VIENNA

EARTH AND LUNAR SCIENCE

INTERACTION BETWEEN BASIC SCIENCE AND PUBLIC NEED

David Strangway, PhD, FRSC, OC

President Emeritus, University of British Columbia and Canada Foundation for Innovation

I am honoured to be one of the keynote speakers at this Science Forum of the CBTBO. This is an organization that has not only done remarkable work on the issue of nuclear detection, but through global monitoring has made major contributions to our understanding of earth system science. As was noted in my introduction, I have been active over a long career in several aspects of earth science. These range from developing techniques for mineral exploration for mining companies, to work on returned lunar samples, to working on meteorites to determine the nature of the magnetic field that was present during the formation of the solar system. The thesis that I have chosen to pursue today is the remarkable interactions between basic science, applied science and innovation. The process of innovation is typically described in the literature as a simple linear process in which the track is from basic science, to applied science, to innovation, to applications and to adoption. Somewhere along the way, this is supposed to lead to the creation of intellectual property. Eventually the process leads to spin off companies and in a few cases to wide spread adoption. If only it were so simple, it would be easy to identify and support the various parts of this linear sequence. I want to talk today, about what seems to be a more appropriate way to describe the interactions between these so-called discrete steps. The basis for innovation is much more integrated, as can be seen by the incredible revolutions that have taken place over the past two centuries. Much of today's economic and social activity can be traced to the new physics of the 1920's, as wave after wave of new impacts have affected our world. It has been estimated that some 50% of today's Gross Domestic Product in the United States has its roots in this revolution. And this is just as true in earth system science, as in any other field, as CBTBO knows better than any other agency.

A recent book on innovation by Steven Johnson describes the process of discovery and innovation in a very interesting way. The book is called "Where Good Ideas Come From – The Natural History of Innovation." He describes the process of scientific and technological development as a form of evolution and draws extensively on Charles Darwin. . The first chapter is Reef, City, Web. The last chapter is the Fourth Quadrant. In the first chapter he compares the extensive and diverse interdependent life that accumulates and develops around marine reefs. He compares this to the vibrant life that develops on so many fronts in the dynamic cities of the world. He compares these hubs of interacting complexity to the development of the web, that has linked so many parts of the world together to create new ideas. In the last chapter, he gives a list of innovations from the last two centuries, that show the move from individual innovation to networked innovation. Sometimes I say we have moved from the Renaissance Man to the Renaissance Team with both men and women. He then further separates the list of innovations into market and non market driven to show the fourth quadrant. The rise of networks and complexity is key to his book. It is in this sense that he sees the analogy to evolution in which networking and communication are the drivers. The overarching theme is that interaction and communication between so many different threads of research and practice lead to innovation .

Turning now to earth science, let me describe briefly a few interactive events. The early development of the airborne magnetometer is a case in point. The airborne flux gate magnetometer was known and developed in the 1930's by Gulf Oil, that patented the device for their exploration purposes. It was soon realized that this particular airborne system could also be used for submarine detection. The patent was turned over to the US Navy. They in turn contracted the manufacture of the device to Texas Instruments. Texas Instruments was itself already a spin-off of a seismic exploration company. The link between the private sector need and government procurement to meet a government need is evident. After the war, the instrument became available. The Canadian government, facing the prospect of mapping a very large land mass, decided to start aeromagnetic mapping of much of the Canadian shield. This they did by contracting the work out to private companies. But they still faced the problem of patent infringement. An enterprising civil servant found a modification that got them around the patent and they were in business. Here again, we see the complex interaction between technology development, meeting government needs and the creation of a private industry to meet the need through smart procurement. Much of Canada has now been mapped in this way and indeed so has much of the rest of the world. The Canadian mapping proved immensely useful in direct prospecting for iron ore deposits and a number of them were discovered. But of much greater significance, it turned out to be a truly important geological mapping tool, that set the framework for detailed ground mapping by filling in between outcrops. I was fortunate at the time to be working for a mining company and was able to compile these maps to outline the most incredible series of dike swarms. These could be traced for thousands of kilometers across the shield. This provided a fascinating insight into the tectonics of the Canadian shield.

The point I want to extract from this story, is one that comes again and again in the sciences and is relevant for this meeting with its focus on the earth sciences. Which came first, The technology of the fluxgate? The military need to detect submarines? The geologic need for mapping huge areas quickly and efficiently? The answer is all of them. As Steven Johnson points out in his first chapter Reef, City and Web, the reefs and the cities are places of intense interactions. The reef teems with life and now the web connects the world. And as we will see later, the magnetometer again played a very important role in the plate tectonics revolution.

I was fortunate, during the time I worked in the mining industry, that I was able to carry out a great deal of work on new electromagnetic techniques for mapping and searching for conducting orebodies. I was able to use artificial transmitters as well as the natural sources of audio frequencies provided by nature. Thunderstorm energy is trapped in the earth ionosphere wave guide and the electromagnetic impulses can be detected around the world.

I will turn now to what I call the planetary revolution. You will have heard in the introduction, that I was privileged to be Chief of Geophysics and of the Earth and Planetary Science Division in Houston for NASA during the Apollo lunar missions. As you can imagine, this was a very exciting time as the first full scale exploration of another planetary body was carried out. It is important to remember that the decision to land a man on the moon had nothing to do with studying an adjacent planetary body. The decision to go to the moon was not based on the need to do science. Instead the objective of the Apollo missions was to demonstrate that the United States had technical superiority and could successfully carry out such a complex technological feat. This was in its day, an expensive mission. How many times were we asked whether landing on the moon meant that other important things were not done? My answer was to point out that the money was not deposited in a bank on the moon. It was largely spent on people and the money spent went into banks right here at home. It has always been my view, that we the scientific community, were extremely privileged to be able to participate in this exploration and to be funded to do so as a small part of the Apollo missions. Again, technology was developed to meet a very specific public need as defined by government. From this technological development flowed remarkable scientific breakthroughs. This is a reversal of the traditional linear chain model that leads from basic science to applied science to innovation.

The earth scientists had finally taken over the moon from the astronomers. We could now do actual surface experiments and work on returned lunar samples. Many experiments were carried out. Five stations were established on the surface that monitored a number of phenomena. There was at one time a network of five seismometers working simultaneously, admittedly on the front face of the moon and largely in the equatorial plane. Because the moon is so dry, seismic waves do not attenuate much and travel long distances. We were fortunate, for example, to have some meteorite hits on the far side of the moon and to detect them at all five stations on the front side. This told us that if there was any core at all, that it must be too small to be detectable with this array. There were magnetometers on board, but the moon has no overall magnetic field. The magnetometers largely detected fluctuations in the solar wind fields. These fluctuations could have caused electromagnetic induction in the moon, if it had been warm and electrically conducting. But again there was no sign of a hot core.

There were a number of surface geophysical experiments. Holes were drilled a few meters into the soil and then used to determine the heat flow. A very insulating, powdered soil in a perfect vacuum made an almost perfect thermal blanket. The wide surface temperature variations from day to night hardly penetrated. This confirmed the earth based mapping of thermal emissions in the infrared and microwave frequency ranges. There were shallow seismic refraction profiles carried out. There were lots of signals bouncing around due to the very low absorption characteristics of the dry soil, and the highly fractured subsurface. There were no coherent reflectors. I was fortunate that on Apollo 17 I was able to send an electromagnetic sounding experiment. This was of course quite different than my earlier experience on the earth, since the moon, like ice is quite transparent to radio waves. A transmitter was placed near the lunar module and the receiver was mounted on the Rover. Signals clearly penetrated to a depth of over one kilometer, but again there were no reflectors. There was a lot of scattering from the crushed near surface material, especially at the higher frequencies. We were able to determine the electrical properties of the surface. This experiment followed my experience earlier in mining exploration, where electromagnetic sounding had reached a highly developed level. The earth based testing for the lunar work was done on glaciers. The glaciers were good analogues since ice is highly transparent to radio waves. This in turn, formed the basis for later developments in Ground Penetrating Radar, now widely used

The orbiting spacecraft had minor variations in velocity, that were detected and measured with the result that significant gravity anomalies could be mapped. And with laser and radar altimeters there could be robust interpretations. These became even more detectable along with local magnetic signals when subsatellites were left behind in low orbit.

Perhaps most importantly, through much work on the returned lunar samples it was possible to determine much of the evolutionary history of another planetary body. The lunar highlands had been intensely fractured by bombardments from the earliest days of the solar system, formed 4.6 billion years ago. This early bombardment by meteorites slowed down about 4 billion years ago. Subsequently, there was some limited volcanic activity, that filled some of the mare basins on the front side of the moon from about 3.8 billion years to about 3.3 billion years. And then even these lava flows ended. Following my own earlier work on terrestrial samples, we were able to measure the presence of a small field that had existed in the early stages of the moon's history. This small field is likely related to the field that was present during the accretion of the solar system.

The moon is in a perfect vacuum . This means that it was possible to do a considerable amount of geochemical mapping from orbit. This included X-ray spectrometer mapping as well as Gamma Ray spectrometer mapping and alpha particle detection. Since the lunar surface is under steady bombardment from solar particles, there is steady emission of secondary X-rays. This emission could be detected at orbit levels and so geochemical maps of elements such as Al, Mg, Si and others such as O, Fe, Na, K and Ca could be made. From the gamma ray spectrometer, it was possible to map the distribution of U, Th, and K, as well as some elements activated by cosmic rays. The alpha particle spectrometer detected Radon and Polonium.

It seems to me, that this is a case in which a major undertaking to meet a national goal led to immense technological capacities to go and come from the moon. As a result the science of the moon and planets was taken to a new and revolutionary level. This has led on to learning more and more about the other planets and satellites as well as about comets and asteroids. There is little doubt that this new understanding of the origin and evolution of the moon was the basis for a revolution in earth and planetary science.

Now let us turn to the other scientific revolution. Plate tectonics. Once again this new approach to earth system science has many parents. Sea floor mapping was one of the keys. And much of this was financed by several agencies, in particular the US Navy. This demand by the Navy, stemmed from many needs including how to hide submarines in the ocean. Systematic mapping of the magnetic anomalies of the sea floor was one of the critical needs. Fortunately again, the scientific community was given the opportunity to study these records for their intrinsic scientific value. This was at the very time that regular reversals of the earth's magnetic field had been widely recognized and documented. It was an important conceptual step to make the link between the time sequence of reversals and the recognition that this could be closely correlated to distance from the mid ocean ridges. Suddenly, the translation from distance from the mid ocean ridge to being a measure of the time since the upwelling of the ridge became obvious. It is interesting that the first paper to make this link was rejected by the journal Nature. It was by the same person who many years earlier had initiated the use of aeromagnetic mapping of the continents. People at the CTBTO will know better than anyone about the major investments made in an attempt to do earthquake prediction. It was at least in part, because of this need that the idea of the global seismic network was started. And of course there was the need to detect nuclear explosions that might be set off clandestinely. This massive investment in the world wide network, was a key to the Plate Tectonics revolution. It was now possible to systematically map earthquake distribution around the globe. This clearly identified the mid ocean ridge spreading centres in spectacular fashion and the nature of the activity at colliding plate boundaries. These maps and the nature of the various types of earthquakes have been integral to the plate tectonics revolution. Massive investments to meet well determined needs for military purposes and human security needs have been one of the key planks in the evolution of earth system science. Basic science has benefited from the need to solve problems and from the advances in technology driven by global monitoring by CTBTO.

The links I have been describing go far beyond the earth sciences. Much of our modern world is the beneficiary of the many interactions between applications and need-driven efforts. New technologies may derive from basic science, but cutting edge science also derives from the opportunities provided by new technologies. Yes, scientific breakthroughs and revolutions do not arise from the linear chain as is so often depicted.

Now I want to turn my attention for a few minutes to some of the thinking that might drive the next steps in on site inspection. It is interesting to contemplate that seeking ground truth of nuclear underground explosions has some comparisons to the search for ore bodies or to the search for suitable disposal sites for nuclear and other wastes. Kimberlite pipes are where diamonds are found. The diamond explorer is always searching for ways to detect the presence of these pipes. The scale of these pipes is comparable to the signature left by a nuclear explosion and would be good test sites. In the sedimentary basins of Western Canada, there are a number of buried paleocraters or astroblemes as they are called, resulting from meteorite impacts hundreds of millions of years ago. These are detected from time to time during seismic reflection exploration. These would also be interesting test sites. There are a number of geophysical techniques that are in widespread use, which are clearly adaptable to the search for nuclear explosion sites. These are both airborne and ground based.

Magnetic mapping can be done from ground based surveys and from airborne surveys. The signature of material that has been heated above 580 degrees celsius, the Curie point of magnetite, the predominant magnetic mineral, is likely to be distinctive. Just as it is, in the case of explosively implanted kimberlite pipes which also became magnetized as they cooled. Magnetic mapping is one of the major methods that has been used to detect often hidden kimberlite pipes. This has largely been done using airborne magnetometers, using fixed wing or helicopter borne aircraft. We are of course today, all aware of the use of manned drones for surveillance. But a whole new generation of small, unmanned aircraft are now in use. These are both fixed wing aircraft and helicopters that can readily carry magnetometers and other devices and follow a predetermined track, as they conduct very low level surveys, just above the ground . Tracking by use of GPS provides accurate locations. Magnetometers can be mounted on all terrain vehicles or towed behind them.

There are other approaches that can be taken. In the past few years, it has become possible to conduct gravity mapping on aircraft and it is only a matter of time, before the weight of these devices will be suitable for unmanned aircraft. The use of GPS and laser ranging to provide the topographic information needed to interpret gravity data is readily at hand. This approach will help greatly in detecting underground cavities for example.

There is a wide range of electromagnetic sounding techniques in common use. These are typically used for detecting electrically conducting parts of the shallow crust. In this case, a source of audiofrequency energy is transmitted from a transmitter and received by a receiver looking for the induction due to eddy currents. Again ground based and aircraft based systems are in common use. Changes in the electrical structure resulting from an underground explosion could be detected in this way. Another electrical technique in common use is the induced polarization technique. In this case not only is the electrical conductivity measured, but the polarization associated with disseminated metals or clay particles in the subsurface is mapped. It seems possible that a nuclear underground explosion will disturb the natural polarization and might thus be detected.

Ground Penetrating Radar systems could also be deployed and can be rapidly and efficiently used. GPR does not penetrate very far in the presence of near surface conducting material such as many clay deposits. In many terrains it can usefully be employed for shallow mapping and detecting subsurface disturbances. These can easily be mounted on surface vehicles.

There are of course many other approaches including shallow seismic mapping. And it may be that the use of infrared thermal mapping could be useful. A great deal of work has been done to search for the thermal signature of oxidizing ore bodies, by over flights at the earliest hours of the morning when the effect of the sun is at its lowest point. This could be supplemented by microwave thermal emission studies that are less sensitive to the very surface temperature and provide an average of the top few meters. And of course synthetic aperture radar together with emission data is a powerful combination. Perhaps there will be disturbance in the thermal properties that can be actively exploited.

And finally there is gamma ray spectrometry which is widely used for mapping of naturally radioactive minerals in the mineral exploration field, as well as in geological mapping.

And now I conclude. My principal point is that innovation is a process that involves many different ideas and participants. It knows no discipline boundaries and can come from unexpected and unpredicted directions. Sometimes it is driven by basic research, but just as often it is driven by specific needs to solve problems Often innovation comes from national or international demands. And that activity in return is often the source of breakthroughs in basic science. No one knows this better that than the CTBTO. The work of nuclear detection has in one sense derived from basic science, but the CTBTO has played an enormous role in the development of earth system science. Yes, indeed we live in an interconnected world, in which innovation is a form of evolution. No doubt we will hear a lot about this in the next two days.