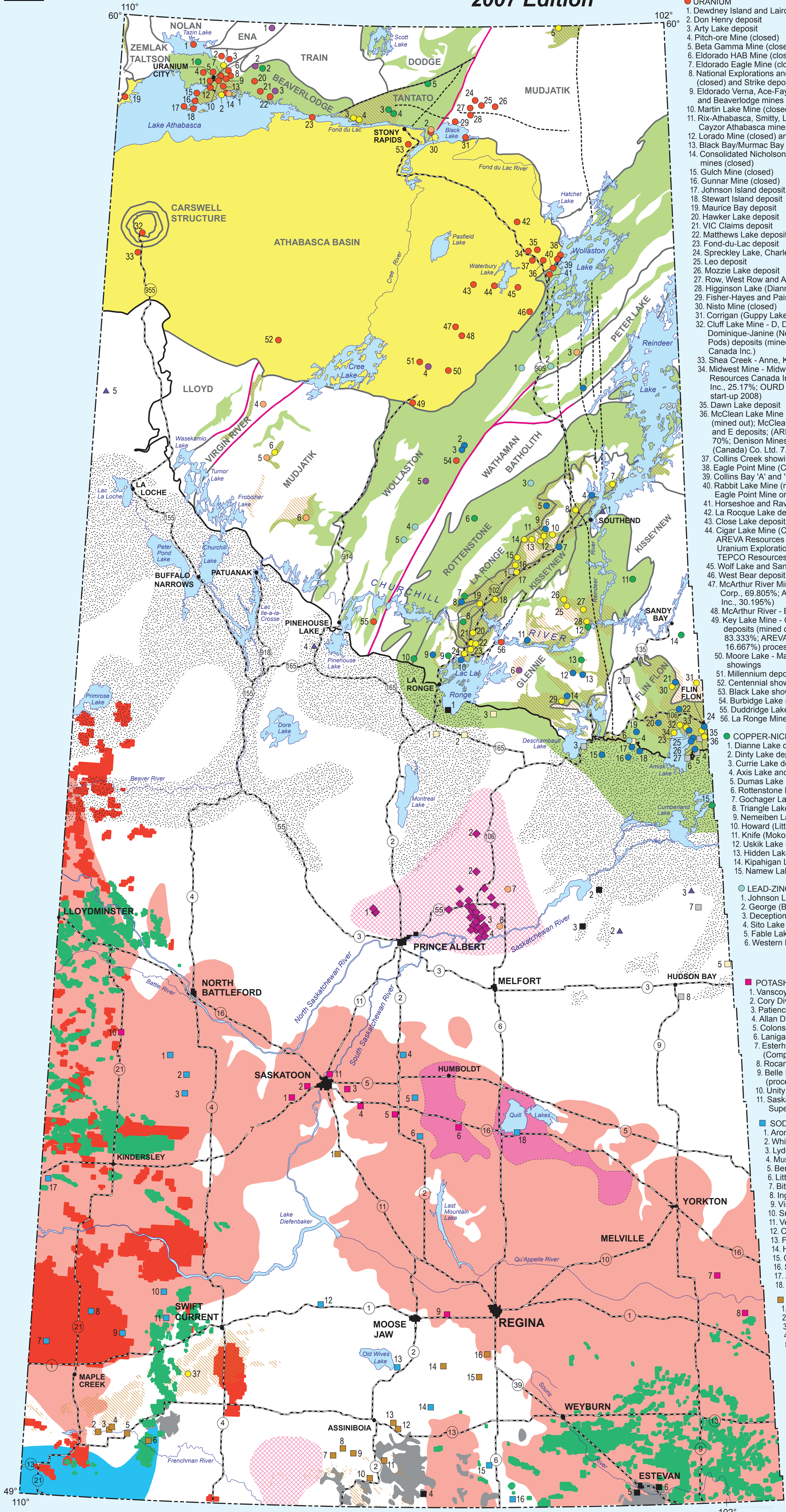
Also available at: http://www.ir.gov.sk.ca/resourcemap

Saskatchewan Industry and Resources

MINERAL RESOURCE MAP OF SASKATCHEWAN

2007 Edition



KEY TO NUMBERED MINERAL DEPOSITS†

URANIUM
1. Dewdney Island and Laird Island deposits
2. Don Henry deposit
3. Arty Lake deposit
4. Pitch-ore Mine (closed)
5. Beta Gamma Mine (closed)
6. Eldorado HAB Mine (closed) and Baska prospect
7. Eldorado Eagle Mine (closed) and ABC deposit
8. National Explorations and Eldorado Dubyna mines (closed) and Strike deposit
9. Eldorado Verna, Ace-Fay, Nesbitt Labine (Eagle-Ace) and Beaverlodge mines and Bolger Open Pit (closed)
10. Martin Lake Mine (closed)
11. Rix-Athabasca, Smitty, Leonard, Cinch Lake and Cayzor Athabasca mines (closed); St. Michael deposit
12. Lorado Mine (closed) and Uranium Ridge deposit
13. Black Bay/Murmac Bay Mine (closed)
14. Consolidated Nicholson Bay and Fish Hook Bay mines (closed)
15. Gulch Mine (closed)
16. Gunnar Mine (closed)
17. Johnson Island deposit
18. Stewart Island deposit
19. Maurice Bay deposit
20. Hawker Lake deposit
21. VIC Claims deposit
22. Matthews Lake deposit
23. Fond-du-Lac deposit
24. Spreckley Lake, Charlebois Lake and David deposits
25. Leo deposit
26. Mozzie Lake deposit
27. Row, West Row and ART deposits
28. Higginson Lake (Dianne) deposit
29. Fisher-Hayes and Paisley Lake deposits
30. Nisto Mine (closed)
31. Corrigan (Guppy Lake) deposit
32. Cluff Lake Mine - D, Dominique-Peter, Claude and Dominique-Janine (North, EX OP, UG and EX Pods) deposits (mined out, AREVA Resources Canada Inc.)
33. Shea Creek - Anne, Kianna and Colette deposits
34. Midwest Mine - Midwest and Mae deposits (AREVA Resources Canada Inc., 69.16%; Denison Mines Inc., 25.17%; OURD [Canada] Co. Ltd., 5.67%; start-up 2008)
35. Dawn Lake deposit
36. McClean Lake Mine - JEB, Sue A and C deposits (mined out); McClean Lake, Caribou Lake, Sue B and E deposits; (AREVA Resources Canada Inc., 70%; Denison Mines Inc., 22.5%; OURD (Canada) Co. Ltd. 7.5%)
37. Collins Creek showing
38. Eagle Point Mine (Cameco Corp.)
39. Collins Bay 'A' and 'B' Zone deposits (mined out)
40. Rabbit Lake Mine (mined out); mill processing Eagle Point Mine ore
41. Horseshoe and Raven deposits
42. La Rocque Lake deposit
43. Close Lake deposit
44. Cigar Lake Mine (Cameco Corp., 50.025%; AREVA Resources Canada Inc., 37.1%; Idemitsu Uranium Exploration Canada Ltd., 7.875%; TEPCO Resources Inc., 5%; start-up 2007)
45. Wolf Lake and Sand Lake deposits
46. West Bear deposit
47. McArthur River Mine (P2 Zone deposit; Cameco Corp., 69.805%; AREVA Resources Canada Inc., 30.195%)
48. McArthur River - BJ Zone deposit
49. Key Lake Mine - Gaertner and Deilmann deposits (mined out); mill (Cameco Corp., 83.333%; AREVA Resources Canada Inc., 16.667%) processing McArthur River Mine ore
50. Moore Lake - Maverick deposit; 525 and 527 showings
51. Millennium deposit
52. Centennial showing
53. Black Lake showing
54. Burbidge Lake (BURR) deposit
55. Duddridge Lake (Thor) deposit
56. La Ronge Mine (closed)

GOLD
1. Neeley Lake deposit
2. Box and Athona mines (closed) and deposits and Greenlee/Anderson deposit
3. ELA deposit
4. Camille Bay deposits
5. Nirdac Creek showing
6. Ithingo Lake deposit
7. Rosie and Narrow Lake showings
8. Fleming Lake showing
9. Twin Zone and Wedge Lake deposits
10. Golden Heart deposit and Weedy Lake showing
11. Komis Mine (closed) and EP deposit
12. Corner Lake (Augustus) deposit and Oven Lake showing
13. Tower East and Memorial deposits
14. Niko deposit, Kaslo and Birch Crossing showings
15. Jojay deposit
16. Star Lake and Jolu mines (closed) and Rod, Mallard and Rush Zones (mined out)
17. Jasper Mine (closed); Fork Lakes, Tamar and Transom deposits
18. Greywacke deposit
19. Bingo deposit
20. North Lake deposit
21. Contact Lake (Bakos zone) Mine (closed)
22. Preview North and South, PAP A, B and C deposits
23. Sulphide Lake deposits
24. Lynx Lake (GEM) deposit
25. Seabee Mine (Claude Resources Inc.) and Boundary Zone deposit (ore milled at Seabee Mine) (Claude Resources Inc. and Currie Rose Resources)
26. Porky Lake deposits
27. Santoy Lake showings
28. Georges Lake showings
29. Brownell Lake showings
30. Manson Bay (Schotts Lake) deposit
31. Eccles Lake (Dolly) deposit
32. Graham Mine (closed) and deposit
33. Robinson Creek deposit
34. Prince Albert (Monarch) Mine (closed) and Laural Lake deposit
35. Newcor, Bootleg (Rio), and Henning-Maloney mines (closed)
36. Phantom Lake and McMillan mines
37. Simmie paleoplacer showing

COPPER-ZINC
1. Campbell River showings
2. Janice Lake showings
3. Jansem showings
4. Stackhouse Bay showing
5. Elephant Lake deposit
6. Discovery Lake deposits
7. Brabant Lake PEG/McKenzie deposit
8. Borys Lake deposit
9. Elizabeth Lake deposit
10. Anglo-Rouyn Mine (closed)
11. Pitching Lake deposit
12. SAD Zone (HBED Zone) deposit
13. Hook Lake (Gee Lake) deposit
14. Brownell Lake deposit
15. Bigstone Lake deposit
16. Miskat Lake deposit
17. McIlvenna Bay deposit
18. McDermott Lake (Balsam Zone) deposit
19. Ramsay (Quandt/Keputch) deposit
20. FON Zone deposit
21. Schotts Lake deposit
22. Otonadah Lake deposit
23. Black Prince showing
24. Flin Flon Mine (closed) and Callinan Mine (Hudson Bay Mining and Smelting Co. Ltd.)
25. Birch Lake and Flexar mines (closed)
26. Konuto Lake Mine (closed)
27. Coronation Mine (closed)

COPPER-NICKEL AND COPPER-COBALT
1. Dianne Lake deposit
2. Dinty Lake deposit
3. Currie Lake deposit
4. Axis Lake and Rea Lake deposits
5. Dumas Lake deposit
6. Rottenstone Mine (closed)
7. Gochager Lake deposit
8. Triangle Lake deposit
9. Nemeiben Lake (Dunlop) deposit
10. Howard (Little Clam) Lake deposit
11. Knife (Mokoman) Lake deposit
12. Uskik Lake deposit
13. Hidden Lake deposit
14. Kipahigan Lake deposit
15. Namew Lake Mine (closed) (in Manitoba)

IRON FORMATION
1. Fish Hook Bay showing
2. Triana deposit
3. Spence Lake showing
4. Nyberg Lake (VH) deposit
5. Ithingo Lake showing
6. Dot Lake showing
7. Kelsey Lake deposit
8. Choiceland deposit

RARE EARTH OCCURRENCES
1. Nisikkatch Lake - Hoidas Lake
2. Alces Lake
3. Archie Lake (+ uranium)
4. Maw Zone (+ uranium)
5. Kulyk Lake (+ uranium)
6. Jahala Lake (+ uranium)

LEAD-ZINC
1. Johnson Lake (Marina) showing
2. George (Brakewell) Lake deposit
3. Deception Lake showing
4. Sito Lake deposits
5. Fable Lake showing
6. Western Nuclear Mine (closed)

KIMBERLITE OCCURRENCES
1. Sturgeon Lake
2. Candle Lake
3. Fort à la Corne kimberlite field
4. Star Kimberlite

MISCELLANEOUS OCCURRENCES
1. Deep Bay graphite deposit
2. Pasquia Hills oil shale deposit
3. Bainbridge River nodular manganese deposit
4. Pinehouse limestone deposit
5. Axe Lake oil sand deposit

POTASH AND SALT
1. Vanscoy potash mine and salt plant (Agrium Inc.)
2. Cory Division potash mine (Potash Corp. of Sask. Inc.) (by-product $CaCl_2$ brine)
3. Patience Lake Division potash solution mine (Potash Corp. of Sask. Inc.)
4. Allan Division potash mine (Potash Corp. of Sask. Inc.)
5. Colonsay potash mine (The Mosaic Company)
6. Lanigan Division potash mine (Potash Corp. of Sask. Inc.)
7. Esterhazy K-1 and K-2 potash mines (The Mosaic Company) and salt plant (Compass Minerals International)
8. Rocanville Division potash mine and salt plant (Potash Corp. of Sask. Inc.)
9. Belle Plaine potash solution mine (The Mosaic Company) and fine salt plant (processes waste salt from potash mine) (Mosaic Canada ULC)
10. Unity solution salt mine and plant (Sifto Canada Inc.)
11. Saskatoon chloride-based chemical plant (ERCO Worldwide, a Division of Superior Plus Inc.)

SODIUM SULPHATE AND POTASSIUM SULPHATE
1. Aroma Lake sodium sulphate deposit
2. Whiteshore Lake (Palo) sodium sulphate plant (Millar Western Industries Ltd.)
3. Lydden Lake sodium sulphate deposit
4. Muskiki Lake sodium sulphate deposit
5. Berry Lake sodium sulphate deposit
6. Little Manitou Lake sodium sulphate deposit
7. Bitter Lake sodium sulphate deposit
8. Ingebrigt Lake sodium sulphate plant (closed)
9. Vincent Lake sodium sulphate deposit
10. Snakehole Lake sodium sulphate plant (closed)
11. Verlo East sodium sulphate deposit
12. Chaplin Lake sodium sulphate plant (Saskatchewan Minerals)
13. Frederick Lake (Bishopric) sodium sulphate plant (closed)
14. Horseshoe (Shoe) Lake sodium sulphate plant (closed)
15. Ceylon Lake (Salt Lake) sodium sulphate deposit
16. Sybouts East (East Coteau Lake) sodium sulphate plant (closed)
17. Alsask Lake potassium sulphate plant (closed)
18. Big Quill Lake potassium sulphate plant (Big Quill Resources Inc.)

CLAY RESOURCES
1. Saskatoon clay quarry and plant (Cindercrete Products Ltd.)
2. Ravenscrag clay quarry (brick) (I-XL Industries Ltd.)
3. PR-1 clay deposit (stoneware)
4. PR-3 clay deposit (stoneware)
5. Eastend clay deposit
6. Frenchman clay prospect
7. Wood Mountain - Fir Mountain kaolin prospect
8. Flintoft clay pit (refractory and ball clay) (closed)
9. Gollier Creek kaolin deposit (Whitemud Resources)
10. Rockglen clay pit (brick clay)
11. St. Victor bentonite deposit (swelling bentonite)
12. Readlyn ball clay deposit
13. Willows clay pit (refractory and ball clay)
14. A.P. Green Claybank brick plant (closed)
15. Truax bentonite quarry (stoneware) (Canadian Clay Products Inc.)
16. Wilcox bentonite plant (Canadian Clay Products Inc.)

COAL AND PEAT
1. Lac La Ronge lignite (sub-bituminous) deposit
2. Carrot River Peat Moss Mine (Premier Sask. Inc.)
3. Carrot River peat moss plant (Premier Sask. Inc.)
4. Poplar River Coal Mine (Prairie Mines)
5. Boundary Dam (Shand, Costello, and Utility) Coal Mine (Prairie Mines)
6. Bienfait Coal Mine (Prairie Mines)

BUILDING MATERIALS
1. Neyrink Lake black and grey granite (diorite) building stone
2. Sahli green granite building stone
3. Deschambault marble (dolomite) quarry (Graham Construction and Engineering (1985) Ltd.)
4. Mystic Lake "Verde Antique" marble (veined amphibolite) building stone
5. McNally Lake buckskin marble (dolomite) building stone
6. Amisk Lake red marble (dolomite) building stone
7. Waskwei River cement rock deposit
8. Hudson Bay cement rock deposit

SILICA SAND
1. Bow River silica sand deposit
2. Nipekamew River silica sand deposit
3. Wappawekka Lake silica sand deposit
4. Hanson Lake silica sand quarry (Winn Bay Sand)
5. Red Deer River silica sand deposit

LEGEND
- Uranium potential
- Base metal potential
- Gold potential
- Diamond potential
- Major peat resource potential
- Carbon dioxide (CO_2) resource potential
- Oil pools
- Gas pools
- Coal fields
- Potash and salt resource areas
- Carnallitic regions (magnesium)

SYMBOLS
- Edge of Precambrian Shield
- Precambrian domain boundaries and names
- Major bounding shear zones
- Major faults
- Roads
- Cities
- Towns

SCALE
25 0 25 50 75 Kilometres
25 0 25 50 Miles

† Mine = Past, present, and test producing mines
Deposit = Deposits (calculated reserves - resources not 43-101 compliant in all cases) and developed prospects (drilling delineated mineralization)
Showing = Mineral occurrence with assays

This map was produced in 2007 and is available from:
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Publications Office
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Regina, SK Canada S4P 2H9
Tel: (306) 787-2528 E-mail: publications@ir.gov.sk.ca

Potash in Saskatchewan
Saskatchewan is the world's largest producer of potash!

What is Potash?

- **Potash** is a general term for any potassium (K) bearing salt. In Saskatchewan the two most common potash minerals are **sylvite** (KCl) and **carnallite** ($KCl.MgCl_2.6H_20$). Typical potash ore is about two thirds common **halite** salt (NaCl), mixed with varying amounts of sylvite and/or **carnallite**, along with minerals such as **quartz**, **anhydrite**, **dolomite**, and **clay,** which are insoluble during the potash refining process.

Did you know?

- That the pinkish red colour that most people associate with potash (Fig. 1) is actually caused by iron staining.

Figure 1. Photo of raw potash ore and different processed materials (K_2O).

- Most potash mines target the ore richest in sylvite, because sylvite is the mineral with the highest potassium content. The mines extract the potassium and sell the nutrient (K_2O) product, which varies in particle size and potassium purity (Fig. 1).

Where did the potash come from?

- Around 390 million years ago, during the **Middle Devonian** age, the southern half of Saskatchewan was covered by a shallow inland sea that stretched from the Northwest Territories to the middle of Southern Manitoba, and into northern Montana and North Dakota (Fig. 2). The flow of ocean water became restricted by a barrier in the Northwest Territories, and this, combined with a hot, arid climate**,** caused the sea to evaporate and shrink, and eventually conditions became right for potassium (K) and sodium (Na) salts to precipitate out. Deposits that form through evaporation are called **evaporites**.

Figure 2. Map showing the location of areas of preserved anhydrite, halite and potash deposits that formed in the Middle Devonian inland sea.

- The potash deposits of Saskatchewan can be divided in 4 main **stratigraphic layers.** The Esterhazy, White Bear, Belle Plaine and Patience Lake Members range from 6-15 m in thickness with each member having one or more zones of concentrated potash ore 1-7 m thick. Each of the members was named for the area at which it was first mined, except for the White Bear Member, which is not currently mined.

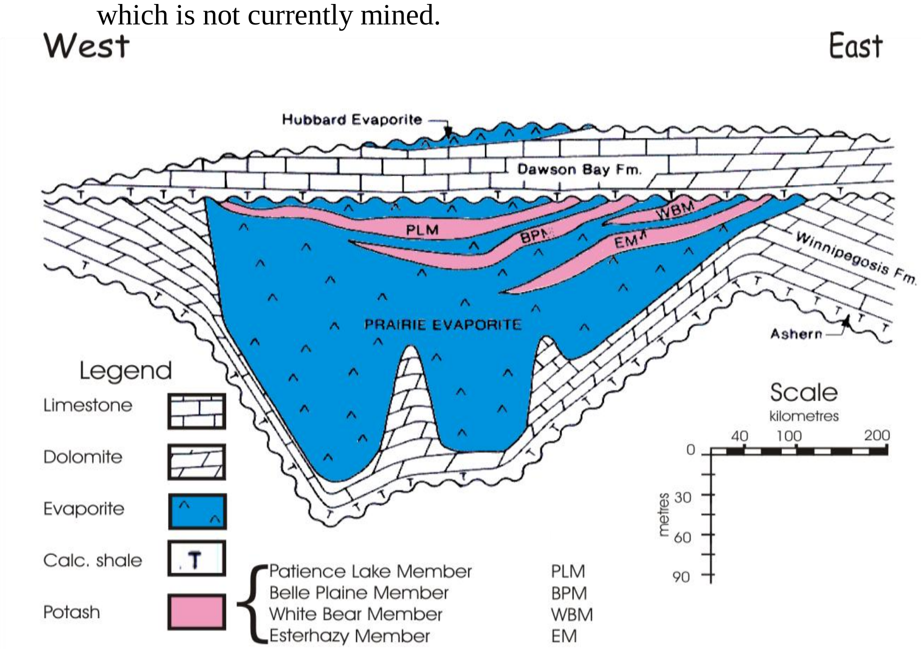

Figure 3. Cross section of the rock layers of Southern Saskatchewan (Fuzesy, 1982).

How Much Potash is in Saskatchewan?

- Saskatchewan's potash deposits are massive and stretch across most of the southern half of the province. It is estimated that there is over 100 billion tonnes of potash that could be extracted by conventional and **solution mining** techniques. At the current rate of consumption, that's enough potash to supply the world for over 2000 years.

What are the socio-economic benefits of potash mining in Saskatchewan?

- The potash industry is a major employer in the province. In 2005, the industry employed over 3,700 workers either directly or through contractors. That means that 6 out of every 10 workers in Saskatchewan's mining sector, works in potash. In 2005, potash workers received $358 million in wages and benefits.
- In terms of volume, potash is the third most important commodity for Canada's railways after coal and wheat. In 2005 potash production filled more than 140,000 train cars. This is equivalent to more than three full trains every day.

Scientific/technical terms

The following definitions can be found at http://www.earthnet-geonet.ca/glossary/

Sylvite (KCl)	Quartz
Halite (NaCl)	Clay
Anhydrite	Dolomite

Learn more about **evaporites** at:
http://seis.natsci.csulb.edu/bperry/Sedimentary%20Rocks%20Tour/evaporites.htm
More lots more information on minerals, including **carnellite** ($KCl.MgCl_2.6H_20$), explore:
http://www.galleries.com/minerals/
A few more interesting facts about **potash** can be found at:
http://www.thecanadianencyclopedia.com/index.cfm?PgNm=TCE&Params=A1ARTA0006428
Information on **solution mining** can be found at:
http://www.potashcorp.com/learn_about_fertilizer/about/processes/potassium/page_2.zsp
NOTE: Mosaic's Belle Plaine potash mine originated as a solution mine (potash deposits in that area are too deep to mine using conventional underground mining methods) whereas PCS' Patience Lake mine was converted from a conventional mine to a solution mining operation in 1988.
To explore the **Middle Devonian** (385 to 397 million years ago) go to:
http://www.ucmp.berkeley.edu/devonian/devonian.html

References:

Fuzesy, A. (1981): Potash in Saskatchewan; Saskatchewan Energy and Mines Report No.181, 44p.
Holter, M.E. (1969): The Middle Devonian Prairie Evaporite of Saskatchewan; Department of Mineral Resources-Geological Sciences Branch-Industrial Minerals Division-Province of Saskatchewan; Report No.123, 134p.

Other Sources:

Saskatchewan Mining Association Website:http://www.saskmining.ca/
Potash Corporation of Saskatchewan Website:http://www.potashcorp.com/
International Fertilizer Association Website:http://www.fertilizer.org/ifa/default.asp
Agrium Website:http://www.agrium.com
The Mosaic Company Website:http://www.mosaicco.com

DIAMONDS IN SASKATCHEWAN

History of Diamonds in Saskatchewan

- In 1948 Johnny Johnson claimed to have found 5 diamonds in the Prince Albert-Carrot River area. His claims were never verified because the diamonds were sent to South Africa for evaluation where they were said to have been lost in a fire.

- In the early 1960's Max Pellack, who had recently taken a prospectors' course in the Prince Albert Penitentiary, staked 30 claims over an area north of Prince Albert claiming that he had recovered 2 diamonds each about a quarter of an inch in diameter. Although no results were confirmed a large staking rush ensued.

- In 1988 the province's first **kimberlite** (rock type that hosts diamonds) was discovered at Sturgeon Lake. De Beers later abandoned the project when it was determined that the two kimberlites in the area were actually large pieces of **glacially transported** material from an unknown source, and were therefore not economic.

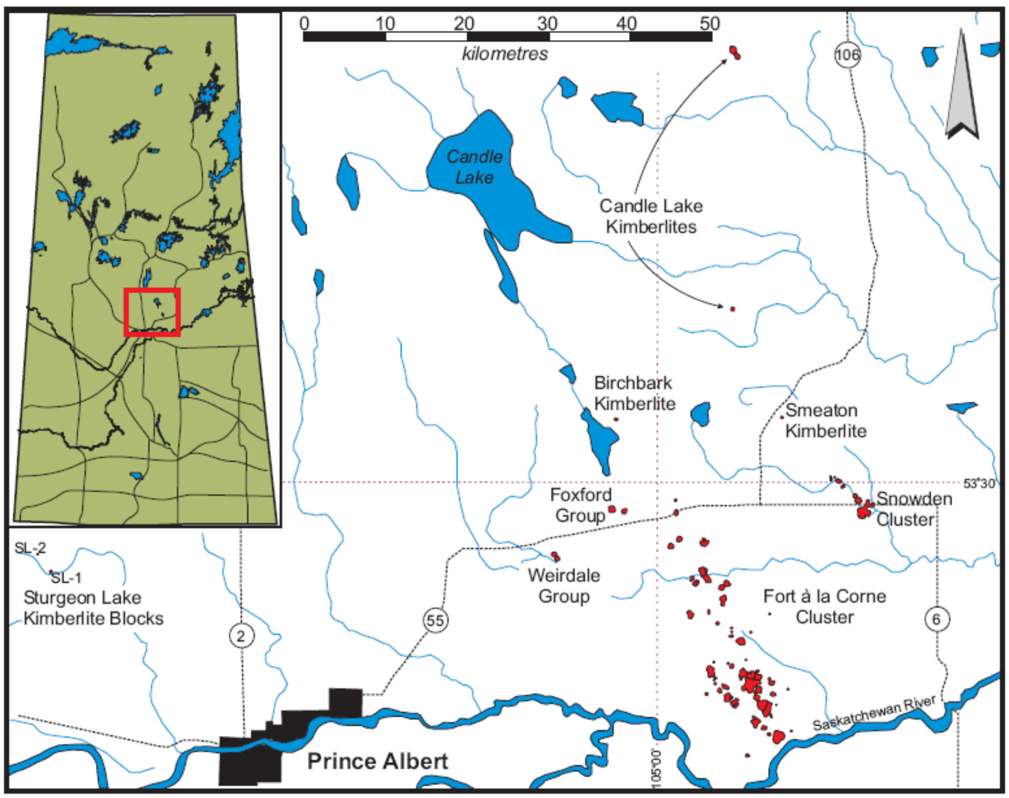

Figure 1: Central Saskatchewan kimberlite clusters, groups, and the ice-rafted (Scott-Smith, 1995a) Sturgeon Lake kimberlite blocks (kimberlites in red; paved highways as dashed black line).(Harvey et al., 2004)

- In the late 1980's Uranerz Exploration and Mining examined aeromagnetic maps produced by the Geological Survey of Canada, and located 11 circular **anomalies** in the Fort à la Corne (FalC) Provincial Forest.

- In 1989 the first in-situ kimberlite in the province was drilled, and over the next 7 years an additional 70 kimberlites were found in central Saskatchewan, making the area one of the largest kimberlite fields in the world (Figure 1).

Saskatchewan's Unique Kimberlites

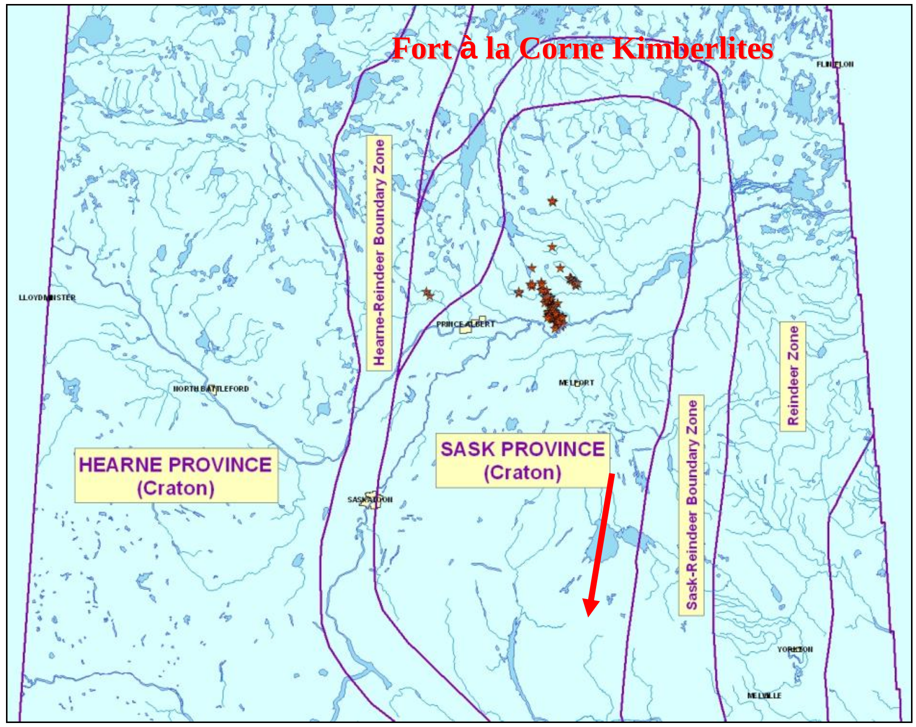

Figure 2: Saskatchewan craton and kimberlite occurrences (Simplified from: "Geology, and Min. & Petroleum Resources of SK, 2003)

- **Kimberlite** is a fragmental volcanic rock formed when magma generated deep in the mantle travels rapidly up and explosively erupts at the surface forming a volcanic cone of loose debris (**tephra**). As the magma moves up through the crust and mantle it entrains samples along the way, sometimes (but not always) including diamonds.
- The Saskatchewan kimberlites found to date are all located on the tectonically stable, Archean-aged, **Sask Province Craton**, which is one of three old **Archean cratons** that constitute Saskatchewan's **Precambrian Shield** (Rae Province, Hearne Province & Sask Province) (Figure 2).
- The FalC kimberlites erupted ~100 million years ago, along the margin of a **Cretaceous** seaway (Figures 3 & 4).
- It is this **depositional environment** that helps to make the FalC kimberlites unique in size, morphology and composition.
- The advancing sea helped to shape the kimberlites and successive seaway **transgressions** and **regressions** buried the large amounts of kimberlite in alternating layers of more or less unconsolidated sandstone and shale. Much later in Cenozoic times, these sediments also helped shield the kimberlites from the scouring effects of five glacial events, preserving the bulk of the crater facies material. This is a contrast to traditional kimberlite models and forms of preservation.

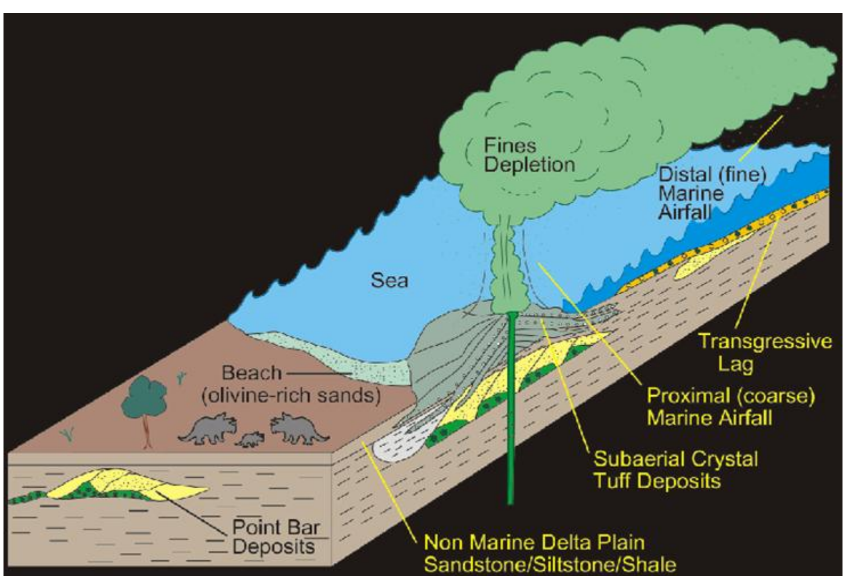

Figure 3: Example of a kimberlite depositional environment based on Leckie et al., 1997.

Figure 4: Locations of Seaways (Wikipedia: http://en.wikipedia).

- Most known kimberlites follow the traditional carrot-shaped kimberlite emplacement model (Figure 6). In this model the bulk of the pipe volume is comprised of the **root zone** and **diatreme facies**, with minor **crater facies**. Most of the pipes in other parts of Canada follow this model and few have crater facies material preserved.

- There are contrasting theories regarding Saskatchewan kimberlite emplacement models (Figure 6), but all agree that the unique sedimentary environment played a significant role in the preservation of the uniquely large amounts of the crater facies that are found.

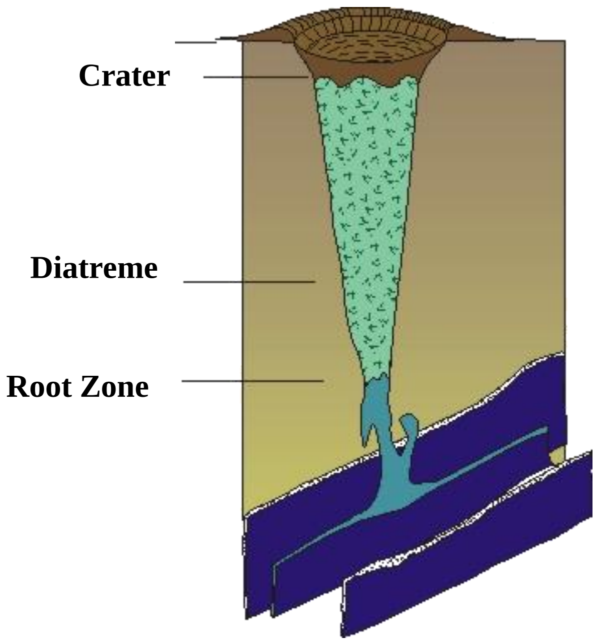

Figure 5: Traditional kimberlite model (adapted from Mitchell, 1986)

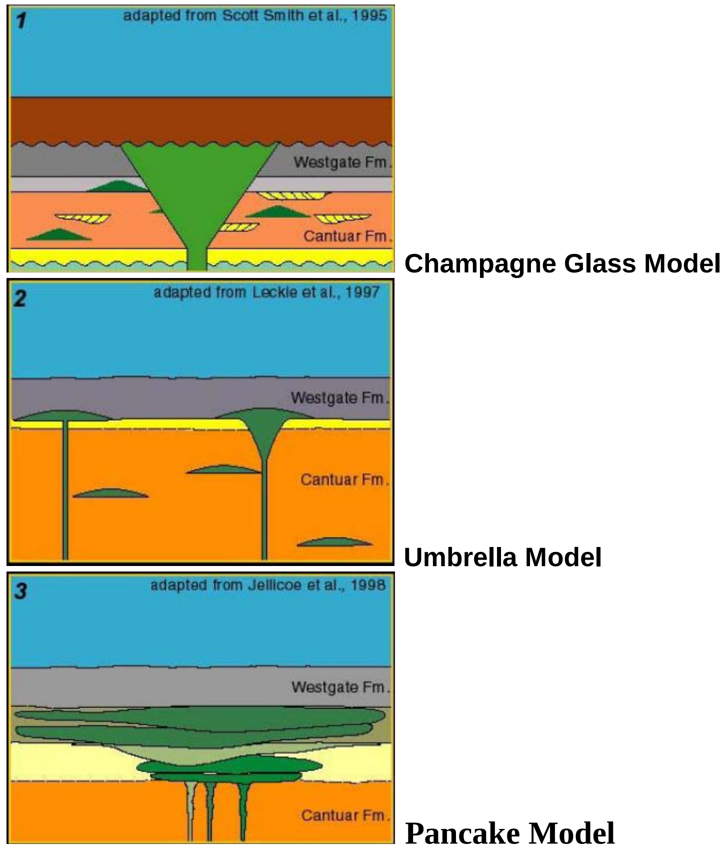

Figure 6: Various Saskatchewan kimberlite models (Adapted from: Zonneveld et al., 2002).

- It is believed that over a prolonged period of time the root zones became reactivated and acted as conduits for additional layers of kimberlite to intrude and deposit over each other (Figure 7). The result is that many of the FalC kimberlites comprise a series of overlapping kimberlite layers **interbedded** / **interstratified** with sedimentary rocks, such as marine shales, sandstones and **aeolian** deposits etc.(Figures 3 & 7).

- Zonneveld et al. (2004) proposed an emplacement model that explains how Saskatchewan's unique kimberlites came to be. Figure 7 details each step of this model.

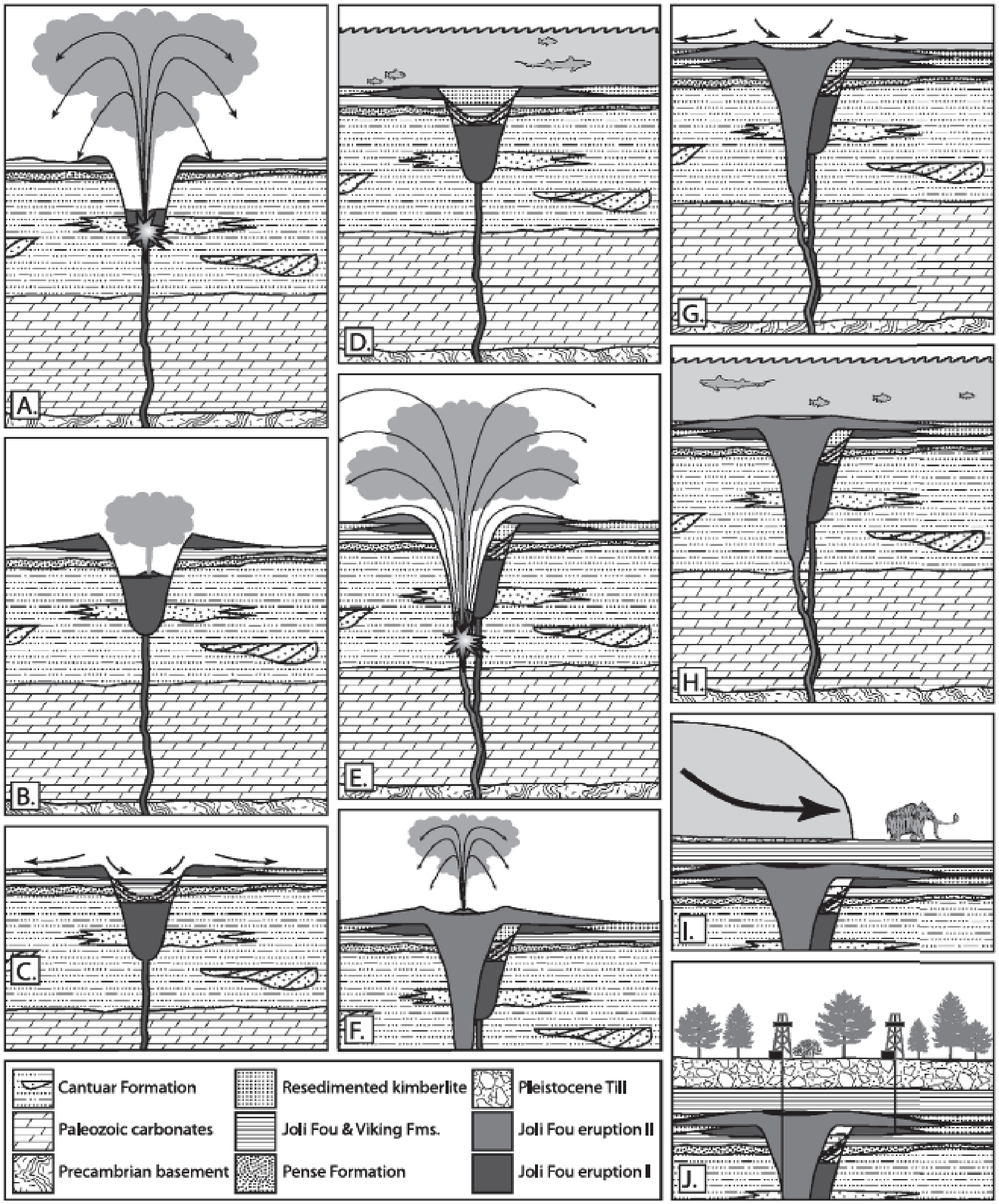

Figure 7: Emplacement Process for Sask Kimberlites *(Zonneveld et al., 2004)*

Schematic illustration of the interpreted e olution of oli Fou e ui alent kim erlite comple es at the FalC Star kim erlite The initial kim erlite eruption was iolent, possi ly as result of interaction etween kim erlite magma and a local groundwater source **(A**) This eruption resulted in a lowrelief tephra ring and partial crater infill **(B)** Volcanic acti ity associated with the early oli Fou ent ceased and post e ent erosional modification resulted in crater infill and a reduction in olume of the tephra cone **(C)** A mid oli Fou transgression resulted in su a ueous inundation and urial under a aria ly thick package of marine shale and siltstone **(D)** Renewed olcanic acti ity at late oli Fou time coincided with local retreat of the inland seaway Initial olcanic acti ity likely resulted in e ca ation of a narrow feeder pipe **(E)** Su se uent eruptions infilled the feeder pipe, further infilled the early oli Fou crater and deposited additional olcaniclastic material onto the e isting tephra cone **(F)** After erupti e acti ity ceased, the olcanic edifice was erosionally modified resulting in reduced edifice height and an e tensi e apron of resedimented kim erlite **(G)** Late oli Fou and Westgate transgressions resulted in urial of the entire comple under marine shale and siltstone **(H)** Much of the sediment co er o erlying most Fort a la Corne kim erlite comple es (including Star) was remo ed y Ceno oic erosion after the final retreat of the Cretaceous seaways Pleistocene glaciation resulted in urial under to m of unconsolidated glacial till and glacioflu ial outwash sediment **(I)** Air orne and ground magnetics, followed y drilling, resulted in disco ery and delineation of the Star Kim erlite comple **(J)**

- This model for deposition and preservation also explains why the kimberlites have such large surface expressions, (Figure 8).

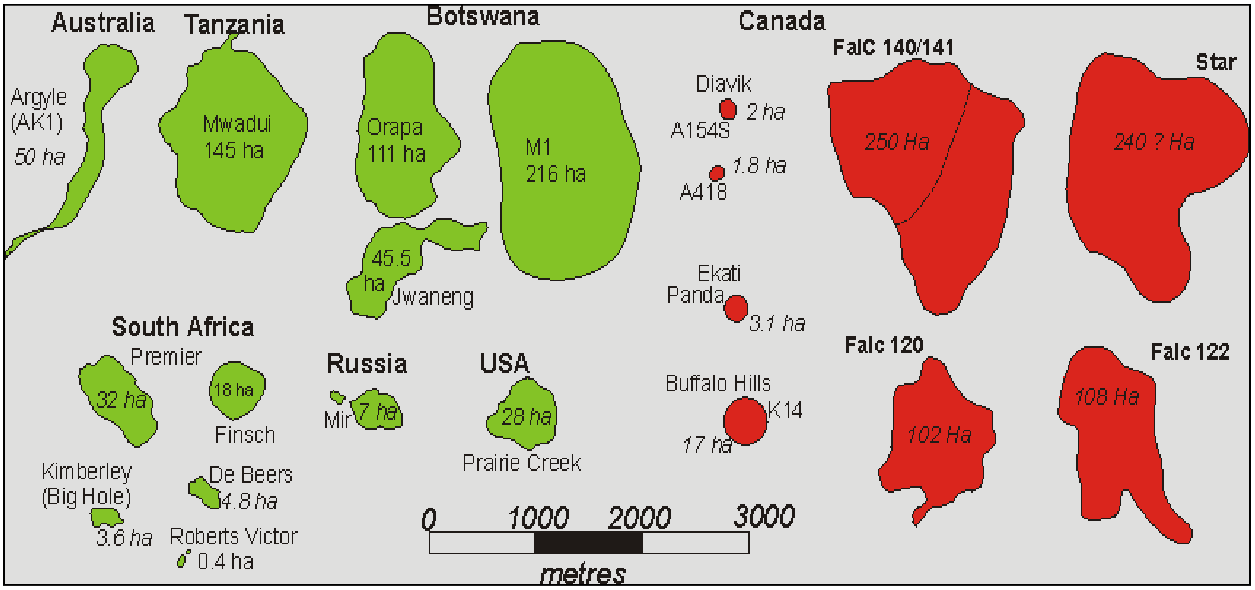

Figure 8: Comparison of the surface area of kimberlites (Source:http://www.summit2005.ir.gov.sk.ca/)

- A combination of delineation drilling and extensive geophysical interpretations have shown that the FalC kimberlites can have a surface expressions up to 250 hectares, and weigh as much as 390 million tones (Jellico and Marcia, 2002).

- Once thought to be a series of closely spaced individual kimberlites, the Orion Kimberlite Cluster in the Fort a la Corne kimberlite field, is now believed to be contiguous. This massive coalescence of kimberlite is estimated to be 7 km long and contains between 1.3 and 1.5 billion tonnes of ore, (Figure 9).

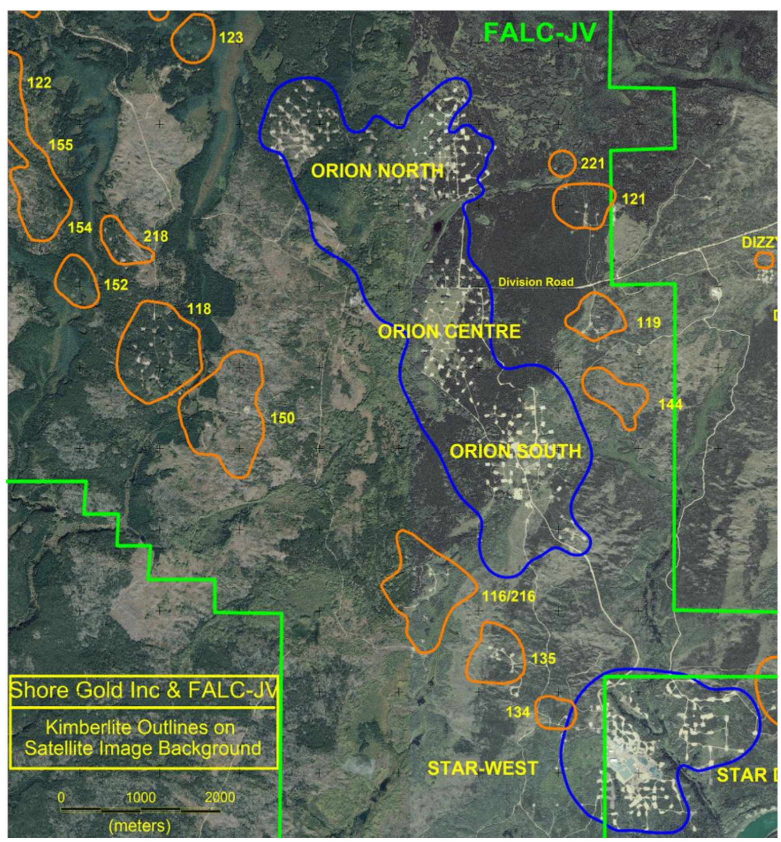

Figure 9: Orion Kimberlite Cluster (Courtesy of: Shore Gold Inc., http://www.shoregold.com/.)

- The Saskatchewan emplacement model is unique to scientists for a number of reasons:
  - The model uses knowledge of **sedimentary structures** (eg., bedding, ripple marks, sorting), to develop an understanding of the depositional environment of the kimberlites.
  - By observing fossil types (eg. foraminifera, diatoms) found in sedimentary rocks of various ages, the timing of kimberlite emplacement can be determined and the different pulses or eruptive events of the kimberlite volcano can be distinguished (Figure 10).

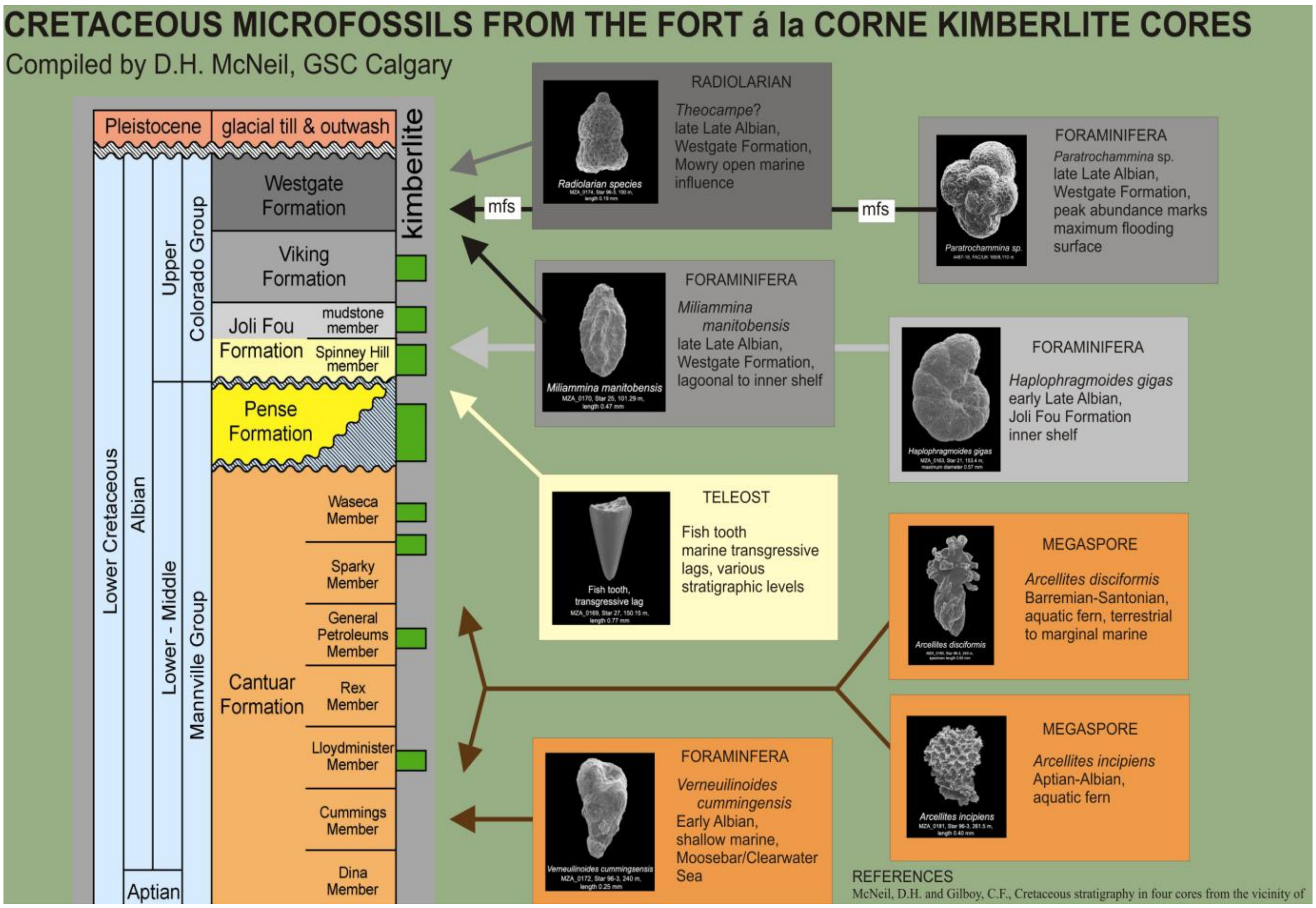

Figure 10: Fossils & Stratigraphy in the FalC vicinity *(McNeil and Gilboy, 2000)*

Exploring for Kimberlites in Saskatchewan

- Multiple ice sheets have advanced and retreated over Saskatchewan during the **Cenozoic** and as a result, the Fort a la Corne kimberlite field has been covered by ~100m of glacial **overburden**.

- These sediments are important to kimberlite exploration in that k**imberlite indicator minerals** can often be found in them.
  - Both the **Phanerozoic** and Cenozoic sediments are quiet in terms of magnetic content as compared to kimberlite which has magnetic constituents (minerals). This is important when it comes to searching for kimberlites.

- Geophysical surveys are completed over an area to search for particular kimberlite-type signatures .
- Saskatchewan kimberlites for example show as distinct magnetic highs as compared to magnetic signature of the surrounding sediments.

Potential for Diamonds in Saskatchewan

- "The central Saskatchewan kimberlite province, consisting of more than 70 in situ bodies, is one of the largest diamondiferous kimberlite provinces in the world" (Scott-Smith et al., 1995).
  - Since much of Saskatchewan is dominated by large stable cratonic areas, and thus similar to most of the world's known diamondiferous kimberlites, the province holds great potential for diamond exploration and development.
  - There is an abundance of unexplained kimberlite indicator mineral occurrences throughout the province, suggesting the existence of more kimberlites that are yet to be discovered.
  - Several parts of the province are currently being explored for potential kimberlite deposits.

- The potentially economic kimberlites found in Saskatchewan to date are characterized by low to moderate grades, very high tonnages, and an above average diamond value.

Potential Socio-Economic Impact of Diamond Mining in Saskatchewan

- **Sustainable Development** is the buzz word when mine planning comes into effect: How does it affect us socially, economically and environmentally and, most importantly, do these three key aspects have balance and continuity?
- Saskatchewan is fortunate to have a diverse abundance of mineral resources, not the least of which is diamonds.
- A mine in Saskatchewan would definitely impact not only the province, but nearby communities.
- Anticipated benefits range from the preliminary studies of mine development (jobs with environmental studies, social studies etc.), jobs within the mine itself, and jobs created by spin-offs such as increased cash flow (local business) and improved local infrastructures (roads, power etc.) in local areas.

<u>Scientific/technical terms</u>

Explanations for many of the following terms can be found at http://www.earthnet-geonet.ca/glossary/)

Aeolian Deposits	Glacially Rafted Block	Regression
Anomalies	Interbedded/Stratified	Root Zone
Cenozoic	Overburden	Sedimentary Structures
Crater Facies	Paleontology	Shield
Craton	Phanerozoic	Transgression
Diatreme Facies/zone	Precambrian	

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- http://www.nrcan.gc.ca/ms/diam/Kimberlite-EN/Kimberlite.html
- http://en.wikipedia.org/wiki/Western_Interior_Seaway
- http://en.wikipedia.org/wiki/Sustainable_development
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- http://www.shoregold.com/SGF11Dec2007.pdf

Oil and gas in Saskatchewan

Introduction

Beneath our feet in many areas in southern and west-central Saskatchewan, oil and natural gas are trapped in layers of sedimentary rocks of different ages which originated as deposits in shallow inland seas that covered much of Saskatchewan several times in the last 500 million years (Figures 1, 2, and 3)

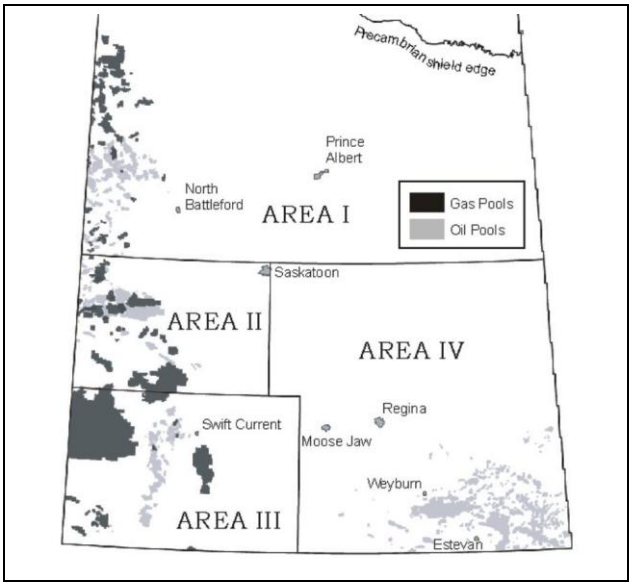


Figure 1: This map illustrates the locations of oil and gas pools in Saskatchewan. Also shown are the four areas into which the province is divided for administrative purposes (modified from Saskatchewan Geological Survey, 2003)

How are oil and gas formed?

Most crude oil and natural gas originate from simple plants and animals that lived in ancient oceans and lakes, were preserved in sediment at the bottom of these water bodies and then buried under hundreds of metres of younger sediments. Rocks with organic content high enough to generate hydrocarbons are termed source rocks. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Once the organic matter is buried, many different things can happen to it. As burial depths increase so do temperatures and, starting at about 60°C, oil can begin to be generated; an optimum temperature for oil generation is around 150°C. Oil is converted into thermogenic gas when temperatures exceed 200°C, and once a temperature of 300°C has been reached all organic matter is driven off and no hydrocarbons are preserved.

Gas can also be generated by biogenic processes. Biogenic gas is generated in source rocks (predominantly shales) at shallow depths and low temperatures where methane-generating microbes that live in the Earth's subsurface where oxygen is not available convert the kerogen in the shales into methane (methanogenesis). This is the same chemical reaction that occurs in landfills and wetlands. It is estimated that this source of gas accounts for ~20% of the global natural gas reserves.

Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Therefore, gas is often associated with coal beds and, if found within coal seams, it is called coal-bed methane. However, if this gas is able to escape from the coal, it becomes gas that is essentially indistinguishable from the gas produced by "cooking" oil or the biogenic gas produced from highly organic shales (http://geoinfo.nmt.edu/faq/energy/petroleum/Petroleum_geology_intro.pdf).

What is the chemical composition of crude oil and natural gas?
Crude oil and natural gas are hydrocarbons composed of carbon and hydrogen. A typical sample of thermogenic gas when it is collected at its source is a mixture of gases dominated by methane (CH_4), with lesser volumes of ethane (C_2H_6), propane (C_3H_8), and butanes (C_4H_{10}); impurities such as water, liquid hydrocarbons, carbon dioxide and hydrogen sulphide (H_2S) may also be present (www.naturalgas.org/overview/background.asp). Biogenic gas consists of methane plus impurities.

Crude oil is a complex liquid mixture of hydrocarbons with lesser quantities of other components including natural gas, water, carbon dioxide and sulphur compounds. "Light" crude oil (specific gravity <870 kg/m^3) contains small hydrogen-rich molecules whereas "heavy" crude oil (>910 kg/m^3) contains many large carbon-rich molecules (Bott, 2004). The composition of "medium" crude (870 to 910 kg/m^3) falls in between these two.

Why are oil and gas found in Saskatchewan?
Accumulation of economic volumes of oil and gas requires 1) generation of hydrocarbons from source rocks, and 2) subsequent migration of hydrocarbons to an area with both reservoir rocks (rocks with sufficient porosity and permeability to store and produce hydrocarbons) and an effective trapping mechanism to capture the hydrocarbons for future production.

Due to the pressure of overlying rock layers, oil and gas seldom remain in the source rock. Instead, they migrate updip from a zone of higher pressure to one of lower pressure with water serving as the transportation medium. The beds that have interconnected pathways (the spaces between the individual rock particles is known as porosity and the interconnectivity between the pores spaces is known as permeability) will allow for hydrocarbons to travel freely. Hydrocarbons, lighter than water, will continue upwards through the layers of rock until they either escape at the surface or are trapped by an impermeable barrier. If both oil and gas are present, gas, being less dense than oil, will rise above oil.

Much of Saskatchewan's oil and gas was generated from source rocks at greater depths and pressures in North Dakota, Montana, and Alberta. A minor amount of oil produced in southeastern Saskatchewan is sourced from rocks in the immediate vicinity of the producing wells. Natural gas produced in western Saskatchewan at shallow depths of less than 500 metres is deemed biogenic and is found in low permeability, thin bedded or muddy reservoirs. Commonly these large continuous reservoirs are interbedded with the source rock. Coal bed methane (or natural gas from coals) also occurs in Saskatchewan, but as most of the coal found in Saskatchewan are the lower coal ranks (lignitic to sub-bituminous), most of this gas at this time is deemed to be sub-economic to be produced by itself.

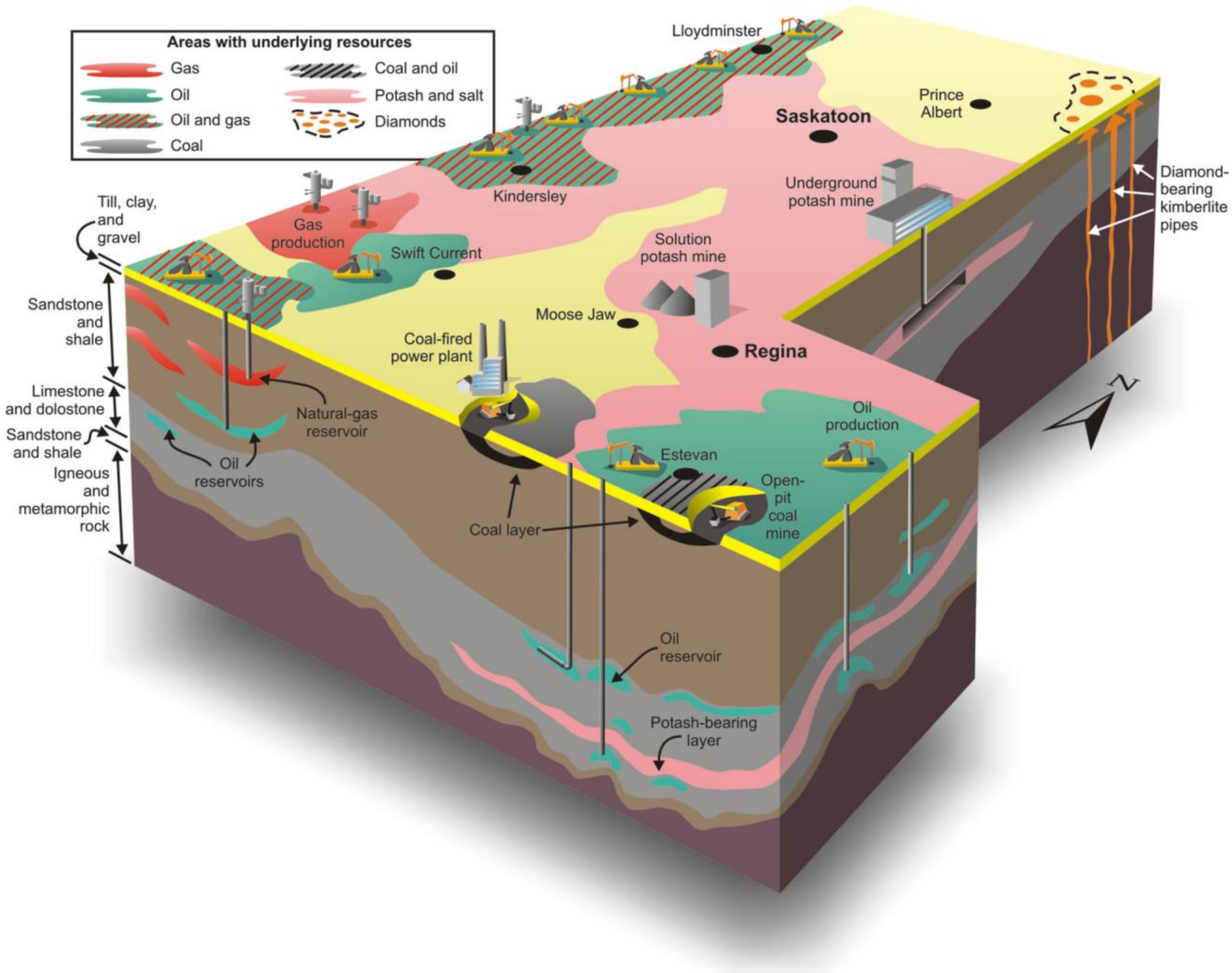


Figure 2: Block diagram illustrating the valuable resources contained in the layers of sedimentary rocks that underlie southern Saskatchewan. From *Geoscape Southern Saskatchewan*, 2004. Available online at: http://geoscape.nrcan.gc.ca/sask/index_e.php

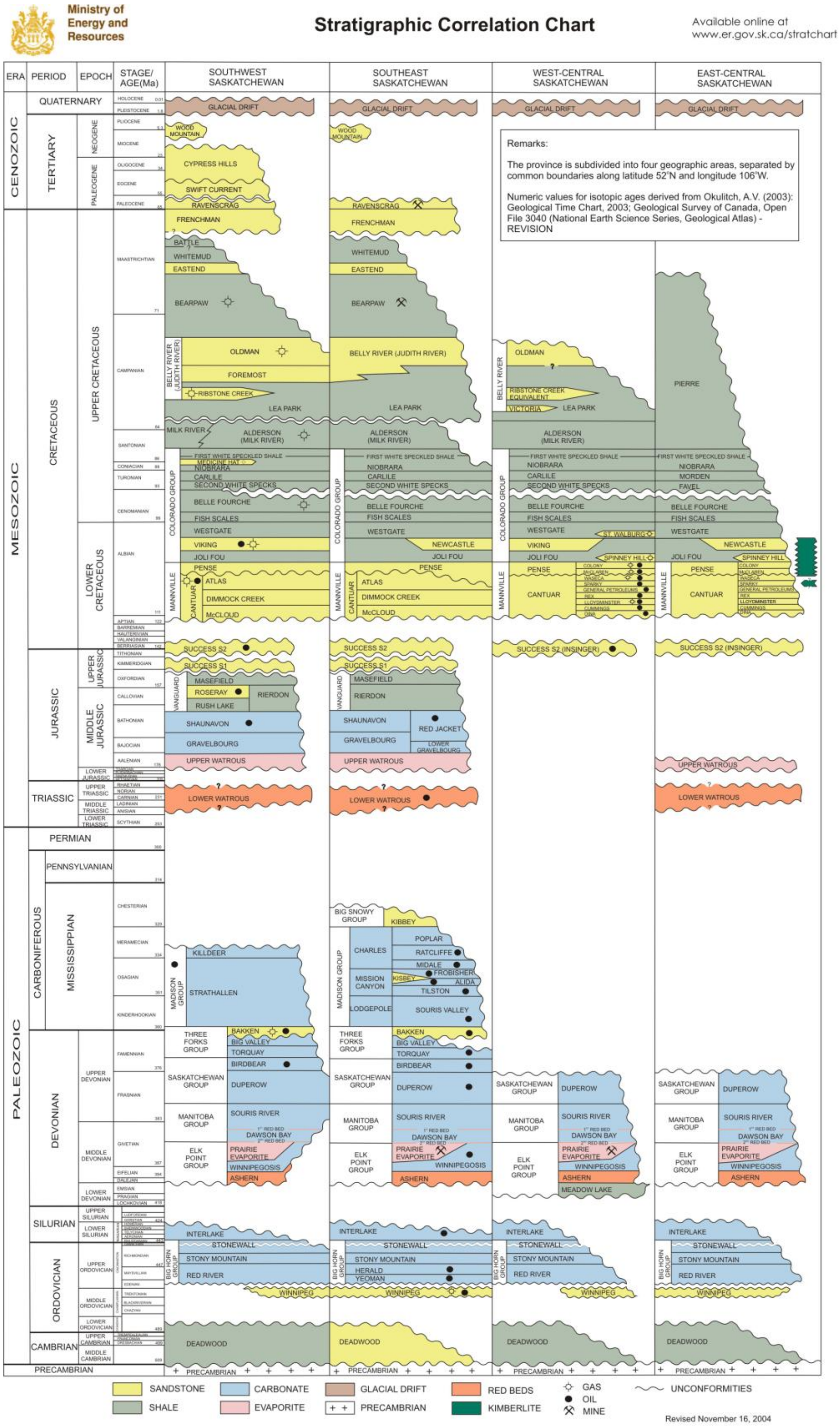


Figure 3: Saskatchewan statigraphic correlation chart (modified from www.er.gov.sk.ca/stratchart).

A variety of geologic conditions have provided traps for hydrocarbons in Saskatchewan. The main types of traps are stratigraphic and structural, or a combination of these. **Stratigraphic traps** occur when overlying impermeable layers act as a seal above the permeable strata below. The porous reservoir fills up with fluids (Figure 4).

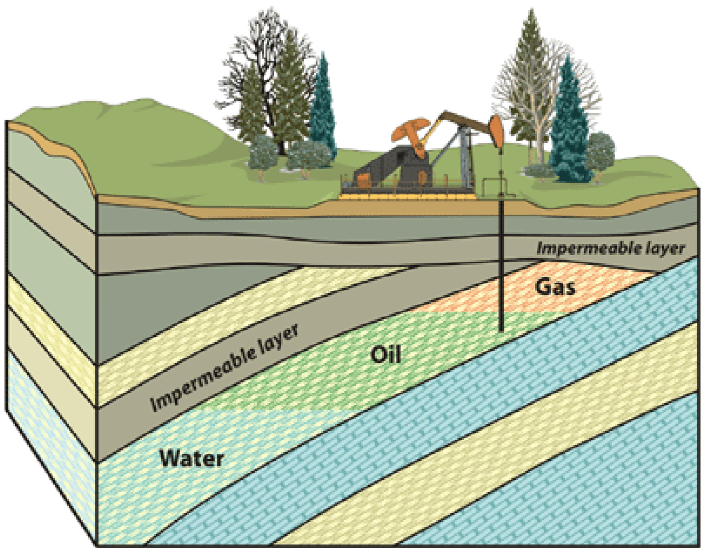


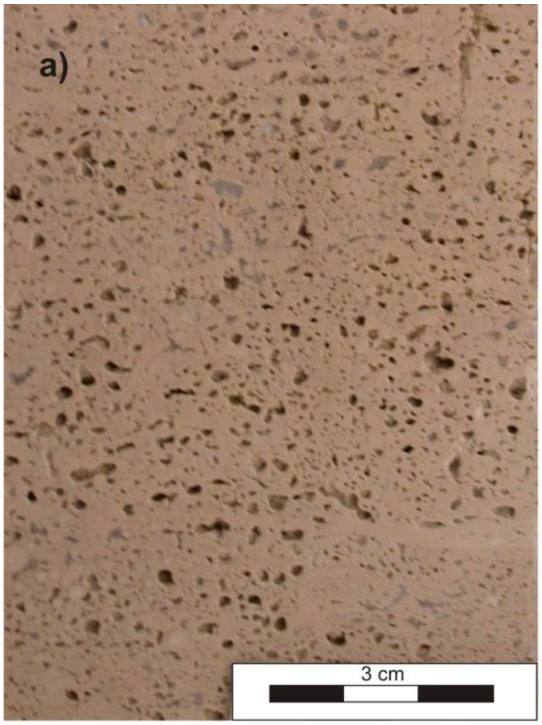
Figure 4: In this stratigraphic trap, oil and gas are trapped in a reservoir by an impermeable layer of sedimentary rock (from Geoscape Calgary; http://geoscape.nrcan.gc.ca/calgary/index_e.php).

Structural traps occur when horizontally lying beds of porous rock such as sandstone or limestone, covered by impermeable beds of shale or evaporite, have been shaped into anticlines (arches) by tectonic forces, differential compaction of underlying sediments or dissolution of underlying evaporites. Oil tends to accumulate in the top of anticlinal closures. Less common structural traps occur as a result of faulting which brings impermeable strata into updip contact with permeable oil-bearing strata.

Saskatchewan reservoir rocks

A wide variety of reservoir rocks are found in Saskatchewan. In southeastern Saskatchewan, limestone and dolostone reservoirs are most common but recently the spotlight has been on a sandstone reservoir (Bakken Formation). In the past years, the number of wells producing from the Bakken in southeastern Saskatchewan has increased dramatically. Over 500 wells that have produced oil from the Bakken were drilled in the last four years; more than 1.8 million m^3 (> 11 million barrels) has been produced from this reservoir during this time. Each Bakken well costs up to $2 million dollar to drill and complete. The recent sales of crown land leases for Bakken development have generated hundreds of millions of dollars in revenue for the province.

Oil and gas reservoirs in western Saskatchewan are predominantly composed of sandstone. Photographs provided in Figures 5, 6 and 7 illustrate characteristics of three Saskatchewan reservoirs.



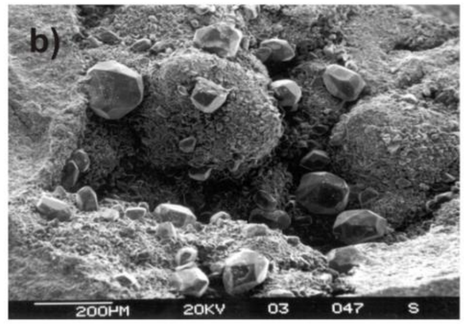
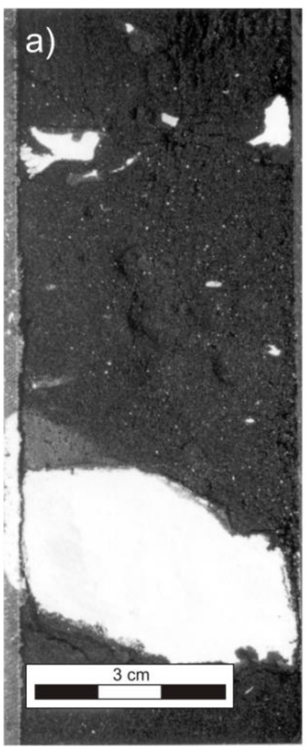


Figure 5: a) Core photograph of a carbonate oil reservoir (~340 million years old) at a depth of approximately 1120 m in the Alida area in southeastern Saskatchewan. Oil is stored in the holes that are visible in this photograph and in the spaces between the rounded carbonate grains visible in b) a scanning electron photomicrograph in which the grains are magnified (scale bar in bottom left corner is 0.2 mm in length). Note that the oil was removed from the sample in b). From Saskatchewan Geological Survey, 2003.



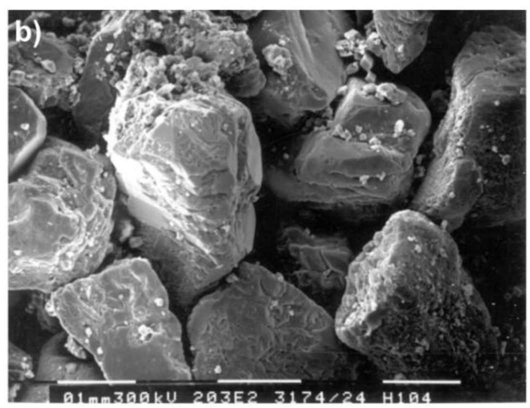


Figure 6: a) Core photograph of a heavy oil sandstone reservoir (~100 million years old) at a depth of approximately 485 m in the Westhazel area in west-central Saskatchewan. Oil is stored between the sand grains (dark-coloured portions of photograph); light-coloured fragments are shale clasts which are not saturated by oil; b) scanning electron photomicrograph of sample from core; black and white scale bars near bottom are 0.1 mm in length. Note that the oil was removed from this sample. From Saskatchewan Geological Survey, 2003.

Figure 7: Core photograph of a natural gas sandstone reservoir (~88 million years old) at a depth of approximately 475 m in the Hatton area in southwestern Saskatchewan. From Saskatchewan Geological Survey, 2003.

How is oil and gas found in Saskatchewan today?

Several sources of data are utilized to explore for and develop oil and gas accumulations. Rock samples (drill cuttings and cores) and geophysical well logs (which measure rock and fluid properties indirectly) taken during drilling of other wells in the area are examined and interpreted. Seismic surveys are also often undertaken to obtain “pictures” of the rocks beneath the surface. This technique is based on how different rock layers reflect energy waves back to the surface. In the majority of cases, the acoustic energy waves are produced by denonating dynamite in shallow drill holes. In areas where this method may have undesirable environmental impact, a mechanical vibroseis technique is utilized. Statistics obtained in early 2008 indicate that in Saskatchewan 80% of seismic surveys used dynamite and 20% used vibroseis. The energy waves returned to the surface by either method are captured by listening devices called geophones and converted to electrical impulses that are recorded, processed, and interpreted.

There are two primary types of seismic surveys: two-dimensional (2-D) and three-dimensional (3-D). With 2-D seismic, the geophones are arranged in one line at regular intervals with the energy source points arranged along the same line at greater intervals. The resulting information is displayed as a two-dimensional vertical cross-section of the earth directly beneath the line. A 3-D seismic survey utilizes several lines of geophones and the resulting data can be displayed as a three-dimensional cube from which can be derived planes or cross-sections at almost any angle. A new technique called 4-D seismic involves shooting 3-D surveys over the same area at different times to measure changes in reservoir fluids over time and is used in development activities. Figure 8, reproduced from Bott (2004), provides a summary of acquisition of data for a vibroseis 3-D seismic survey. Figure 9 illustrates a seismic cross section based on 3-D seismic data acquired in the Weyburn-Estevan area. The “bumps” labeled as “Winnipegosis buildups” represent reefs built by corals, bryozoans, sponges and algae living in a warm shallow sea that covered much of Saskatchewan more than 390 million years ago.

Once all the available rock and geophysical data have been compiled, interpreted and evaluated, an economic analysis is done taking into account such factors as risk of failure, price of oil, and availability of infrastructure. A decision is then made as made as to whether to take the next step – drilling a well.

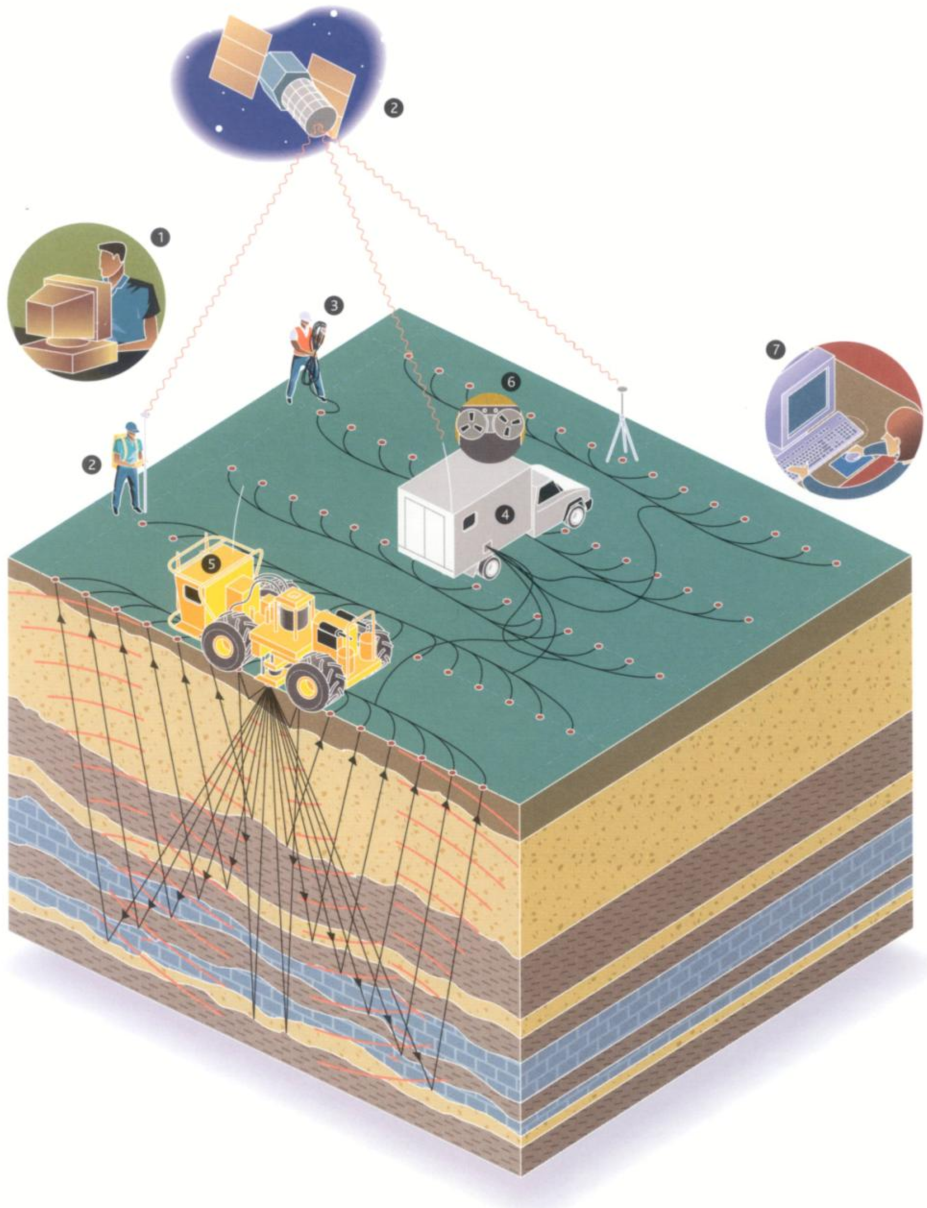
Drilling

Two different drilling methods are used to drill oil wells in Saskatchewan. Most wells are vertical wells in which the drill bit penetrates the subsurface along a vertical path. The second method is horizontal drilling in which the drill bit drills vertically until it approaches the targeted reservoir when it is steered along a curved path until it enters the reservoir at an angle of 80 degrees or higher to the vertical. The horizontal section can be 1500 metres or more in length. The number of horizontal wells drilled in a year reached a high of 901 in 2007 compared to 759 in 2006; 1394 vertical wells were drilled in 2007 (www.ei.gov.sk.ca/factsheets); www.er.gov.sk.ca/oilgasfacts)

Gas wells are drilled vertically or directionally at a slant. In 2007, 1156 gas wells were drilled in Saskatchewan.

Figure 8 (from Bott, 2004; *Our Petroleum Challenge*)

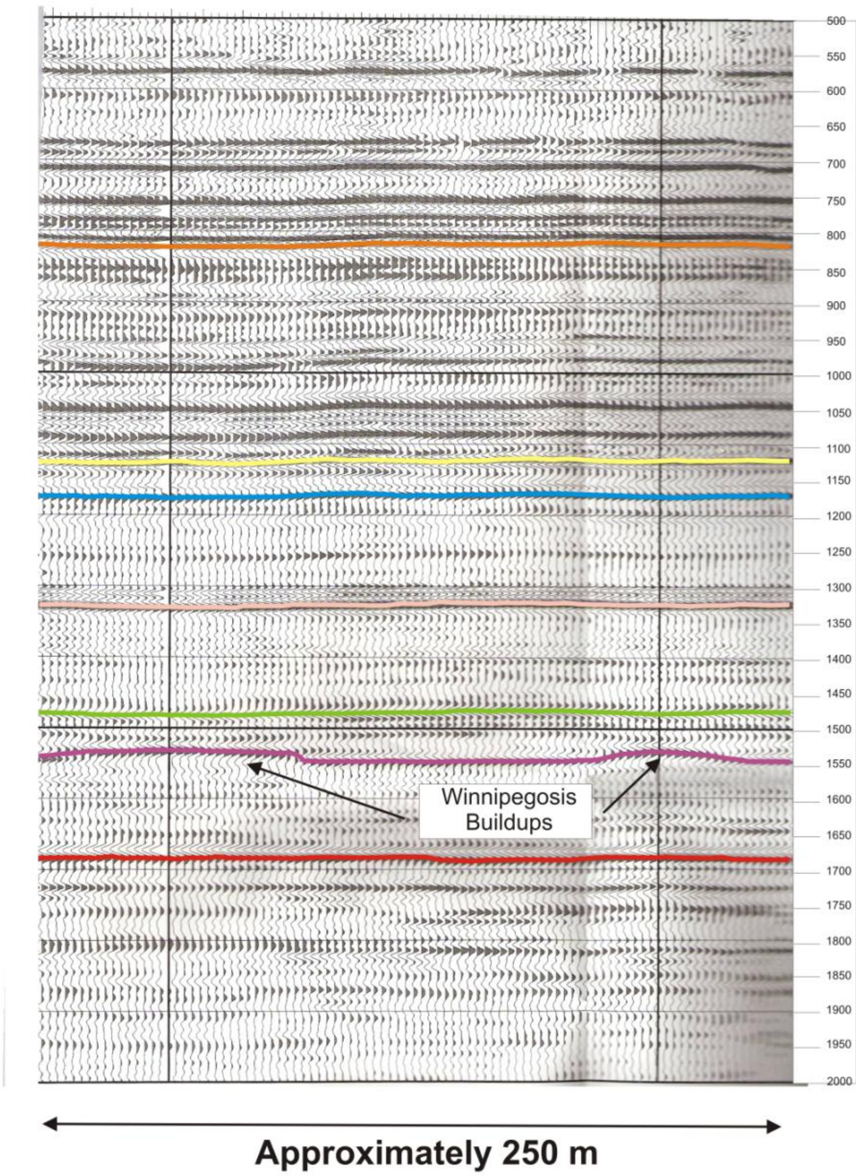
Vibroseis 3D seismic method



1. Company plans and designs a seismic program.
2. Surveyors use satellite-based global positioning system (GPS) to precisely position source and receiver locations.
3. Seismic crew members lay out cables and geophones.
4. Cables are attached to recording system.
5. Vibrator trucks generate a controlled vibration force of up to 32,000 kilograms at each source point.
6. Underlying geologic structures reflect some of the vibrations back to the surface where the geophones convert them into electrical impulses that are recorded on magnetic tape.
7. Magnetic tapes are sent for processing and interpretation of the recorded data.

Figure 9 (courtesy of Caprice Resources Ltd.)

Fence Display from 3-D Seismic
Weyburn-Estevan Area



Horizon Legend

- Second White Specks
- Lower Gravelbourg
- Mississippian Unconformity
- Torquay
- Prairie Evaporite
- Winnipegosis
- Deadwood

Display Parameters

Line Scale	12.000000 Lines/Inch
Trace Scale	12.000000 Traces/Inch
Time Scale	7.500000 Inches/Second
Excursion	3.000000 Traces
Clipping	3.000000 Traces
VD_Clip_Index	128
Min Scale Value	-26400.863281
Max Scale Value	25400.853281
Scale Type	JD
Scale Mode	File Mode
Plot Direction	LTOR
Polarity	Normal
Display Mode	VA Wiggle
Bias	0 Trace Spacing

Saskatchewan production
Saskatchewan is Canada's second largest oil-producing province (about 17% of all Canadian production). In 2007, almost 25,000 oil wells and approximately 19,500 gas wells were productive in Saskatchewan. Oil production was 24.8 million cubic metres (156.1 million barrels); value of sales was approximately $8.3 billion (www.er.gov.sk.ca/oilgasfacts (www.ei.gov.sk.ca/factsheets). A total of 8.8 billion cubic metres of gas were produced in 2007 with sales valued at approximately $1.5 billion. Saskatchewan is Canada's third largest gas-producing province.

Three different recovery methods are utilized in Saskatchewan. Primary recovery relies solely on oil being pumped from the wellbore to the surface. In secondary recovery (waterflooding), water is injected into one well and oil forced out by the water is recovered from a neighbouring well. Tertiary recovery or enhanced oil recovery (EOR) is becoming more important in Saskatchewan as companies try to recover the large volumes of oil that remain in the ground after primary and secondary recovery. EOR techniques involve the injection of steam, solvents, carbon dioxide, and other substances into the reservoir to flush out the remaining oil. In addition to recovering 42.5 million m^3 (267 million barrels) of incremental oil, the CO_2 projects at Weyburn and Midale are projected to provide underground storage for almost 35 million tonnes of CO_2 over the life of the projects (http://www.ei.gov.sk.ca/factsheets; www.er.gov.sk.ca/oilgasfacts).

Transporting Saskatchewan's oil and gas
Numerous pipelines transport most of Saskatchewan's crude oil, natural gas, condensates, and refined petroleum products within the province and en route to western and eastern Canada, and the United States. Lesser volumes are transported by truck and rail.

Processing oil and gas
Thermogenic gas requires removal of any impurities and of the C_3, C_4, and C_5 hydrocarbons before the gas is sold for commercial use. The propane and butanes removed from natural gas are usually liquefied under pressure and sold as liquefied petroleum gases (LPG). Most Saskatchewan natural gas is low in LPGs and sulphur and therefore requires limited processing (www.er.gov.sk.ca/oilgasfacts). Processed natural gas is odourless and, therefore, mercaptan (methanethiol, CH_4SH), which has a strong odour somewhat like rotten eggs, is added to the gas as a safety precaution so that leaks can be detected.

Conventional crude oil is initially processed at batteries located in the area of production. Here, in storage tanks, density differences are utilized to separate natural gas, crude oil, water, and fine rock particles; these products are then distributed to different storage facilities. Ideally, natural gas is placed in a gas gathering system but if no gathering system is available the gas may be flared. Since 1988 there has been a sharp reduction in the amount of natural gas that is flared (Bott, 2004).

Heavy crude oil requires special treatment. It is too viscous to flow through pipelines so it must be diluted using condensates. Heavy oil must also be upgraded to lighter oil or synthetic lighter oil before it can undergo the refining process. The upgrading process utilizes temperature, pressure and catalysts to crack large hydrocarbon molecules into smaller ones. Carbon is then removed and/or hydrogen is added to create the synthetic oil (Bott, 2004). There are two upgrading facilities in Saskatchewan: the NewGrade Upgrader in Regina, and the Husky Energy Upgrader in Lloydminster (see www.lloydminsterheavyoil.com/ and www.er.gov.sk.ca/oilgasfacts for more details).

The first step in refining oil involves separating the oil into different hydrocarbon fractions using an atmospheric distillation tower (Figure 10; reproduced from Bott, 2004). After distillation, "many of the separated streams require further chemical processing or purification before they can be blended into marketable commodities" (p.100, Bott, 2004). Cracking, alkylation, isomerization, and catalytic reforming are other processes that may be utilized to produce specific products.

About 18% of Saskatchewan's oil production is used in the province, primarily as feedstock for the two upgraders and the asphalt plant in Moose Jaw; approximately 66% is exported to the United States, and the remainder is sold in eastern Canada with a small amount sold to Alberta www.er.gov.sk.ca/oilgasfacts .

Importance of oil and gas to Saskatchewan's economy

In 2007, an estimated 27,000 person years of direct and indirect employment were associated with the upstream oil and gas industry. The industry provides well over $1 billion a year in revenue to the provincial government and contributes approximately 9% of real GDP which is one of largest components (www.ei.gov.sk.ca/factsheets)

What is Oil and Gas used for?

Natural gas is widely used as a fuel source. It is the energy source for heat in the majority of homes in Saskatchewan (>90% in 2002); for household appliances such as water heaters, fireplaces, stoves and clothes dryers; for farm equipment such as grain dryers, generators and irrigation systems; and for vehicles such as buses, trucks and cars (www.saskenergy.com/learningcentre/index.asp). Natural gas is also used in Saskatchewan for generation of electricity; currently about 15% of Saskatchewan power is generated using natural gas (www.saskpower.com/poweringyourfuture/today/electricitybasics.shtml). In addition, many industries use large volumes of natural gas, including the SaskFerco fertilizer plant near Belle Plaine that uses natural gas as a feedstock for production of ammonia-based fertilizer (www.er.gov.sk.ca/oilgasfacts).

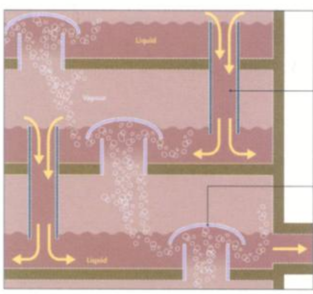
The transportation industry relies heavily on the refined products of crude oil which include gasoline and diesel for cars, trucks, and trains; kerosene for jet aircraft; fuel oil for ships; and lubricants. Other oil products include heating oil and asphalt.

Hundreds of petrochemicals are derived from oil and natural gas and these petrochemicals in turn are widely used in the manufacture of plastics, synthetic fibres, synthetic rubber, and many other commodities.

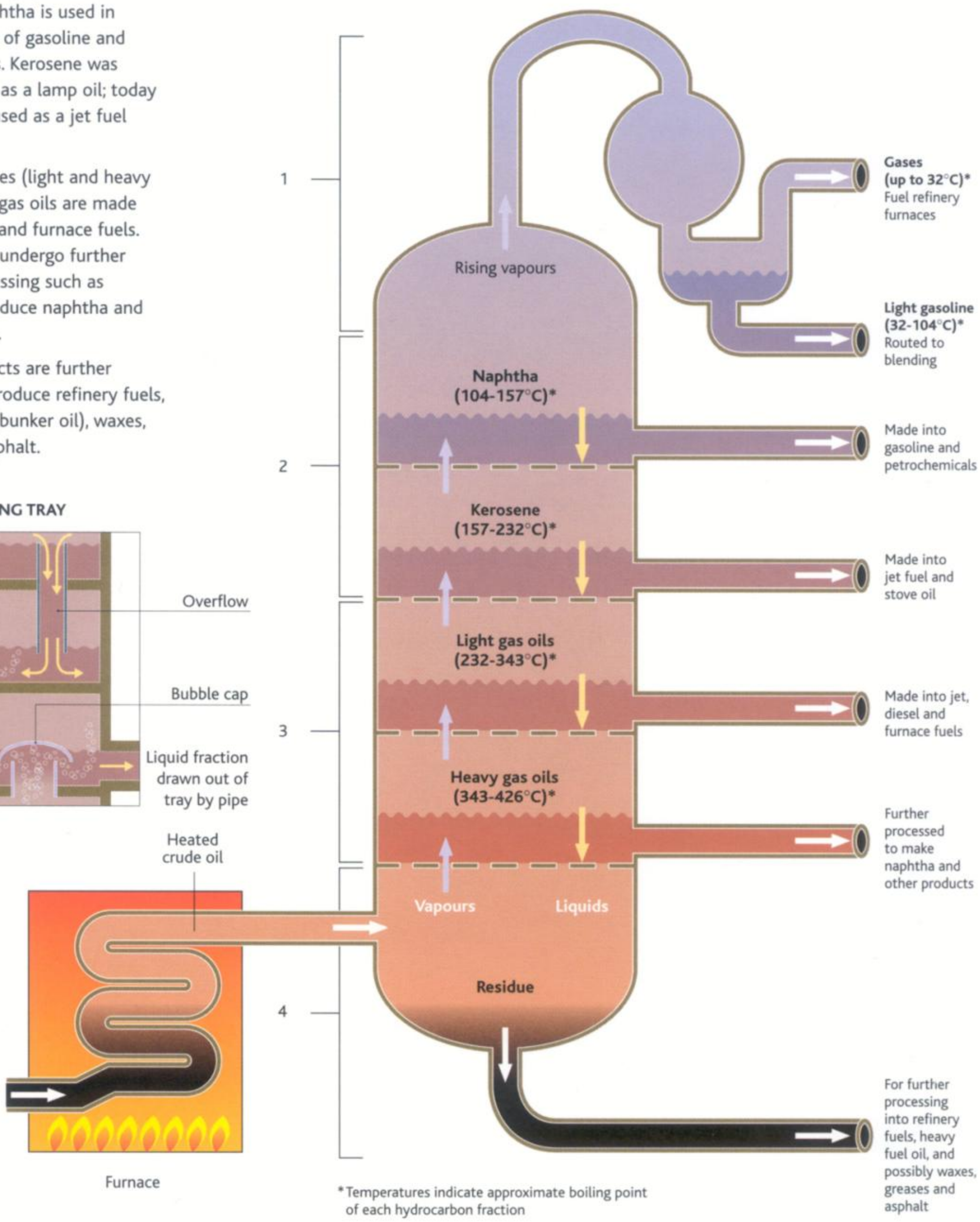
Atmospheric distillation

1. Gases and light gasoline. The gases (methane, ethane, propane, and butane) are commonly used to fuel refinery furnaces while the light gasoline is routed to gasoline blending.
2. Light distillates (naphtha, kerosene). Naphtha is used in the production of gasoline and petrochemicals. Kerosene was originally used as a lamp oil; today it is primarily used as a jet fuel and stove oil.
3. Middle distillates (light and heavy gas oils). Light gas oils are made into jet, diesel and furnace fuels. Heavy gas oils undergo further chemical processing such as cracking to produce naphtha and other products.
4. Residual products are further processed to produce refinery fuels, heavy fuel oil (bunker oil), waxes, greases and asphalt.

DETAIL OF PERFORATING TRAY



SIMPLIFIED CROSS-SECTION OF DISTILLATION TOWER



*Temperatures indicate approximate boiling point of each hydrocarbon fraction

References

Bott, R. (2004): Our Petroleum Challenge: Sustainability into the 21st Century; Canadian Centre for Energy Information, Calgary, AB; 131p.

Poulton, T., Neumar, T., Osborn, G., Edwards, D., and Wozniak, P. (2002): Geoscape Calgary; Geological Survey of Canada, Miscellaneous Report 72.

Saskatchewan Geological Survey (2003): Geology, and mineral and petroleum resources of Saskatchewan; Saskatchewan Industry and Resources, Miscellaneous Report 2003-7, 173p.

Turner, R.J.W., Franklin, R.G., Haidl, F.M., Gilboy, C.F., and Clague, J.J. (2004): Geoscape Southern Saskatchewan; Geological Survey of Canada, Miscellaneous Report 84.

Useful website links

www.er.gov.sk.ca/oilgas
www.ei.gov.sk.ca/factsheets
www.er.gov.sk.ca/oilgasfacts
www.saskenergy.com/learningcentre/index.asp
www.ptrc.ca/weyburn_overview.php
www.gac.ca/publications/Energy.html
www.lloydminsterheavyoil.com/
www.centreforenergy.com
www.naturalgas.org/overview/overview.asp
www.adventuresinenergy.org/
www.capp.ca
www.careersinoilandgas.com

Gold (Au), Copper (Cu) and Zinc (Zn):
Formed at an Ancient Plate Boundary in Northern Saskatchewan

Saskatchewan's relatively flat landscape is currently situated in the middle of the North American continent, but it was not always so. About 2 billion years ago an ancient ocean (the '**Manikewan' Ocean**), similar in size to the Pacific Ocean, ran diagonally across northern Saskatchewan and separated two early continents, the '**Superior**' and "**Hearne**" (Figure 1), which now form geological provinces of the **Canadian Shield**.

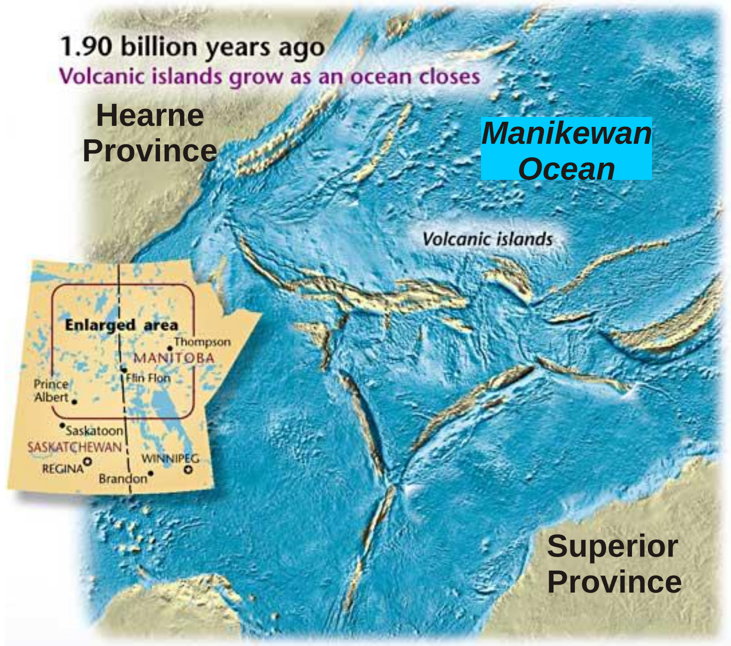


Figure 1: Schematic depiction of the Manikewan Ocean about 2 billion years ago, including **volcanic island arcs** and flanking continents (figure modified from Canadian Geographic magazine, Jan/Feb 2006 issue: http://www.canadiangeographic.ca/Magazine/ja06/alacarte.asp).

Plate tectonics processes (http://pubs.usgs.gov/gip/dynamic/dynamic.html) resulted in the closure of this ocean, mainly through the formation of **subduction zones** along the margins of adjacent tectonic plates. Within the ocean, chains of island volcanoes made primarily of **basalt** lava formed at the boundary between two **oceanic plates**, a similar scenario to that found in the South Pacific today. As plate subduction continued, large mountain belts similar to the western Cordillera of present-day North America, formed along the ocean margins, where oceanic plates were subducted beneath **continental plates**. Eventually the ocean closed completely, causing collision between the flanking continents and formation of a huge mountain belt that was similar to the Himalayas (Fig. 2).

"**Orogen**" is another name for mountain belt and this ancient mountain belt is called the "Trans Hudson Orogen". During the collision, the continental crust at deeper levels was subjected to intense heat and pressure, causing **metamorphism** of the rocks. Various types of **mineral deposits** formed at specific stages during the development of this orogen, including **base metal** (Cu-Zn) and gold deposits. Over the last 1.8 billion years since the orogen formed, this vast mountain belt has been progressively worn down by erosion to become part of the rocky land of lakes and trees known as the Canadian Shield, within which important mineral deposits are now located at or near the surface.

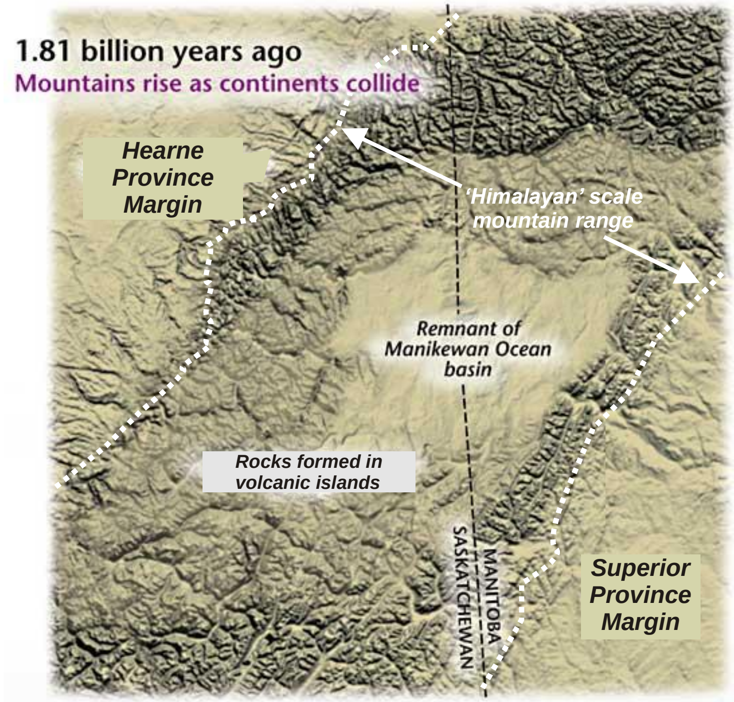


Figure 2: Development of a Himalayan-scale mountain range in northern Saskatchewan around 1.8 billion years ago, following closure of the Manikewan Ocean by tectonic plate subduction (figure modified from Canadian Geographic magazine, Jan/Feb 2006 issue: http://www.canadiangeographic.ca/Magazine/ja06/alacarte.asp).

The **Trans-Hudson Orogen**: interesting facts….

- This ancient mountain belt is over 2000 km long
- It starts at the eastern edge of the Rocky Mountains, where it is buried beneath younger rocks
- It extends toward the northeast all the way across Saskatchewan, Manitoba, Hudson Bay and beyond
- If you closed the Atlantic Ocean back up (as plate tectonics will eventually do) the Trans Hudson Orogen would connect with an ancient mountain belt in the northern part of Europe
- The ages of rocks in the orogen are determined by analysis of minerals that contain specific **isotopes** of elements that have undergone radioactive decay. This technique is known as '**geochronology'** (http://en.wikipedia.org/wiki/Geochronology) and the most commonly used '**radioisotope system'** is the **uranium-lead (U-Pb) system**.

Where have Cu and Zn been mined in Saskatchewan?

- They have been mined near the town of Flin Flon, which is on the border between Saskatchewan and Manitoba
- Cu and Zn were mined from rocks of the Flin Flon **Greenstone Belt**
- A greenstone belt is made mostly of basalt volcanic rocks, which when metamorphosed in a mountain belt are changed from black to green

How do Cu and Zn form mineral deposits?

- Cu and Zn deposits form as part of the volcanic activity at subduction zones in the ocean
- Cu and Zn bond with sulphur (S) to create sulphide minerals (**chalcopyrite** - $CuFeS_2$; **sphalerite** - ZnS) that are deposited as a layer on the sea floor
- They are eventually covered over by more volcanic rock and become part of the volcanic **stratigraphy (Figure 3)**. Stratigraphic layers are grouped into related rock types that are called '**formations**'. Formations can be subdivided into stratigraphic '**members'.** Owing to the importance of seafloor volcanism in the origin of these deposits, they are referred to as '**volcanogenic massive sulphide' (VMS)** deposits (http://en.wikipedia.org/wiki/Volcanogenic_massive_sulfide_ore_deposit)
- VMS deposits commonly form in the main crater or **caldera** of the volcano in association with **normal faults** (Figure 3).

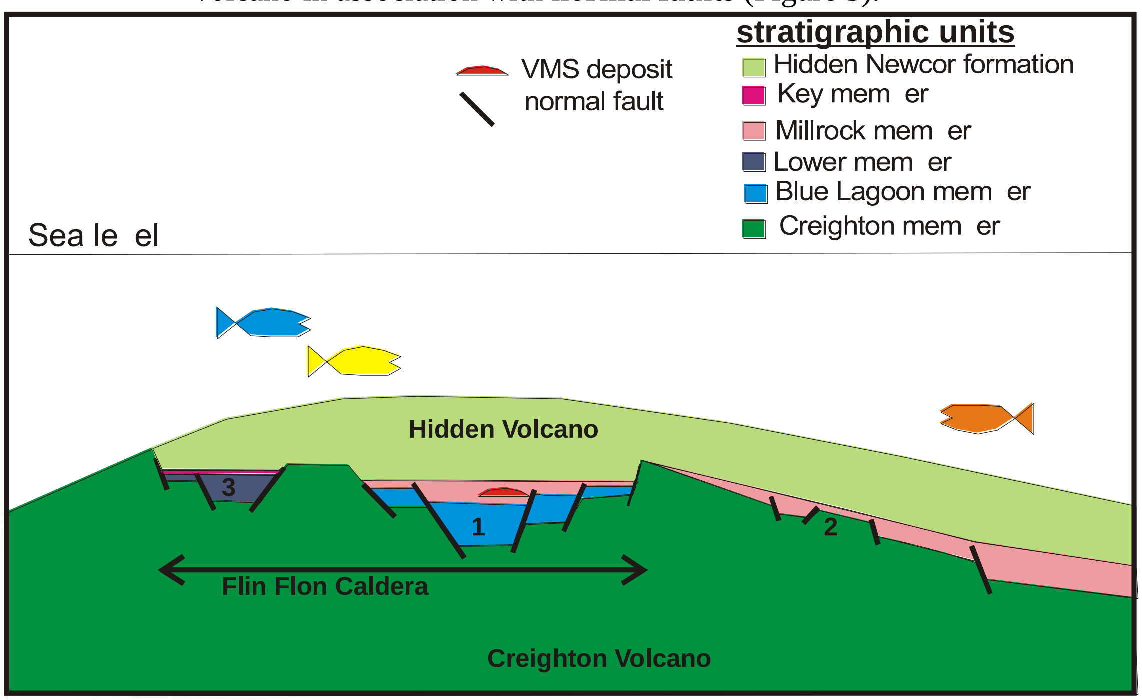


Figure 3. Schematic diagram showing stratigraphic layers of volcanic rocks in the Flin Flon mining camp where Cu and Zn are mined from VMS deposits. (Modified from MacLachlan and Devine, 2007).

Where have gold deposits been found in Saskatchewan?

- The majority of known gold deposits in Saskatchewan are found within rocks of the Trans Hudson Orogen, though some have also been found along the northern shore of Lake Athabasca
- The gold deposits are situated within a range of different rock types, including metamorphosed basalt, granite, and sedimentary rocks

How did these gold deposits form?

- Some gold was deposited on the sea floor along with the Cu-Zn deposits. An example of this type of gold deposit is the Anglo Rouyn deposit.
- Many gold deposits are found within quartz (SiO_2) veins situated in **metamorphic rocks** in the Trans Hudson Orogen. The quartz and gold in these veins were originally dissolved in very hot water ('**hydrothermal' fluids**) that flowed through the deep **continental crust** around the time of metamorphism during formation of the orogen. These '**orogenic gold deposits'** are found primarily in a belt stretching between Lac LaRonge and Reindeer Lake

Why are Cu, Zn, and Au important?

- An important industrial metal because of its high electrical and thermal conductivity, Cu is most commonly used for electrical wiring and gas and water tubings. It is also used as a decorative metal and in coins (http://resources.schoolscience.co.uk/CDA/14-16/chemistry/index.html).
- Zinc can be combined with copper to make brass (an 'alloy'). Due to its unique electrochemical properties, zinc is used to galvanize metals (e.g. steel) to prevent corrosion. It is also used in dry batteries and for manufacturing of a variety of construction materials (http://chinese-school.netfirms.com/Zinc-information.html).
- Gold is an important metal because it does not tarnish, has a beautiful colour and **lustre**, is malleable, and is an excellent electrical conductor. Historically, Au has been most important for cosmetic and decorative purposes (e.g. jewelry) and for currency. However, in modern society it is also an integral component of electronics and computers and even has important medical applications (http://geology.com/minerals/gold/uses-of-gold.shtml).

How are base metals and gold important to Saskatchewan's economy?

- Exploration companies in Saskatchewan spent an estimated $16 million and $19.5 million on base metal and gold exploration, respectively, in 2007.
- Both the Seabee gold mine, located 125 km northeast of LaRonge, and the Flin Flon Cu-Zn mine, on the SK-MB border, currently employ numerous residents of Saskatchewan. Several other known gold and base metal deposits in the province are prospective mine sites in the short term future.

Scientific/Technical Terms

Many definitions can be found at http://geoscape.nrcan.gc.ca/nsask/index_e.php, http://www.earthnet-geonet.ca/glossary/ and http://vulcan.wr.usgs.gov/Glossary/

Manikewan Ocean
Superior Province
Hearne Province
Volcanic island arc
Canadian Shield
Plate tectonics
Subduction zones
Basalt
Oceanic plate
Continental plate
Orogen
Trans Hudson Orogen
Metamorphism
Geochronology
Radioisotope system

Uranium-lead (U-Pb) system
Greenstone belt
Stratigraphy
Base metals (e.g., Copper and Zinc)
Normal fault
Chalcopyrite
Sphalerite
Volcanogenic Massive Sulphide (VMS)
Caldera
Formation
Member
Metamorphic rocks
Orogenic gold deposits
Hydrothermal fluids
Lustre

References

MacLachlan and Devine (2007): Stratigraphic evidence for volcanic architecture in the Flin Flon Mining Camp: Implications for Mineral Exploration; in Summary of Investigations Volume 2, 2007, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2007-4.2

Uranium (U) in Saskatchewan

Saskatchewan in the world's largest producer of uranium!

Uranium is a very common element in the Earth's crust. It is about 40 times more common than tin, about 40 times more common than silver and 500 times more common than gold. Saskatchewan leads the world in uranium production due to the uniqueness of the **Athabasca Basin**. The Athabasca Basin (Figure 1) was developed by deposition of eroded sediments into a large depression in the middle of a stable continent and is therefore, an '**intracratonic basin**'. These sediments were deposited between 1.7 and 1.5 billion years ago and were derived from the mountains of the **Trans Hudson Orogen** (See Copper and Gold).

What is the geomorphology of the Athabasca Basin?

- It is elliptical in shape, is about 400 km from east to west, 250 km from north to south and up to 1.75 km deep.
- It is located primarily in northern Saskatchewan and partially in northern Alberta.
- The basin is filled predominantly with **sandstone** but also contains **conglomerate**, **mudstone** and some **limestone**, which are all **sedimentary rocks**.
- Younger undeformed sedimentary rocks of the Athabasca Basin are separated by an erosion surface from older deformed **metamorphic rocks** of the Rae and Hearne Provinces of the **Canadian Shield (Figure 2)**. This erosion surface is called an **unconformity**.
- Uranium is generally found in the sedimentary rocks of the Athabasca Basin, at the contact between the basin and the underlying rocks (the unconformity) and in the underlying rocks themselves.

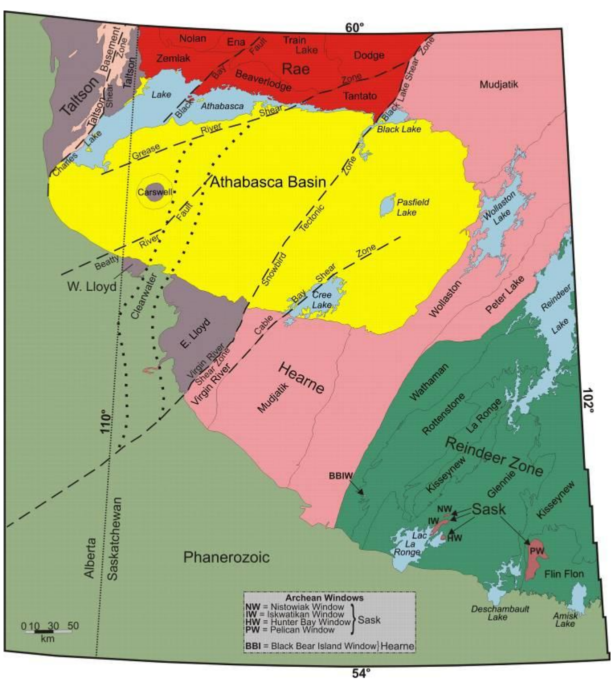


Figure 1. A map of the geological provinces of the Canadian Shield in Saskatchewan

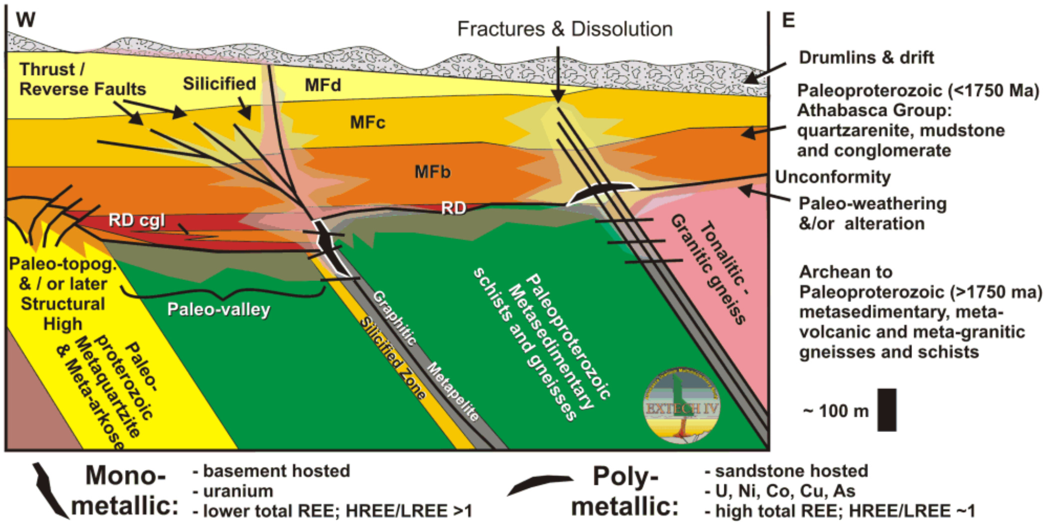


Figure 2. Schematic cross section showing the the Athabasca basin sedimentary rocks overlying the metamorphosed rocks of the Canadian Shield and the location of uranium deposits. Taken from http://gsc.nrcan.gc.ca/mindep/synth_dep/uranium/index_e.php

Why is uranium important?

- Uranium-powered generators supply nearly 19% of the world's electricity, providing an energy source that does not contribute greenhouse gases to the atmosphere.
- Uranium is important in treating cancer through radiation.
- Uranium aids in preserving food by controlling the ripening of stored fruits and vegetables.
- Uranium helps in the analysis of pollutants in the environment.
- http://www.uic.com.au/peac.htm

Where would you find a uranium mine in Saskatchewan?

- All the past and present uranium mines are located in and near the margin of the Athabasca Basin.
- Most of the uranium is found near the base of the Athabasca Basin or in the underlying rocks.
- Some of the current mines in northern Saskatchewan include McArthur River (the world's richest uranium mine), Cigar Lake (the world's second richest uranium mine), Rabbit Lake, McClean Lake and Midwest.

How does a uranium deposit form?

- Although uranium is very common in the Earth's crust, soil and water it is typically not economic to mine unless it has been concentrated.
- To concentrate uranium, oxidized fluids dissolve the uranium and transport it until it encounters a reduced environment where it is precipitated.
- Reduced environments are typically found around **faults** and where graphite is present.
- Uranium is an element which is found in many minerals. **Uraninite** is the primary uranium bearing mineral which is often referred to as '**pitchblende**'.

- The concentrated uranium deposits of the Athabasca Basin are not fully understood. One of the most popular models for the source of all this uranium is that it was derived from the sandstones themselves.

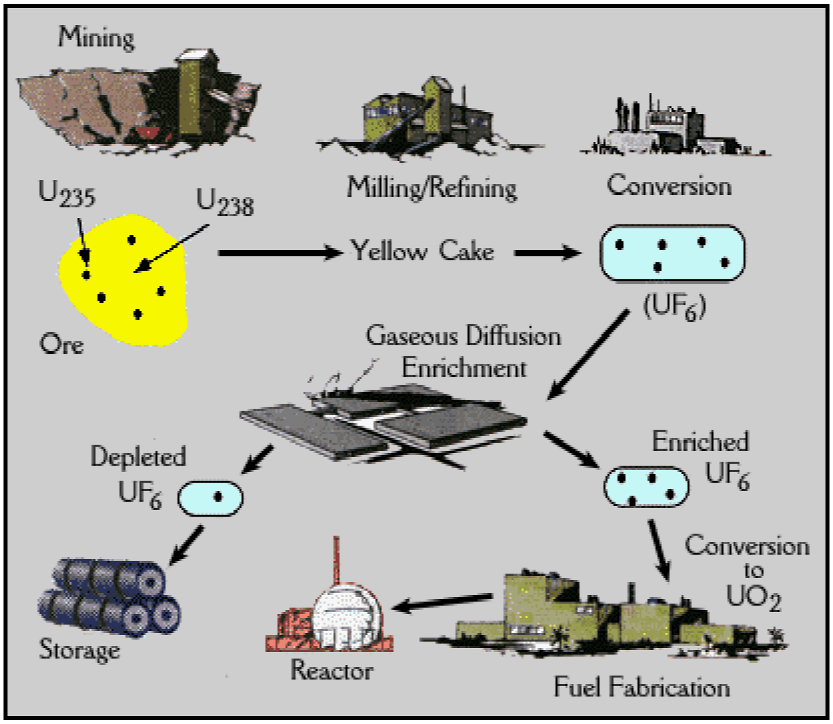


Figure 3. A depiction of the uranium production cycle. Taken from http://web.ead.anl.gov/uranium/guide/overview/uprocess.cfm

Uranium Ore

Yellow Cake

Storage of Depleted Uranium

How do you get the energy out of uranium?

- Uranium has several isotopes with the most common being **uranium 235** and **uranium 238**.
- Uranium 235 is the isotope that undergoes nuclear fission. When an atom of uranium 235 splits (fissions), it releases energy in the form of heat. This reaction causes the release of two or three other neutrons from its nucleus which can cause other uranium 235 atoms in their vicinity to split.
- This reaction produces heat and when this happens over and over again many millions of times, a very large amount of heat is produced from a relatively small amount of uranium.

- The heat generated is used to create steam, which powers turbines, which in turn create electricity.
- A nuclear power station that can supply energy for 1 million people requires approximately 74 kg of fuel a day – an amount that would fit in a small suitcase!
- http://www.cameco.com/uranium_101/ click the "nuclear fuel process" launch button

Uranium is a very concentrated energy source. Compare the energy output of the following resources.

Energy Source	**Electricity Produced**
1 kg of firewood	1 kWh (kilowatt hour)
1 kg of coal	3 kWh
1 kg of oil	4 kWh
1 kg of uranium	50,000 kWh

http://72.14.205.104/search?q=cache:BuZNaRbn9dsJ:www.alberta-star.com/s/Uranium.asp+compare+oil+to+uranium&hl=en&ct=clnk&cd=10&gl=ca

Did you know?

- Uranium is formed when stars explode. The uranium that is mined today formed in a **supernova** about 6.6 billion years ago.
- Uranium was discovered in 1789 be Martin Klaproth, a German chemist. It was named after the planet Uranus which had been discovered eight years earlier.
- **Radioactive decay** is thought to be one of the primary sources of heat inside the Earth, causing convection that leads to **plate tectonics**.
- Uranium is extremely heavy so it is used to make keels of yachts, as a counterweight for aircraft control surfaces as well as for radiation shielding.

What are the socio-economic benefits of uranium mining in Saskatchewan?

- The uranium industry directly employs approximately 1,770 people in Saskatchewan. An addition 950 people are employed as industry contractors bringing the total to approximately 2,700 people.
- Over half of all mine site employees are residents of Saskatchewan.
- Approximately 47% of mine site employees are of Aboriginal ancestry.
- The uranium industry is responsible for approximately 8,100 jobs in the province which includes direct jobs and spin-off jobs.
- The uranium industry spent more than $157 million on wages for its direct employees in 2007. Of this, over $57 million was paid to residents of Saskatchewan's north. The industry's contractors paid out an additional $109.5 million to their employees.

Uranium and the Environment

- Nuclear power plants release no pollutants to the environment and therefore do not contribute to global warming, acid rain or urban smog.
- Space requirements for nuclear power plants are very small in comparison to wind or solar generating systems.
- Nuclear power generation is the only energy industry which takes full responsibility for all its wastes, and costs this into the product.
- Although much of the waste from nuclear reactors is radioactive it is carefully managed and regulated using strict guidelines such as those provided by the Canadian Nuclear Safety Commission (CNSC). http://www.nuclearsafety.gc.ca/eng/

Other useful website links

http://www.saskmining.ca/
http://www.arevaresources.com/

Scientific/technical terms
You can find definitions for many of these terms at http://www.uic.com.au/education.htm, http://www.earthnet-geonet.ca/glossary/) and http://geoscape.nrcan.gc.ca/nsask/index_e.php

Intracratonic basin
Athabasca Basin
Trans Hudson Orogen
Geomorphology
Sandstone
Conglomerate
Mudstone
Limestone
Canadian Shield

Sedimentary rocks
Metamorphic rocks
Unconformity
Faults
Uraninite
Pitchblende
Uranium 235
Uranium 238
Plate tectonics

BRITISH COLUMBIA
Ministry of Energy and Mines
Energy and Minerals Division
Geological Survey Branch

BRITISH COLUMBIA GEOLOGICAL SURVEY

GeoLogos

A collection of word puzzles with geological and mineral themes

By Nick Massey and Dorthe Jakobsen

Information Circular 2002-2

Rocks I

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T A C E I N R H Y O L I T E L E B A S A L T
E E S I E T I T A M G E P T E T I R O I D A
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I R D N S C T L S Y N F P H Y L L I T E A E
F N A E E U O U O E O R E T E R P S B E C R
S F A N S I R N M V D V A T U A L U N O I B
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C A V A R M A U B E D M E T A M O R P H I C
L A U Y I E L B R A M Y R Y H P R O P S O E
L Q P L U P T R A C H Y T E Y H E T I C A D
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amphibolite
andesite
argillite
basalt
bed
breccia
clastic
clay
chemical
chert
coal
conglomerate
dacite
diabase
diorite
dolomite
dunite
dyke
foliated
gabbro
gneiss
granite
granodiorite
greenstone
hornfels
igneous
intrusion
volcanic
lava
limestone
marble
metamorphic
mudstone
obsidian
pegmatite
peridotite
phyllite
pluton
plutonic
porphyry
pyroxenite
quartzite
rhyolite
sandstone
schist
sedimentary
serpentinite
shale
siltstone
sill
skarn
slate
stratum
syenite
trachyte
tuff
volcano

Rocks II

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E T I M O L O D T P N C P Y R O X E N I T E
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I E S E N O T S D N A S I N E T I C A D U E
E T I R O I D O N A R G E S K E R E G T N T
B A R P H T R A C H Y T E E U I T R U C I I
A I L G O I I C P P N S E S G R A I S C T R
S L L E R H Y O L I T E I N T N T E N S E O
A O A N N M E N U E S M E L I R D N T E B I
L F C O F A S G T L L O U T T I A I I S Y D
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E U E N S L A M B C C G N S M T I O T M Y R
N V H E S E I E D I I T I P E A O I N G L Y
O O C E L D D R N C A H H L N T T N N E Q H
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S C I G T B C T Y H B S A R M I I S A T T R
E A N N E L S E Y O C I C G O S T R E U A O
M N O S O A Y L L H C H E S S M T E F D P P
I O T V L A L I I C E P E N T Z A F L E N L
L S U C L I T S E R P E N T I N I T E O L A
N C L C T E T R T L A O C T D Y K E E I I T
R N P E O R B B A G I B E L A V A I S M T S
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amphibolite
andesite
argillite
basalt
bed
breccia
clastic
clay
chemical
chert
coal
conglomerate
dacite
diabase
diorite
dolomite
dunite
dyke
foliated
gabbro
gneiss
granite
granodiorite
greenstone
hornfels
igneous
intrusion
volcanic
lava
limestone
marble
metamorphic
mudstone
obsidian
pegmatite
peridotite
phyllite
pluton
plutonic
porphyry
pyroxenite
quartzite
rhyolite
sandstone
schist
sedimentary
serpentinite
shale
siltstone
sill
skarn
slate
stratum
syenite
trachyte
tuff
volcano

Minerals and their Properties I

T	E	T	I	M	O	R	H	C	E	T	A	G	A	E	T	I	R	O	L	H	C	E	I
E	A	A	Z	L	A	T	S	Y	R	C	S	E	C	T	I	L	E	C	H	E	D	D	C
S	T	S	M	E	V	E	R	M	I	C	U	L	I	T	E	L	X	G	T	E	U	E	I
T	P	I	T	C	O	C	T	O	G	A	L	E	N	A	H	E	Y	I	G	C	T	A	L
D	T	H	V	E	I	L	M	A	G	N	E	T	I	T	E	P	G	A	T	I	Y	T	L
I	S	I	A	O	E	T	I	E	L	N	T	I	A	I	S	U	V	I	N	B	R	E	A
A	V	L	R	L	C	T	E	T	L	C	F	R	E	U	A	A	L	O	A	V	S	P	T
T	E	M	U	M	E	S	I	N	E	E	O	H	M	T	E	E	D	R	O	A	Y	E	E
O	T	A	O	O	A	R	U	M	G	S	R	P	N	L	I	O	I	E	L	H	T	L	M
M	I	L	D	P	M	G	I	M	O	A	M	E	C	Z	H	T	T	C	T	R	A	D	E
I	R	A	O	Y	I	E	N	T	R	L	M	N	O	R	E	I	O	R	A	D	B	M	K
T	Y	C	E	R	C	P	E	E	E	C	O	U	C	E	L	H	A	H	I	O	A	A	G
E	P	H	P	O	A	I	D	R	S	O	L	D	T	R	T	E	E	O	R	S	E	E	L
C	O	I	Y	X	H	D	A	T	D	I	V	I	E	R	R	D	Y	N	S	R	C	I	A
I	C	T	R	E	P	O	J	U	M	G	T	P	O	A	R	R	I	I	T	O	Y	L	S
N	L	E	O	N	Y	T	R	O	L	A	E	E	P	I	T	T	V	S	L	C	E	P	S
N	A	O	P	E	R	E	N	N	M	L	C	S	T	O	E	E	R	O	B	N	U	N	Y
A	H	P	H	R	I	I	E	E	B	P	D	E	B	S	E	R	U	T	C	A	R	F	Y
B	C	A	Y	E	T	L	H	A	O	L	I	V	I	N	E	R	R	E	V	L	I	S	C
A	A	L	L	E	E	H	T	C	E	I	E	A	R	S	E	N	O	P	Y	R	I	T	E
R	C	A	L	C	I	T	E	F	G	A	R	N	E	T	G	E	T	I	T	O	I	B	E
T	T	S	I	D	E	R	I	T	E	O	P	H	D	D	O	O	A	Z	U	R	I	T	E
T	S	O	T	S	E	B	S	A	I	P	Y	R	O	E	L	M	Z	T	R	A	U	Q	L
I	P	L	E	A	E	L	O	B	I	H	P	M	A	E	D	G	I	L	U	S	T	R	E

agate
amphibole
arsenopyrite
asbestos
augite
azurite
barite
biotite
bornite
calcite
chalcopyrite
chlorite
chromite
cinnabar
diatomite
dolomite
epidote
feldspar
galena
garnet
gold
gypsum
hematite
hornblende
jade
limonite
magnesite
magnetite
malachite
mica
muscovite
nephrite
olivine
opal
orthoclase
perlite
plagioclase
pyrite
pyrophyllite
pyroxene
pyrrhotite
quartz
rhodonite
siderite
silver
sphalerite
talc
tetrahedrite
vermiculite
zeolite
botryoidal
cleavage
colour
crystal
ductile
earthy
form
fracture
glassy
lustre
magnetic
massive
metallic
odour
sectile
streak
taste

Minerals and their Properties II

```
R E I E H A Z E M M M U S P Y G F L O B R Q E A
U Y S P T E N A N S U V L S T E N R A G E U O S
O R O M O I S E E E E S A A L C T E N P V A L P
L C E L E S T C L R X I C D Y H A A E A L R B H
O I I L I T T O M A E O S O O E U R P O I T O A
C T U V O I A I H T G P R C V T G T H B S Z T L
E E E O L B C L I R A M L Y E I I H R O J O R E
E N D E P U I T L R R A A T P T T Y I R A T Y R
T G I N L L E H D I S Y I G E A E E T N D A O I
I A E I E N A L P E C R P N N M B L E I E S I T
T M T E G L O G E M E T I R D E H A R T E T D E
O E N A T G B R I D A V R A C H S A R E A E A L
I E M E K I A N I O I A G A E O S I M I E A L U
B L G I Z A L S R L C A R M B B E O T T T E Y S
L I E L Y E E L O O T L I S E A E T I E T E S T
I T T A D T C R Y E H C A S E R N R I I O C S R
M C I T I I L H T H A L T S U N Y N C M D N A E
O U M S A R E O E S P O A T E P O L I P O A L T
N D O Y T U A D P O S O C P O I A P E C U R G I
I G L R O Z V O I O T A R C O C Y Z Y T R T H U
T Y O C M A A N D B R I L Y A C H L O R I T E C
E P D T I O G I O F T A E U P N C L A T I R A C
D T E T T R E T T R H E O P E R L I T E P T Y C
M R O F E T R E E C E T I H C A L A M E T A E P
```

agate
amphibole
arsenopyrite
asbestos
augite
azurite
barite
biotite
bornite
calcite
chalcopyrite
chlorite
chromite
cinnabar
diatomite
dolomite
epidote
feldspar
galena
garnet
gold
gypsum
hematite
hornblende
jade
limonite
magnesite
magnetite
malachite
mica
muscovite
nephrite
olivine
opal
orthoclase
perlite
plagioclase
pyrite
pyrophyllite
pyroxene
pyrrhotite
quartz
rhodonite
siderite
silver
sphalerite
talc
tetrahedrite
vermiculite
zeolite
botryoidal
cleavage
colour
crystal
ductile
earthy
form
fracture
glassy
lustre
magnetic
massive
metallic
odour
sectile
streak
taste

Gold in B.C. I

```
Y T W E E Z E R S O E S G N I L I A T E N M
R I L C P I C K W I L L I A M S C R E E K I
U O M A G N E T I T E R R S R P L A C E R A
C C T R O R E G R A V E L A E T I R Y P T L
R E V I R R E S A R F V D L R E M T S A E C
E D Z B N E N E B B G I N G D D O E T Z G X
M L Z O V O T G H Y D R A U L I C K I N G O
O P L O U F M D R G O N S O O N T C N A U B
S T R I K E L E R G R O K D W A F U C N N E
P T T O V S O R F O B S C C A Y A B Y O O C
S A Q V S R E D C P R P A O T C H I L B K I
P A Y U E P E K K R U M L L E Y S E V E E U
L U N S A D E K A O S O B O R V V E E L N L
E S N D T R O C R L H H P U W O I R Z T O S
I Y O A B R T L T A F T O R H N C Z L S T A
B A U O E A E Z R O B B K S E I O O A U F M
G N X B E L R A R E R E E T E N R A G D I A
E E N A P R C U K S H G B U L L D O Z E R L
B T I R D E W D N E Y T R A I L V E C A D G
G O L D P A N E M U L F O G N I N N A P D A
E O T A M A R I F F L E E M C R E N I M R M
A K A S A W A T E R A V I C T O R I A L E O
```

amalgam
black sand
bonanza
brush
bucket
bulldozer
claim
clean-up
colour
creek
cyanide
dredge
drift
dust
flakes
flume
garnet
gold pan
gravel
hydraulicking
magnetite
mercury
miner
monitor
motherlode
nozzle
nugget
ore
panning
paystreak
pick
placer
poke
prospector
pyrite
quartz
riffle
rocker box
sandbar
shaft
shovel
sluice box
strike
tailings
tweezers
vein
water
waterwheel
Atlin
Barkerville
Begbie
Cariboo
Dewdney Trail
Douglas
Fraser River
Kootenays
Thompson River
Williams Creek
Victoria

Gold in B.C. II

```
M R B T H O M P S O N R I V E R R A T L I N
I X S H A F T C E L L I V R E K R A B R G E
N K O F V Z Y M N C L E A N U P R L U N T Q
E H C B D I N R S L U I C E B O X O I I B U
R Y Y I R E C A I P T E N R A G L N T R R A
K D A D P E W T N F A I O R E O N E U K O R
A R N M R S K D O O F M N T C A N S E S T B
E A I N I E V C N R B L A E P G H E E E C U
R U D Q E I D R O E I L E L A A R O N K E L
T L E T S U D G A R Y A E M G C H T O A P L
S I C L A I M F E B T T H E S A R R Z L S D
Y C M O T H E R L O D E R M H R M R Z F O O
A K K O O T E N A Y S N A A T W E B L T R Z
P I S N T I S G N I L I A T I V R T E A P E
Q N A E W T L E M U L F L S I L R E A I N R
U G L Y E I O K E L E T I R Y P N F T W A U
A G G R E R O T I N O M R D N A S K C A L B
R R U U Z P P W O A F E B U P C R E E K W D
T A O C E L E K O P S I G D B E G B I E E R
Z V D R R A R E C A L P L C A R I B O O L I
S E Z E S E K I R T S O E D L E V O H S K F
G L E M F E T F N U G G E T E B U C K E T T
```

amalgam
black sand
bonanza
brush
bucket
bulldozer
claim
clean-up
colour
creek
cyanide
dredge
drift
dust
flakes
flume
garnet
gold pan
gravel
hydraulicking
magnetite
mercury
miner
monitor
motherlode
nozzle
nugget
ore
panning
paystreak
pick
placer
poke
prospector
pyrite
quartz
riffle
rocker box
sandbar
shaft
shovel
sluice box
strike
tailings
tweezers
vein
water
waterwheel
Atlin
Barkerville
Begbie
Cariboo
Dewdney Trail
Douglas
Fraser River
Kootenays
Thompson River
Williams Creek
Victoria

MINERALS 'R US

Minerals give us many of the things we use in our everyday lives, from computers to bikes, diaper pins to flashlights, toothpaste to pencils. See if you can match the minerals with their products in the list below. Draw a pencil line between the matching pairs.

Chalcopyrite	Fishing weight
Scheelite	Pop can
Quartz	Table salt
Hematite	Skin cream
Halite	Toothpaste
Bauxite	Wall board
Graphite	Penny
Galena	Thermometer
Sphalerite	Potting soil
Cinnabar	Light bulb
Limestone	Silicon chip
Gypsum	Film
Phosphate rock	Sand paper
Kaolinite	Pencil
Talc	Sculpture
Vermiculite	Jewellery
Garnet	Surgical steel
Gold	Fertilizer
Jade	Talcum powder
Native silver	China plate
Zeolite	Ice skates
Pentlandite	Kitty litter

Can you see any other things made from minerals in your room? How about in your kitchen? Or in your school?

Now try the Wordsearch Puzzle on the next page.

MINERALS 'R US

Wordsearch

E	C	L	I	G	H	T	B	U	L	B	E	T	E	Z	O	B	R	N	R	S	T
N	M	H	B	A	U	O	C	L	T	T	R	A	A	N	T	S	A	I	P	A	N
O	S	P	I	D	L	O	G	L	I	T	H	L	R	K	A	R	B	H	S	N	A
T	I	F	O	N	T	T	R	R	J	P	H	C	C	S	B	E	A	P	C	E	K
S	L	M	P	I	A	H	Y	C	H	I	E	O	P	M	L	L	N	U	U	L	R
E	I	S	C	U	L	P	T	U	R	E	R	N	U	T	E	S	N	E	Q	A	E
M	C	D	S	V	O	A	L	D	L	E	I	S	N	R	S	U	I	E	L	G	T
I	O	M	I	C	S	S	T	A	T	D	P	A	I	Y	A	R	C	L	T	H	E
L	N	H	L	R	U	T	N	A	T	Y	R	T	D	S	L	G	I	L	G	V	M
S	C	A	K	E	R	E	H	T	G	E	E	T	M	Y	T	I	R	I	H	E	O
I	H	L	I	D	R	P	S	U	R	G	I	C	A	L	S	T	E	E	L	R	M
C	I	I	T	W	S	E	D	A	J	L	D	I	L	P	S	W	V	R	T	M	R
E	P	T	P	O	P	C	A	N	F	R	K	I	E	A	G	J	L	E	B	I	E
S	J	E	H	P	I	B	I	E	A	A	O	N	N	N	T	E	I	T	M	C	H
K	E	P	T	M	A	L	R	O	O	S	T	D	I	E	E	W	S	T	A	U	T
A	W	M	N	U	J	T	B	L	G	L	P	H	N	K	T	E	E	I	E	L	N
T	E	L	X	C	I	L	I	N	A	A	S	R	L	I	I	L	V	L	R	I	L
E	L	I	R	L	L	N	I	N	P	I	A	Y	T	T	T	L	I	Y	C	T	I
S	T	F	I	A	I	T	D	E	F	G	E	O	N	T	A	E	T	T	N	E	C
E	L	Z	W	T	T	I	R	E	T	I	L	O	E	Z	M	R	A	T	I	P	N
R	E	P	E	O	T	S	C	H	E	E	L	I	T	E	E	Y	N	I	K	R	E
R	T	I	P	E	G	R	A	P	H	I	T	E	L	E	H	T	T	K	S	L	P

Bauxite
Chalcopyrite
China plate
Cinnabar
Fertilizer
Film
Fishing weight
Galena
Garnet
Gold
Graphite
Gypsum
Halite
Hematite
Ice skates
Jade
Jewellery
Kaolinite
Kitty litter
Light bulb
Limestone
Native silver
Pencil
Penny
Pentlandite
Phosphate rock
Pop can
Potting soil
Quartz
Sand paper
Scheelite
Sculpture
Silicon chip
Skin cream
Sphalerite
Surgical steel
Table salt
Talc
Talcum powder
Thermometer
Toothpaste
Vermiculite
Wall board
Zeolite

Rocks I
solution

```
- - C - - - R H Y O L I T E - - B A S A L T
- - S I E T I T A M G E P - E T I R O I D A
- N - T N E T I M O L O D E N O T S D U M I
- H O G R A N O D I O R I T E C I T S A L C
G O G I - A C - E T I T O D I R E P - - L C
- R - N S C T L S - N - P H Y L L I T E A E
F N A E E U O U O E - R - - E - P S - E C R
S F - N S I R N M V D - A T - - L U N - I B
E E U - I A S T G C - I I K - - U O D - M V
T L R T E T B S N L L L M - S - T E U S E O
I S D P - T E A E I O A E E D S O N N L H L
S - Y - E G I N I B - M Y N N E N G I A C C
E - K E A N O L I D - E E E O T T I T T - A
D - E B T T T H L E T E E R S T A A E E - N
N - B - S I P I T I N R C - A I S R I - - O
A R - T T M N I N O G I - S - T L D Y L - -
O - L R A - Z E T I N R H - - - E L N - O -
- I E C - T X S Y O T A A O B S I D I A N F
S H O A R O E - T S L E - T S I H C S - S -
C A V A R M - U B E D M E T A M O R P H I C
L A U Y I E L B R A M Y R Y H P R O P - - -
L Q P L - P T R A C H Y T E - - E T I C A D
```

Rocks II
solution

```
E T I M O L O D - - N - P Y R O X E N I T E
- D N R A K S E T I T O D I R E P - - - D -
- E - E N O T S D N A S I - E T I C A D U E
E T I R O I D O N A R G - S - E - - G - N T
B A - - H T R A C H Y T E - U I T R - - I I
A I - - O - - C P - - S - S G R A I S - T R
S L L E R H Y O L I T E I N T N T E N - E O
A O A N N M E N U E - M E L I R D N - E B I
L F C O F A S G T - L O U T T I A - I S Y D
T - I T E R A L O A U A E D M S - T I - - S
- - M S L B B O N S R - H E S A T D U E - Y
E - E N S L A M - C C G N S M T I O T M - R
N V H E S E I E - I I T I P E A O I N G - Y
O O C E L D D R N C A H H L N T T N N E Q H
T L C R A E - A I R P I P - L A I E E U - P
S C I G T B C T Y H B S A R M I I S A - T R
E A N - E L S E Y O C I C G O S T R E U - O
M N O - O A Y L L H C H E - S M T E F D - P
I O T V L A L I I C E P - - - Z A F - - N L
L - U C L I T S E R P E N T I N I T E - L A
- - L C T E T R T L A O C T D Y K E E I - -
- - P E O R B B A G - - E L A V A - S M - -
```

Minerals and their Properties I solution

```
T E T I M O R H C E T A G A E T I R O L H C - -
E A - Z L A T S Y R C S E C T I L E - - E - D C
S T S - E V E R M I C U L I T E - - G T E U E I
- P I T C O - T - G A L E N A - - Y I G C T - L
D - H V E I L M A G N E T I T E P G A T I - - L
I - - A O E T I - L - - I - - S U V I N B - E A
A - - R L C T E T - C F R E U A A L O A - S - T
T E M U M E S I N E E O H M T E E D R - A Y E E
O T A O - A R U M G S R P - L I O I E L H T L M
M I L D P M G I M O A M E C - H T T C T R A - -
I R A O Y I E N T - L M N - R E I O R A D B M K
T Y C - R C P E E E C O - - E L H A H I O A A G
E P H P O A I D - S O L D T R T E E O R S E - L
C O I Y X H D A - - I - I E R R D Y N S R C - A
I C T R E P O J - M G T P O A R R I I T O Y - S
N L E O N Y T R O - A - E P I T T V S L - - P S
N A O P E R E N N M L - S T O E E - O - - - - Y
A H P H - I I - E B P D E B - E R U T C A R F -
B C A Y - T - H - O L I V I N E R R E V L I S -
A - L L E E - - - E - E A R S E N O P Y R I T E
R C A L C I T E F G A R N E T G E T I T O I B -
- - S I D E R I T E - - - D - O - A Z U R I T E
- S O T S E B S A - - - - - E L - Z T R A U Q -
- - - E - E L O B I H P M A - D - - L U S T R E
```

Minerals and their Properties II
solution

```
R - - E - A Z E M M M U S P Y G F - O - R Q - -
U - - - T E N A N S U V - - T E N R A G E U - S
O - - M O I S E E E E S - - L - T E N - V A - P
L C E L E S T C L R X - C D - H A A E - L R B H
O I I L I T T O M A E O S O O E U R P - I T O A
C T - V O I A I H T G P R C V T G T H B S Z T L
E E E - L B C L I R A M L Y E I I H R O J - R E
E N D E P U I T L R R A A T P T T Y I R A T Y R
T G - N L L E H D I S Y I G E A E E T N D A O I
I A - I E N A L P E C R P N N M B - E I E S I T
T M T E G L O G - M E T I R D E H A R T E T D E
O E - A T G B - I D A V R A - H S A R E - E A L
I E M - K I - N I O I A G A - - S I - I E - L U
B L - - - A L S R L C A R M B B E - T T T E Y S
L I E L - E E L O O T L I S E A E T I E T E S T
I T T A D T C R Y E H C A S E R N R I I O - S R
M C I T I I L H T H A L T S U N Y N C M D - A E
O U M S A R E O E S P O A T E P O L I - O - L -
N D O Y T U A D P - S O C P O - A P E C U R G -
I - L R O Z V O I - - A R C O C - - Y T R - H -
T - O C M A A N D - R - L Y - C H L O R I T E C
E - D - I - G I O F - A - - P - C L A T I R - -
- - - - T - E T T - H - - P E R L I T E - T Y -
M R O F E - - E E C E T I H C A L A M - - - E P
```

Gold in B.C. I
solution

```
Y T W E E Z E R S - - S G N I L I A T - - M
R - - C P I C K W I L L I A M S C R E E K I
U O M A G N E T I T E R - S - P L A C E R A
C - T R O R E G R A V E L A E T I R Y P T L
R E V I R R E S A R F V D L - E - T - A E C
E - - B N - - E - - - I N G - D - E - Z G X
M L - O - O - G H Y D R A U L I C K I N G O
- P L O - - M D - - - N S O - N T C - A U B
S T R I K E - E - - R O K D W A F U - N N E
P - - O V S - R - O B S C C A Y A B - O - C
S A Q - S R E D C - R P A O T C H - L B K I
P A Y U E P E K - - U M L L E - S E V E E U
- U N S A D E K A - S O B O R - V E E L - L
E S N D T R O C R L H H P U W O I R Z T - S
I Y - A B R T L T A F T O R H N C Z - S T A
B A - O E A E Z R O B - K S E - O - - U F M
G N X - - L R A - E R - E T E N R A G D I A
E E N - - - C - K - H - B U L L D O Z E R L
B T I - D E W D N E Y T R A I L - - - - D G
G O L D P A N E M U L F O G N I N N A P - A
- O T - - - R I F F L E - M - R E N I M - M
- K A - - W A T E R - V I C T O R I A - - -
```

Gold in B.C. II
solution

```
M - - T H O M P S O N R I V E R - A T L I N
I X S H A F T - E L L I V R E K R A B R G E
N K O - V Z - - - C L E A N U P - - U N T -
E H C B D I N R S L U I C E B O X O I I B -
R Y Y I R E C A I - T E N R A G L N T R R -
K D A D P E W T N F A - O R E O N E U K O -
A R N - R - K D O O F M - - C A N S E S T B
E A I N I E V C N R B L A - P G H E - E C U
R U D - - - D R O E I L E L A - R - N K E L
T L E T S U D G A R Y A E M G C - - O A P L
S I C L A I M - E B - T - E S A - - Z L S D
Y C M O T H E R L O D E R M H R M R Z F O O
A K K O O T E N A Y S N A A - W E - L - R Z
P I S - T - S G N I L I A T I V R T E - P E
Q N A - W - - E M U L F - S I L - E A - - R
U G L Y E - - - - L E T I R Y P N - T W - -
A G G R E R O T I N O M R D N A S K C A L B
R R U U Z - - W - - - E - - P C R E E K W D
T A O C E - E K O P S - - D B E G B I E - R
Z V D R R - R E C A L P L C A R I B O O - I
- E - E S E K I R T S O - - L E V O H S - F
- L - M - - - F N U G G E T - B U C K E T T
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Minerals 'R Us

Solution

Chalcopyrite	**Fishing weight**
Scheelite	**Pop can**
Quartz	**Table salt**
Hematite	**Skin cream**
Halite	**Toothpaste**
Bauxite	**Wall board**
Graphite	**Penny**
Galena	**Thermometer**
Sphalerite	**Potting soil**
Cinnabar	**Light bulb**
Limestone	**Silicon chip**
Gypsum	**Film**
Phosphate rock	**Sand paper**
Kaolinite	**Pencil**
Talc	**Sculpture**
Vermiculite	**Jewellery**
Garnet	**Surgical steel**
Gold	**Fertilizer**
Jade	**Talcum powder**
Native silver	**China plate**
Zeolite	**Ice skates**
Pentlandite	**Kitty litter**

Minerals R Us wordsearch solution

E	C	L	I	G	H	T	B	U	L	B	E	T	-	Z	-	-	R	-	-	S	-
N	-	H	-	-	-	O	-	-	-	T	-	A	-	-	T	-	A	-	P	A	-
O	S	-	I	D	L	O	G	-	I	-	-	L	-	K	A	R	B	H	-	N	-
T	I	-	-	N	-	T	-	R	-	P	-	C	C	-	B	-	A	-	-	E	-
S	L	-	-	-	A	H	Y	-	-	-	E	O	-	M	L	L	N	U	-	L	R
E	I	S	C	U	L	P	T	U	R	E	R	N	U	-	E	-	N	-	Q	A	E
M	C	-	-	-	O	A	L	-	-	E	-	S	N	R	S	-	I	-	-	G	T
I	O	-	-	C	-	S	-	A	T	-	P	-	I	Y	A	-	C	-	-	H	E
L	N	H	L	R	-	T	-	A	T	Y	-	T	-	-	L	-	-	-	G	V	M
-	C	A	-	E	-	E	H	-	G	E	E	-	-	-	T	-	R	I	-	E	O
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C	I	I	-	W	S	E	D	A	J	-	D	-	L	P	S	W	V	R	-	M	R
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-	E	-	E	O	T	S	C	H	E	E	L	I	T	E	E	Y	N	I	K	-	E
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