Introduction

In 1823, Sir Walter Scott published a book titled Saint Ronan's Well, in which the inimitable character Meg Dodds, an outspoken, sarcastic woman, described people from the city visiting the country estate of her neighbor, a lady of the upper class:

> *Some rin up hill and down dale knapping the chucky stanes to pieces wi' hammers like sae many road—makers run daft—they say it is to see how the warld was made!*[1]

Obviously geologists. The early nineteenth century was an important stage in the history of geology, as it marked the transition from geology as an amateur hobbyist pastime to the serious scientific study of the physical world.

It is easy for those unacquainted with the field of geology to see geologists in the same way as Meg Dodds saw them: a bunch of people running about collecting odd bits of rock or looking to strike it rich with a big find of gold or gemstones. In a more recent popular portrayal of geology, from the television series "The Big Bang Theory," character Dr. Sheldon Cooper famously stood up in the middle of a paintball fight against a team from the Department of Geology and loudly proclaimed "Geology is not a real science!," upon which he was instantly plastered with paintballs fired from the guns of the geologists.[2] Ironically, Cooper was right; geology is not a real science. It is a scientific practice that is an amalgamation of principles from many different "real" sciences.

Geologists are a rather recent invention in the long history of the universe, which by all reckonings extends some 14.5 billion years into the past. The first "geologist" might be defined as the first hominid that ever picked up a rock and wondered what it was made of, what could be done with it, how it got there, and where it came from. As a scientific endeavor, the practice of geology is much younger still, by a few million years. In the present day, the practice of geology is built upon the application of the scientific principles and technologies of a number of different fields.

The progression of geology from its humble beginnings to its present-day sophistication began in earnest in 1793 with a canal digger named William Smith, who discovered what has been called Earth's fourth dimension, the order of the unseen content below the surface of the ground. Few people, if any, thought of this underworld as anything other than a jumbled mass of earth and rocks. It was obvious that a hole, such as a well, dug at a random location would reveal a succession of soil types and a random assortment of rocks and stones, but such holes were only local samplings of what lies in the ground below, seldom extending below the loose soils to bedrock. What was not obvious from such isolated samples is the continuity of those underground layers of rock. The perception was that what came out of a particular hole was unique to that hole and had no relationship to any other hole.

Canals disproved this perception. Canals are not isolated vertical holes but holes that extend horizontally for some distance through various and different terrains. The layers revealed in a canal excavation might seem as unique as those in a vertical hole, but Smith realized that he could identify the same layers in the same order in widely separated locations in a canal excavation, implying a continuity to the underground world that could be identified. From this realization, which Smith spent the next 22 years verifying, he generated "the map that changed the world"—showing the distribution of underground layers, soil types, rock structures, and all the other components of the underground. The first of its kind, Smith's map eventually encompassed all of Britain and set a precedent that advanced the profession of geologists everywhere.[3]

samples. The location of each sample is carefully recorded on a map and additional data describing the geologic setting of the sample are recorded. These data include thickness, areal extent, weathering, and strike and dip of the location. Photographs are also commonly used to record the surrounding environment of the sample location. Samples are usually given preliminary study at the researcher's field camp.

PETROLOGICAL AND MINERALOGICAL STUDIES

When the fieldwork is over, the researcher returns with the samples to a laboratory setting, where petrological and mineralogical investigations begin. A petrological study of an andesitic sample will include both petrographic and petrogenetic analyses. The petro- graphic analyses will describe the sample and attempt to place it within the standard systematic classification of igneous rocks. Identification of the sample is accomplished by means of examining a thinly sliced and polished portion of the sample under a petrographic microscope—a process known as thin-section analysis. The information obtained by microscopic examination gives a breakdown of the type and amount of mineral composition within the sample. More advanced analysis techniques, such as X-ray fluorescence and electron microprobe, are often used to obtain very precise chemical compositions of samples. Knowing the conditions under which these minerals form allows the researcher to make a petrogenetic assessment.

Petrogenesis deals with the origin and formation of rocks. If a mineral is known to form only at certain depths, temperatures, or pressures, its presence within a sample allows the researcher to draw some specific conclusions concerning the rock's formation and history. Mineralogical studies of field-gathered samples aid in the petrogenetic portion of the analysis. Mineralogy involves the study of how a mineral forms—its physical properties, chemical composition, and occurrence. Minerals can exist in a stable form only within a narrow range of pressure and temperature. Experimental confirmation of this range enables the researcher to make a correlation between the occurrence of a mineral in a rock and the conditions under which the rock was formed. In this sense, mineralogical and petrological analyses complement each other and work to formulate a concise history of a given sample.

When data gathered from the field and laboratory are combined, the geological history of a given field area can begin to be interpreted. When areas of similar igneous rock types, ages, and mineral compositions are plotted on a map, they form a petrographic province. A petrographic province indicates an area of similar rocks that formed during the same period of igneous activity. On a global scale, the Andesite Line marks the boundary between two great provinces: the basaltic oceanic crust and the andesitic continental crust. Both crustal forms have distinctly different geological histories and mineral compositions.

—Randall L. Milstein

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Aquifers

Fields of Study: Geology; Hydrogeology; Stratigraphy

ABSTRACT

An aquifer is a body of earth material that can store and transmit significant amounts of water. The earth material

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The "Deep-Impact" Mission: Geology of a Comet

Fields of Study: Astrogeology; Astronomy; Sub-planet Astronomy

ABSTRACT

Deep Impact was the first space mission designed to study the interior of a primitive celestial body directly. This was accomplished by slamming a heavy impactor into Comet Tempel 1, creating a fresh crater. Never before has any space mission tried to make an impact crater of this size in any object.

KEY CONCEPTS

ejecta: the material explosively ejected from a crater

impactor: essentially a massive body designed for the sole purpose of delivering a load of kinetic energy to a selected target

perihelion: the point in an elliptical orbit at which the satellite is at its closest approach to the Sun

SUMMARY OF THE MISSION

In July, 1999, the National Aeronautics and Space Administration (NASA) approved funding under its Discovery Program for a mission to slam an object into a comet, and to study the ejecta from that impact. This proposed mission became the Deep Impact project. By November, 1999, serious work had commenced in design of the project. Except for minor variations, the plans were finalized by May, 2001. These plans called for development of a flyby spacecraft to study the impact ejecta, and for a smart impactor that would guide itself to the target. The comet selected as the target was Tempel 1, discovered in 1867 by Ernst Tempel (1821-1889). The actual project began on January 12, 2005 and lasted to August 8, 2013.

COMET TEMPEL 1

Comet Tempel 1 orbits the Sun every 5.5 years. It approached perihelion, the closest point to the Sun in its orbit, in early summer, 2005. A target date for comet rendezvous was selected as July 4, 2005. Earth's orbit placed it in position to launch a mission to arrive at Tempel 1 on this date during a period of only a few weeks in January, 2004, and again for several weeks a year later. Periods during which a launch is possible are known as launch windows.

Initially, plans called for the mission to be launched during the first launch window, in January of 2004. However, the spacecraft was not ready for launch at that time, and so launch was postponed

Comet Tempel 1 67 seconds after it collided with Deep Impact, taken by high-resolution camera on flyby spacecraft. The image reveals ridges, scalloped edges and possibly impact craters formed long ago. Photo by NASA/JPL-Caltech/UMD, via Wikimedia Commons. [Public domain.]

mium (Cr). In the crystal structures of these minerals, the cations in the A site are surrounded by eight oxygen anions, while the cations in the B site are surrounded by six oxygens. Most garnets can be described as a mixture of two or more of the following molecules: pyrope ($Mg_3Al_2Si_3O_{12}$), almandine ($Fe_3Al_2Si_3O_{12}$), spessartine ($Mn_3Al_2Si_3O_{12}$), grossular ($Ca_3Al_2Si_3O_{12}$), andradite ($Ca_3Fe_2Si_3O_{12}$), and uvarovite ($Ca_3Cr_2Si_3O_{12}$).

The most abundant and widespread garnets are almandine-rich garnets, which form during the metamorphism of some igneous rocks and sediments rich in clay minerals. Grossular-rich and andradite-rich garnets are found in marbles formed through the metamorphism of limestone. The formation of spessartine-rich or uvarovite-rich garnets occurs during the metamorphism of rocks with high concentrations of manganese or chrome. Rocks with these compositions are relatively unusual, and hence these garnets are fairly rare. Pyrope-rich garnets are widespread in Earth's mantle, although they typically do not occur in abundance (more than 5 or 10 percent of the rock). Garnets that have weathered out of other rocks are sometimes found in sands and sandstones. Garnets may also occur in small amounts in some igneous rocks.

ALUMINOSILICATES

Minerals are called "polymorphs" if they are made up of the same kinds of atoms in the same proportions but in different arrangements. Polymorphs are minerals with the same compositions but different crystal structures. Aluminosilicates are a group of nesosilicate minerals containing three polymorphs: kyanite, sillimanite, and andalusite. Each of these minerals has the chemical formula Al_2SiO_5. The differences in the structures of these minerals are best illustrated by considering the aluminum atoms; in kyanite, all the aluminum atoms are surrounded by six oxygen atoms; in sillimanite, half of the aluminum atoms are surrounded by six oxygens, while the other half are surrounded by four oxygens; in andalusite, half the aluminum atoms are surrounded by four oxygens, and half are surrounded by five oxygens. Kyanite usually forms elongated rectangular crystals with a blue color. Sillimanite typically occurs as white, thin, often fibrous crystals. Andalusite is most commonly found in elongated crystals with a square cross-section and a red to brown color.

Aluminosilicates typically form during the metamorphism of clay-rich sediments; such rocks have the relatively high ratios of aluminum to silicon necessary for the formation of these minerals. The identity of the aluminosilicate formed depends upon the temperature and pressure of metamorphism; kyanite forms at relatively high pressures, sillimanite forms at relatively high temperatures, and andalusite forms at low to moderate temperatures and pressures.

TOPAZ, ZIRCON, TITANITE, AND EPIDOTE

Topaz is another aluminum-rich nesosilicate; however, this mineral also contains fluorine (F) and/or the hydroxyl ion (OH^-). The chemical formula of topaz is $Al_2SiO_4(F,OH)_2$. As the parentheses indicate, this mineral is a solid solution in which fluorine and hydroxyl can substitute for each other. Topaz is formed during the late stages in the solidification of a granitic liquid.

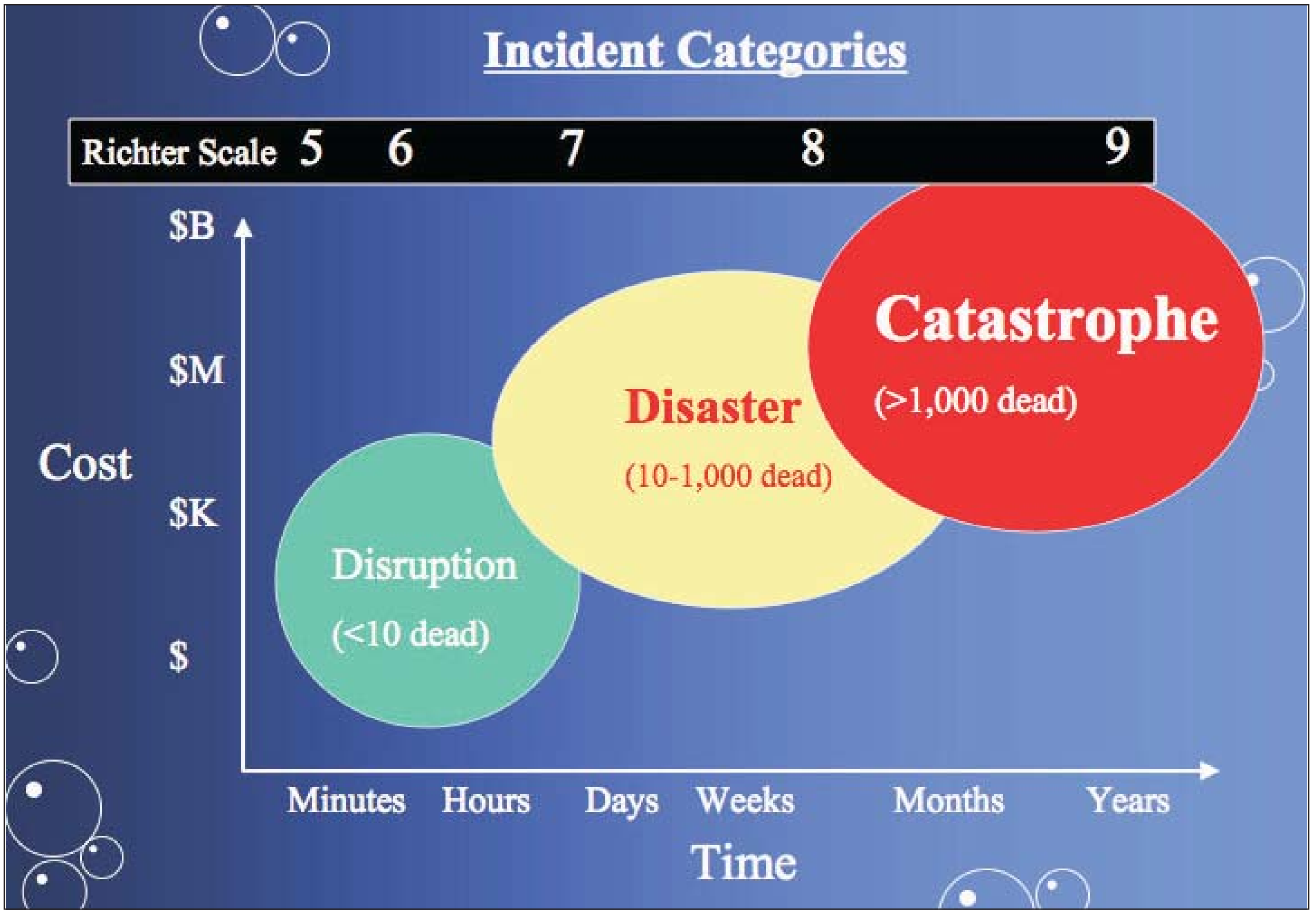
The mineral zircon contains the relatively rare element zirconium (Zr). Zircon has the chemical formula $ZrSiO_4$; it also generally contains small amounts of uranium and thorium. The decay of these radioactive elements can be used to determine the age of a rock, making zircon particularly important to geologists. It is most commonly found as brown rectangular crystals with a pyramid on either end. It is a widespread mineral in igneous rocks, although it generally occurs in relatively minor amounts.

Titanite ($CaTiSiO_5$), sometimes known as "sphene," is one of the most common minerals bearing titanium (Ti). It is a fairly widespread mineral, occurring in many different kinds of igneous and metamorphic rocks, but it is rarely present in abundance.

Epidote ($Ca_2(Al,Fe)Al_2Si_3O_{12}(OH)$) contains both isolated silica tetrahedra and tetrahedra pairs. Epidote, a fairly common sorosilicate mineral, most typically forms during low-temperature metamorphism in the presence of water. It most often occurs as masses of fine-grained, pistachio-green crystals. A pistachio-green mineral in granite is almost certainly epidote.

ANALYTICAL TECHNIQUES FOR NESO- AND SOROSILICATES

To characterize a mineral requires both its chemical composition and its crystal structure. There are



Increasing severity and costs along the Richter scale. Image via Wikimedia Commons. [Public domain.]

measuring method, Richter devised the scale that now bears his name.

Richter defined the magnitude of an earthquake as the logarithm of the height of its seismograph trace in microns (thousandths of a millimeter), as recorded on a standard instrument. Thus, an earthquake that produces a trace one millimeter (1,000 microns) high would be magnitude 3, one that produces a trace 1 centimeter high (10,000 microns) would be magnitude 4, and so on. These measurements were defined for a standard seismograph magnifying ground motion twenty-eight hundred times and located 100 kilometers (about 62 miles) from the earthquake. The magnification of the instrument means that the actual ground motion caused by a magnitude 3 earthquake 100 kilometers away is not 1 millimeter but only 1/2,800 millimeter, or only about three thousand times the diameter of an atom. By comparing records for earthquakes recorded on different devices at different distances, Richter was able to create conversion tables for measuring magnitudes for any instrument at any distance. He also set up the scale so that any event likely to be felt by humans would have a positive magnitude, because scales with zero and negative numbers tend to be confusing to most people.

Richter had hoped to create a rough means of separating small, medium, and large earthquakes, but he found that his scale was capable of making much finer distinctions. Most magnitude estimates made with a variety of instruments at various distances from earthquakes agreed to within a few tenths of a magnitude. Richter formally published a description of his scale in January, 1935, in the *Bulletin of the Seismological Society of America*. Other systems of estimating magnitude had been attempted, downslope, thereby mixing with seawater to form a turbidity current. A rapid sequence of successive breaks in transatlantic cables on the continental margin bordering southern Newfoundland was apparently caused by the downslope movement of a dense, turbulent mixture of seawater and sediment generated from the continental shelf and slope in response to the Grand Banks earthquake of November 8, 1929. Those cables closest to the point on the ocean floor directly above the earthquake, the epicenter, broke first, whereas cables farther from this point broke later. The breaking of the cables indicated the erosive capability of turbidity currents. Subsequent drilling of that part of the ocean floor traversed by the turbulent flow recovered a 1-meter-thick graded bed containing shallow water organic remains, and this discovery strengthened the argument that the flow was indeed a turbidity current. The earthquake induced turbidity current averaged 27 kilometers per hour, although it reached velocities in excess of 70 kilometers per hour in steeper parts of the continental margin, and it covered an area of more than 195,000 square kilometers.

Turbidity currents can also be generated by wave activity on continental shelves, an idea, as already noted, that was postulated in the 1930s. More specifically, large waves produced during great storms such as hurricanes are capable of creating the turbulence required to mix sediment and seawater, thereby creating a turbidity current. An equally plausible mechanism of turbidity current generation involves over steepening of the continental slope by the sudden addition of sediment. This is especially common where large rivers deposit their sediment load near the head of a submarine canyon.

The rate at which turbidity currents are generated was greatest during periods when sea level was much lower than it is today. This was especially typical of glacial periods, when more seawater was locked up in the enlarged polar ice caps, resulting in the lowering of the global level of the oceans. During these times of lowered sea level, rivers were capable of transporting their sediment loads directly across the previously submerged continental shelf into the head of a submarine canyon. There, the sediment mixed with seawater and was fed, via the submarine canyon, directly into the deeper parts of the ocean as turbidity currents. When sea level rose and the shoreline retreated landward as the exposed continental shelf was once again submerged, the river was cut off from the canyon head, thereby precluding the infusion of sediment directly to the canyon and reducing the likelihood of turbidity current generation.

CHARACTERISTICS OF SUBMARINE FANS

Turbidity currents triggered on continental shelves or continental slopes move downhill until they reach a point at which the reduced gradient of the ocean floor causes a reduction in the velocity of the sediment flow. This leads to deposition of a graded bed or turbidite. Many turbidite deposits that are funneled through submarine canyons ultimately accumulate as part of large fan shaped or cone shaped sediment bodies called submarine fans. The submarine fans, which spread outward from the mouths of the submarine canyons, merge with the bottom of the continental slope and comprise the continental rise, the broad, gently sloping feature that rises from the abyssal plain of the ocean floor and merges with the base of the continental slope. Where submarine canyons are close together along the continental shelf and continental slope, the attached submarine fans may coalesce to form a wide, laterally extensive continental rise.

In general, submarine fans are subdivided into three major morphologic elements or parts: the upper fan, midfan, and lower fan. The upper fan, also referred to as the inner fan, is typically characterized by a single submarine channel that is connected to the submarine canyon. Upper fan channels range from 2- to 18-kilometers wide and may be as deep as 900 meters. The single channel is commonly flanked on both sides by levees, low ridges that run along the length of the channel. Most of the sediment transported through the upper fan channel via the submarine canyon is deposited into the midfan, that area of the submarine fan composed of raised, lobe-like sequences of turbidites called “depositional lobes.” The depositional lobes are fed by numerous shallow and unstable distributive channels that branch off the main upper fan channel. Because these channels are generally relatively shallow (several tens of meters deep), they are more likely to be filled in during passage of extraordinarily dense turthe magma along its path of vertical ascent through the crust. Xenoliths in crystalline igneous rocks are embedded within the rock and are not exposed until erosion exposes the xenolith by removing overlying material. Granite rocks typically contain large xenoliths of metamorphic or sedimentary rocks. Such xenoliths reflect the typical intrusive process that produces granites. In this process, subsurface magma chambers expand and move upward by physically plucking country rocks from the wall and roof.

WALL-ROCK XENOLITHS

Three basic varieties of xenoliths are recognized: wall-rock xenoliths, cognate xenoliths, and mantle xenoliths. Wall-rock xenoliths are represented by blocks and pieces of the adjacent country rock that have been incorporated into the magma. Cognate xenoliths are inclusions of the chilled margins of the magma or comagmatic segregations—that is, masses of previously solidified magma that break loose and are later incorporated in more energetic magmatic motions. Mantle xenoliths are presumed to be pieces of the mantle that become incorporated in magmas that are formed by partial melting deep within Earth.

Magmatic intrusions make room for themselves by three processes: forceful injection, stoping, and assimilation. Stoping occurs when the magmatic front advances by injection into fractures and surrounding blocks of country rock. These blocks may sink in the magma, and they may be slightly altered or totally assimilated within the magma depending on the characteristics of the magma and the wall

Gabbroic xenolith in granite in Rock Creek Canyon, eastern Sierra Nevada, California. Photo via Wikimedia Commons. [Public domain.]

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