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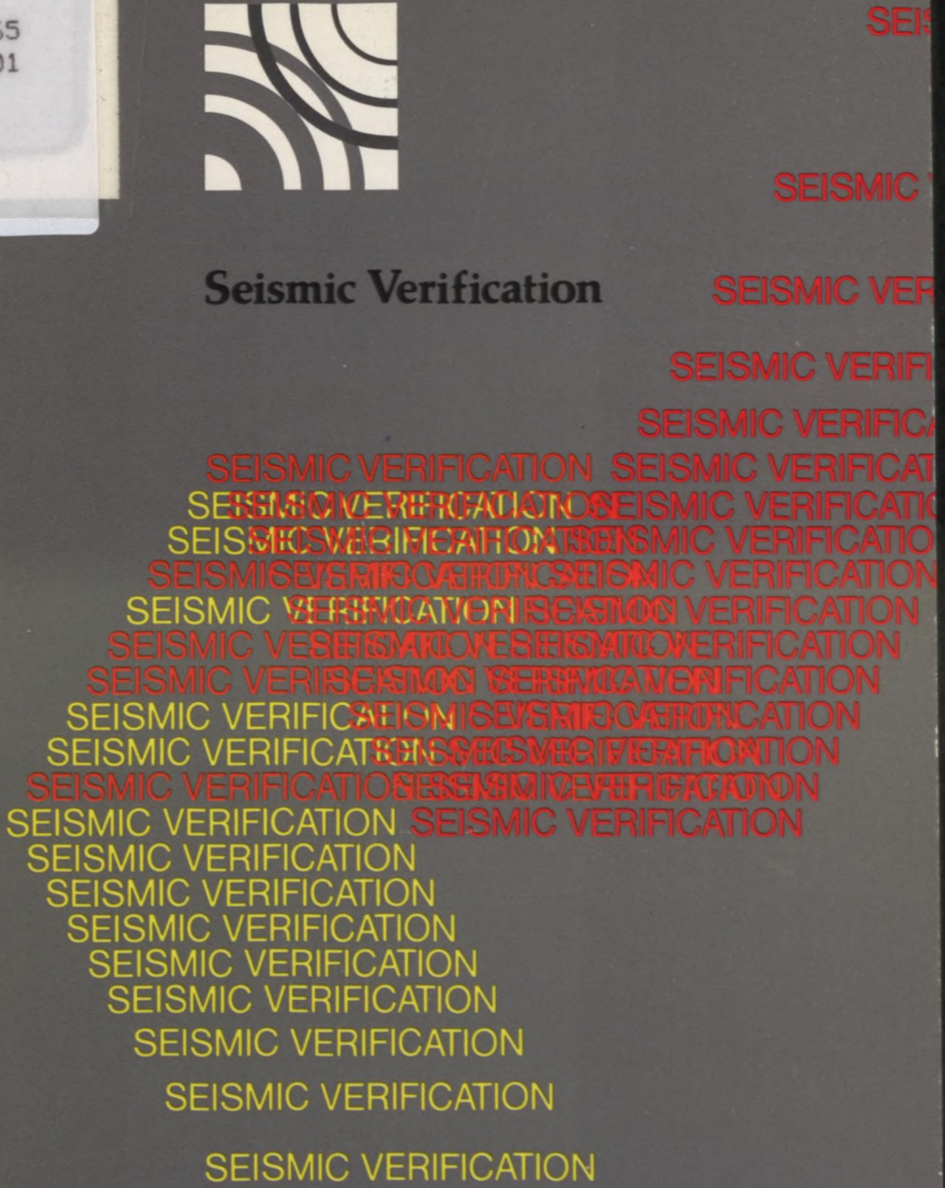
Seismic Verification



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Seismic Verification

"The graphic on the cover page represents the ongoing dialogue on arms control and disarmament issues in Canada and between Canadians and the world community."

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Chapter One

Introduction

Planet Earth, no matter how solid it may sometimes seem, is really a gigantic sounding board. By applying appropriate "ears" to the ground, one can sense vibrations caused by significant events that may have occurred 10 000 kilometres away.

The noises most commonly heard are natural in origin — the results of earthquakes, the pounding of waves on distant shores and weather noise — but humans make their own contributions through daily activities such as mining, construction and the operation of trains and motor vehicles.

The most dramatic of all noises of human origin, however, derives from underground nuclear explosions, which may cause shocks in the Earth's crust comparable to those of sizeable earthquakes.

The instruments that are used to detect such events are called seismographs. These sensitive devices record both vertical and horizontal movements of the Earth's surface that may not be sensed by human beings. The seismograph may be the most important means of verification for a treaty prohibiting all underground testing of nuclear weapons.

When a sufficiently large number of suitably located seismographs sense the same event, it is often possible to compare their findings and determine with a fair degree of certainty the nature of the event causing the shock waves, its location, its depth below the surface and the approximate amount of energy involved.

Canada has a long tradition in geophysics and in the monitoring of earthquakes. Canadian experts who have spent their careers studying such matters believe that Canada has a unique role to play in the development of reliable verification systems that would be an essential prerequisite to the conclusion of any comprehensive test ban treaty. Canada's size, geographical position (see Figure 3), and geological similarity with the great continental rock mass that underlies much of Europe and Asia, as well as our own technical expertise, make this possible.

Figure 1 Definition of verification

"Verification is the establishment of truth or correctness of (something), by examination or demonstration"
(Concise Oxford Dictionary)

No single issue in the 1980s is likely to be of greater significance in international arms control and disarmament negotiations than *verification*. Particularly in an era of increased suspicion and uncertainty, nations are unlikely to accede to treaties affecting their own national security without some adequate means of assurance that other signatories will, in fact, be living up to the terms of the agreement. In simple terms, *verification* is the means by which such assurance is gained. Whether it is through the use of consultative mechanisms, photo-reconnaissance satellites or on-site inspections, the ability to agree upon an effective system of verification can mean the success or failure in the negotiation of an arms control agreement.

Can such systems be developed to the point where they will inspire a reasonable degree of confidence, and thus pave the way to an end to nuclear testing?

Canadian seismic experts who have been involved in the Geneva negotiations on this subject for several decades stress that the problem is a highly complex one that still involves many unknowns on the technical side.

Furthermore, they say the problem can be solved only in an atmosphere of genuine international goodwill that includes a willingness on the part of all nations to make more national seismic information available than in the past. Additional concessions, such as permitting the establishment of an adequate number of international listening stations within their national borders, may also be necessary.

As part of the Government's continuing commitment to keeping Canadians informed on various arms control and disarmament issues, this brochure will examine the present state of technological capability for monitoring an underground test ban, explore the potential for further improving this capability and describe Canadian contributions to this arms control effort.

Figure 2 Number of nuclear explosions 1945-1983.

A total of 1 469 nuclear explosions have been carried out on our Earth since 1945 according to current figures available from the Swedish Defence Research Institute. Of these explosions, 461 have been carried out in the atmosphere and 1 008 underground.

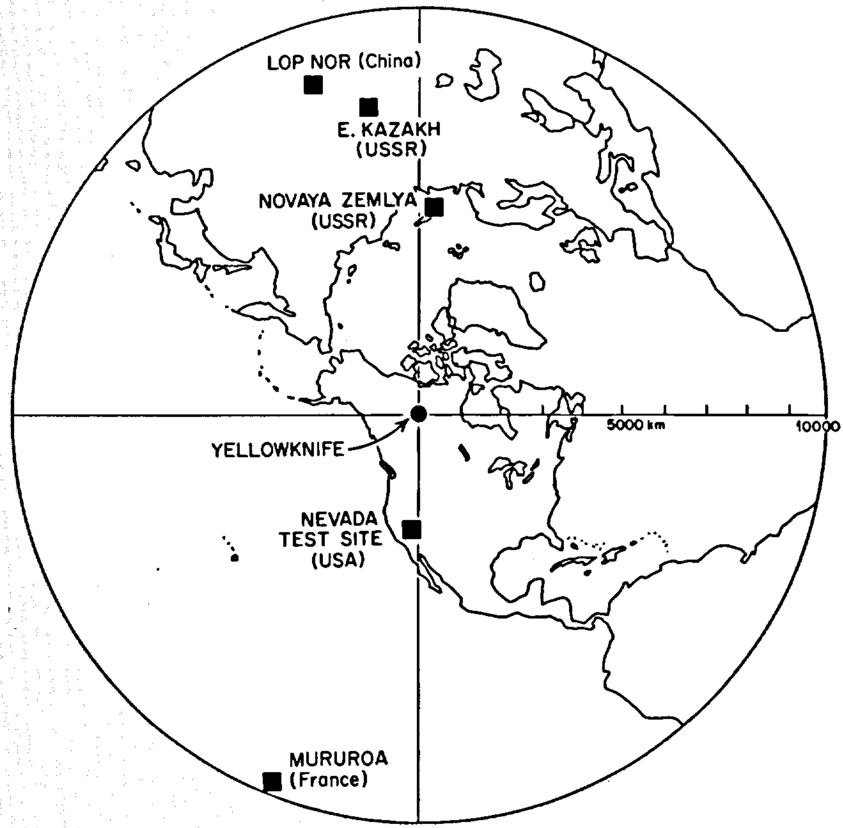
The following table shows nuclear explosions by country of origin:

	Atmosphere	Underground	Total
France	45	75	120
India	—	1	1
China	22	5	27
Soviet Union	161	368	529
United Kingdom	21	15	36
United States	212	544	756
	461	1 008	1 469

The table shows that the United States has carried out the greatest number of nuclear tests and that the two superpowers together have accounted for 87 per cent of the total. In the last few years the USSR has conducted the most nuclear tests, while the total number of tests has been comparatively constant at an average of 51 explosions per annum, i.e., about one test a week.

Seismic evidence indicates that most, if not all, nuclear explosions today are carried out underground. China has not adhered to the Partial Test Ban Treaty and has carried out occasional atmospheric tests, the latest in October 1980. Nor has France adhered to the treaty, although it has officially declared that it will not carry out nuclear weapons testing in the atmosphere. No such tests have been carried out by France since 1974.

Figure 3 Map of nuclear test sites. The Yellowknife seismograph array is within 10 000 km of all principal underground nuclear explosion test sites.



The Physical Setting: 'The Earth as a Sounding Board'

Chapter Two

The Physical Setting: "The Earth as a Sounding Board"

To appreciate the nature of the challenge that scientists face in this vital area of arms control, it is useful to visualize the Earth as a sphere with an approximate radius of 6 500 kilometres and a circumference of about 40 000 kilometres. It consists of three main components: the crust, the mantle and the core (see Figure 4).

The discontinuity between the mantle of the Earth and its liquid core presents an effective barrier to the transmission of most seismic waves, either reflecting them upwards or deflecting them into the Earth's core. Thus, the core of the Earth casts a "shadow" which prevents listening stations from clearly detecting certain seismic waves at distances beyond about 10 000 kilometres.

Another limitation stems from the fact that different geological formations transmit seismic waves with different degrees of efficiency. Hard granitic rocks and salt deposits, for example, transmit high frequency shocks comparatively well, whereas tuff (a rock composed of compacted volcanic fragments) transmits seismic waves poorly. Sedimentary deposits, often of sandy or muddy origin, are even less efficient transmitters of seismic waves. The result is that the recorded size of the seismic waves produced by a given event, when measured some distance away, could vary by a factor as large as 10, depending on the type of terrain in which it occurred.

When a seismic event occurs in the Earth as a result of an earthquake or an underground explosion, it produces different types of seismic waves, of which the two main categories are body waves and surface waves.

Body Waves

Body waves travel through the "body" or mantle of the Earth. The fastest travelling body wave is the P (primary) wave, which is much like a sound wave travelling in the solid Earth. The second type of body wave is the S (shear) wave, which travels at about 60 per cent of the velocity of a P-type body wave.

Figure 4 Cross-section of the Earth showing paths of seismic waves. Shadow zone is caused by waves deflected by the Earth's core. The time delay between direct P and the P wave reflected from the surface (pP) is indicative of the depth of the seismic event.

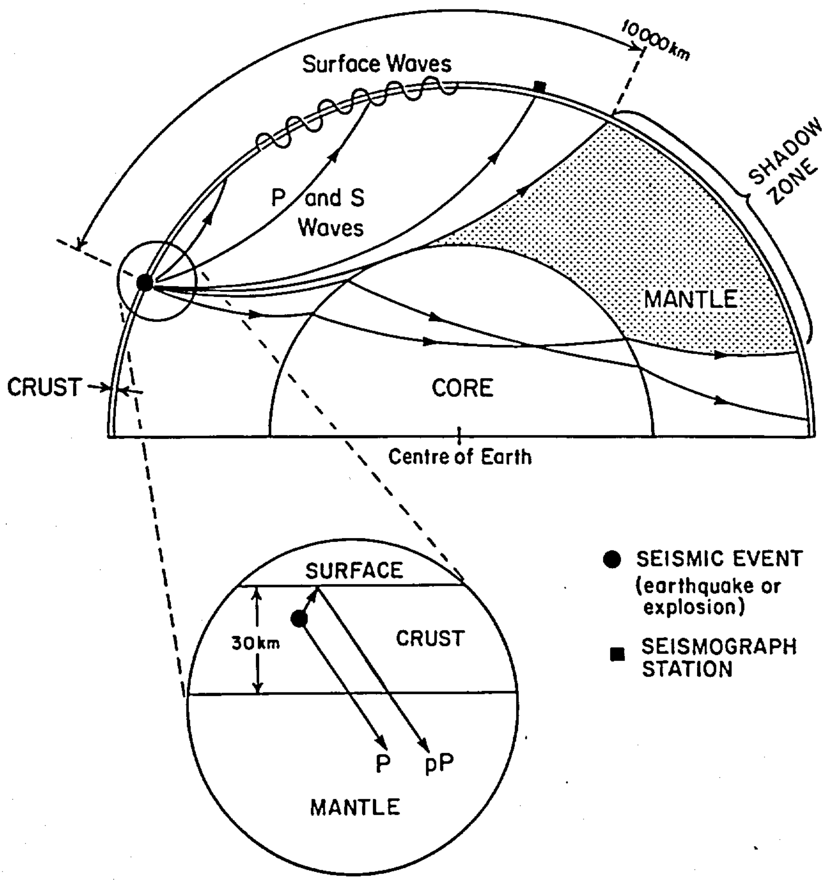


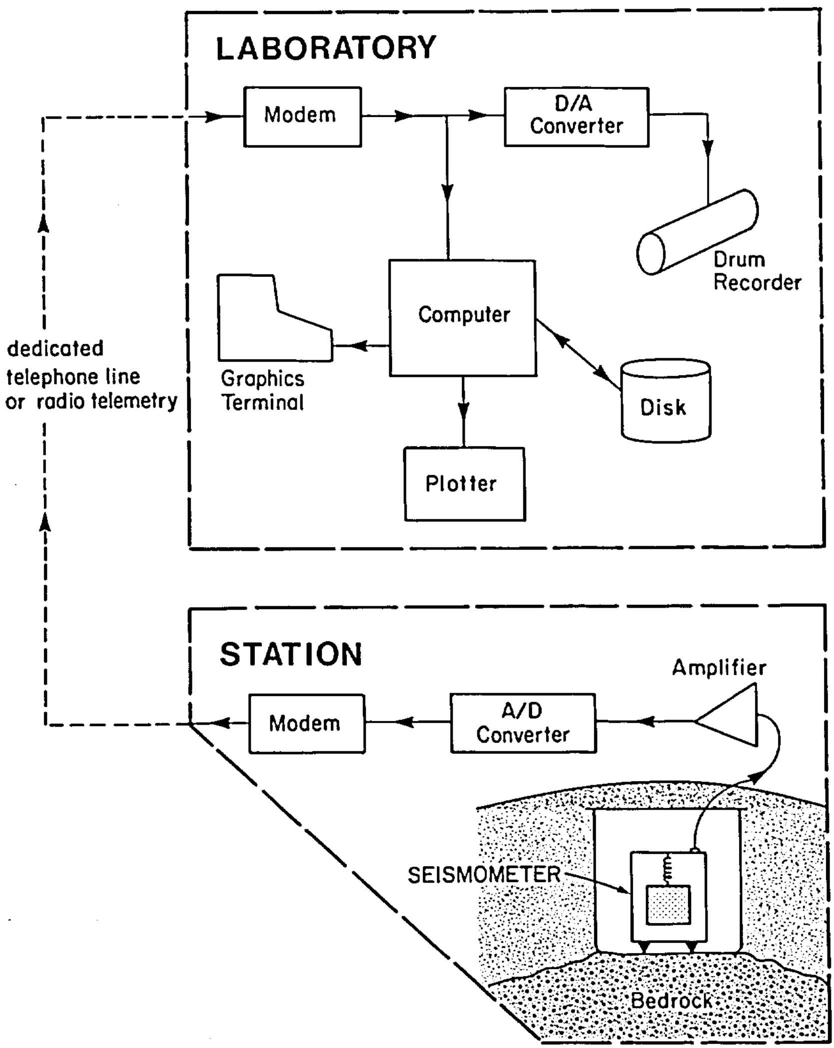
Figure 5 The seismograph. The instrument used to detect seismic waves is called a seismometer (as illustrated on page 19), and usually takes the form of a canister, about 20 centimetres in diameter and 30 centimetres high, lined with a coil of wire. Inside the coil and suspended from the top of the canister by a spring, is a permanent magnet, free to move up and down within the coil.

The coil-lined canister sits on solid rock and any Earth vibration will cause it to move up and down, but the magnet, being somewhat massive, will tend to stay where it is. This relative motion will induce a weak electric current in the coil that can be measured and recorded as a wave form on a moving roll of paper or on magnetic tape.

The current induced in the coil will be proportional to the movement of the magnet within the coil. The natural period of vibration of the spring is that of an average P (primary) wave, or about one second. However, by tuning the electric amplifier that records these movements, one can record seismic waves with frequencies of up to 100 cycles per second.

Although the seismometer is a relatively small and compact device, a seismograph installation may include any number of seismometers, as well as a data laboratory, a computer system and assorted electronic equipment to digitize data for more powerful analysis.

Figure 6 Schematic diagram of a typical modern digital seismograph installation.
(A–analog, D–digital).



All body waves travel at a velocity proportional to the density of the medium in which they are travelling. They tend to follow the fastest path and therefore pursue routes deep in the Earth, where the material is more dense. P-type body waves have a cycle of about one second. It is these higher frequency body waves that are felt by humans and cause damage in the region of a strong earthquake. S-type body waves, which may be recorded by seismographs in the case of earthquakes, are usually absent or of little importance in the case of explosions.

Surface Waves

Surface waves, (also called Rayleigh waves, after the first scientist to describe them) behave like ripples on the surface of a pond. They travel much more slowly than body waves and have a much lower frequency of vibration — surface waves have a period of about 20 seconds — yet have an important part to play in detection seismology, particularly when it comes to identifying the source of an event.

"Different Signatures"

When an Earth shock of sufficient magnitude occurs within the range of a given listening station, the first signal to be recorded will be a P-type body wave. This may be followed by other P waves that follow different and slower routes, and then, particularly in the case of a deep subterranean earthquake, by what are known as pP waves which first travel upwards and then are reflected downwards again by the Earth's surface.

Perhaps 20 or 30 minutes later, if the shock is a distant one, low frequency surface waves will probably be recorded. The difference in the arrival times of P-type body waves and the surface waves will usually provide an approximate estimate of the distance of the seismometer from the source event.

Whereas an earthquake usually provides a complicated assortment of seismic waves because of the large area of geologic movement involved, explosions provide relatively simple signatures. As a result, to the experienced seismologist the waves created by explosions tend to appear very different from those of earthquakes. Those of explosions, for example, are usually of higher frequency and shorter duration. Also, the initial P-type body wave from an explosion tends to be larger than that caused by an earthquake.

It is thus relatively easy for an expert to distinguish between earthquakes and explosions of large magnitude. Problems arise, however, in making distinctions at low magnitudes. Dr. Robert North, senior research seismologist at the Earth Physics Branch of Energy, Mines and Resources Canada, explains that two difficulties are experienced in interpreting the records of smaller events: first, there is a tendency for the seismic wave signals to get buried in background noise such as ocean movements or wind; and second, small explosions and small earthquakes tend to look alike on seismograph records.

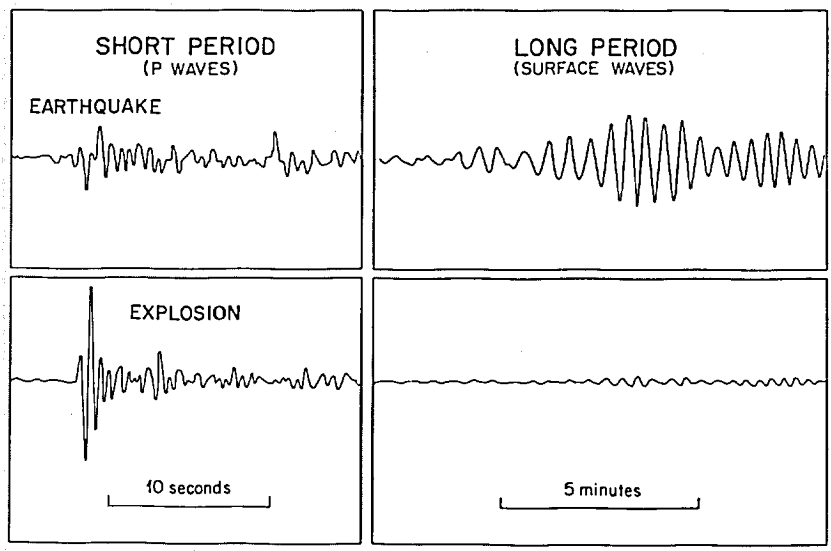
Detection and Identification
Any verification program involves two distinct processes: (i) detection, or the recognition that a seismic event has taken place and where; and (ii) identification of the nature of the event.

In the opinion of Dr. Peter Basham, head of seismic verification research at the Earth Physics Branch, Department of Energy, Mines and Resources, the threshold at which there is confidence in the ability to detect and identify a nuclear explosion against background Earth noise is the key issue in seismic verification as far as drafting any hypothetical treaty is concerned.

Usually, a number of stations will record a specific event. The more stations that do, the better the information will be. Furthermore, if the stations are suitably placed in a geographical sense, then it should be possible to estimate where the event took place with an accuracy of between 10 and 30 kilometres. Once the location has been established, highly sophisticated analysis of the data by a seismologist may be necessary to establish the nature of the event, particularly if the signals are detected just above the level of background noise.

It may also be important to determine the energy released in an explosion, particularly if a treaty (in the absence of a complete ban on testing) establishes a threshold limit on test size. When an event has been identified as being of nuclear origin and it comes to determining the energy released, adjustments are made to the seismic readings (calibration) on the basis of seismic data previously collected for the same region. Ideally, such data would be provided by the country of origin; however, a problem exists be-

Figure 7 Seismograms of body and surface waves, short and long periods. Recorded at the station in Glen Almond, Quebec from an Earthquake and an explosion. Both took place in the USSR in October 1984 at a distance of approximately 8 000 km. As shown by these seismograms, the most important difference between the signals from the two types of events is the much smaller surface waves produced by the explosion.



cause some countries, notably the USA, have provided a great deal of data while others have provided little or none.

The USSR, for example, has its own national seismic network, used for detection of earthquakes within its territory and as part of the global earthquake detection network. While the West has had access to some of these data, the USSR has never released seismic data on any nuclear explosion conducted at their test site.

Peaceful Nuclear Explosions
In 1976 the USA and USSR signed the Peaceful Nuclear Explosions Treaty which requires that both nations share information and access to sites of explosions used for peaceful purposes. Pursuant to this agreement both superpowers have released much information about the purpose of such explosions. For example, although the USA discontinued its use of peaceful nuclear explosions in 1973, they had generally been used until that time to create potential reservoirs for petroleum products or to explore the possibility of extracting heavy oils. In the case of the USSR, purposes have included:

- Excavating surface canals;
- Water diversion;
- Creating cavities for the storage of petroleum products; and, on one occasion;
- Extinguishing an oil-well fire.

Under the agreement, both countries also agreed to share data relating to the energy yields of these explosions, as well as data on the type of rock in which the explosions are carried out. Such information is needed in the calibration and, consequently, the overall verification process. To date, these data have been made liberally available by the USA and it is hoped that similar data will soon be released by the USSR.

Figure 8 Number of announced peaceful nuclear explosions (held outside ordinary testing sites).

Year	USSR	USA	India
1961		1	
1962		2	
1963		4	
1964		8	
1965		3	
1966	1	7	
1967		4	
1968	1	4	
1969	4	2	
1970	3	1	
1971	7	1	
1972	9		
1973	5	3	
1974	3		1
1975	2		
1976	2		
1977	5		
1978	7		
1979	8		
1980	3		
1981	5		
1982	16		
1983	13		
Total	**94**	**40**	**1**

A History of Canadian Involvement in Seismic Verification

Chapter Three

A History of Canadian Involvement in Seismic Verification

Scientists and Diplomats

To sharpen the Canadian capability to monitor underground tests, an inter-governmental program was recently initiated wherein the Department of External Affairs' Arms Control and Disarmament Verification Research Unit has provided funding to the Earth Physics Branch of the Department of Energy, Mines and Resources for additional personnel and hardware. As part of this program, technical experts from Energy, Mines and Resources work closely with diplomats of External Affairs on international negotiations regarding treaties that would limit or prohibit testing of nuclear weapons.

The responsibilities of the Earth Physics Branch include operation of the Canadian Seismograph Network. With the data from this network, the branch makes a continuing contribution to global earthquake monitoring by sharing Canadian data with international agencies. The branch's primary purpose, however, is to monitor Canadian earthquakes and study seismic risk in Canada.

Canadian seismic experts have been involved in arms control efforts since it was realized that seismology could contribute to the monitoring of underground explosions. In 1958-59, for example, the Earth Physics Branch was represented in a conference of experts that met in Geneva to discuss the possibility of seismic monitoring of a future test ban treaty.

Dr. Peter Basham, whose name is now well known in scientific literature on seismological matters, recalls that the single most significant event that brought experts from around the world together on that occasion was the first recorded underground testing of a nuclear device in Nevada in 1957. Its reverberations were detected by seismographs to a much greater distance than had ever been anticipated.

Although there had been negotiations between the USA and the USSR in the late 1950s, the 1958 Geneva meeting of experts was the first significant meeting of East and West to discuss seismic verification at a technical level. Those taking part concluded that an underground test ban treaty could be monitored by the combined efforts of 150–170 seismograph stations distributed throughout the world.

Figure 9 The Dominion Observatory Building on Carling Avenue in Ottawa now houses the Earth Physics Branch of the Department of Energy, Mines and Resources.

Stations in existence at the time were designed purely for the purpose of detecting earthquakes and research started immediately to determine the type of improved seismograph that could be useful in monitoring a hypothetical test ban treaty.

The United Kingdom was first off the mark. The UK Atomic Energy Authority started experimenting with cruciform arrays of seismographs, basically using the then-developing radio antenna theory to detect seismic waves. These arrays could be "steered" electronically to reduce earth noise and improve detection. They were also able to determine an approximate direction and distance (and thus location) of a seismic event.

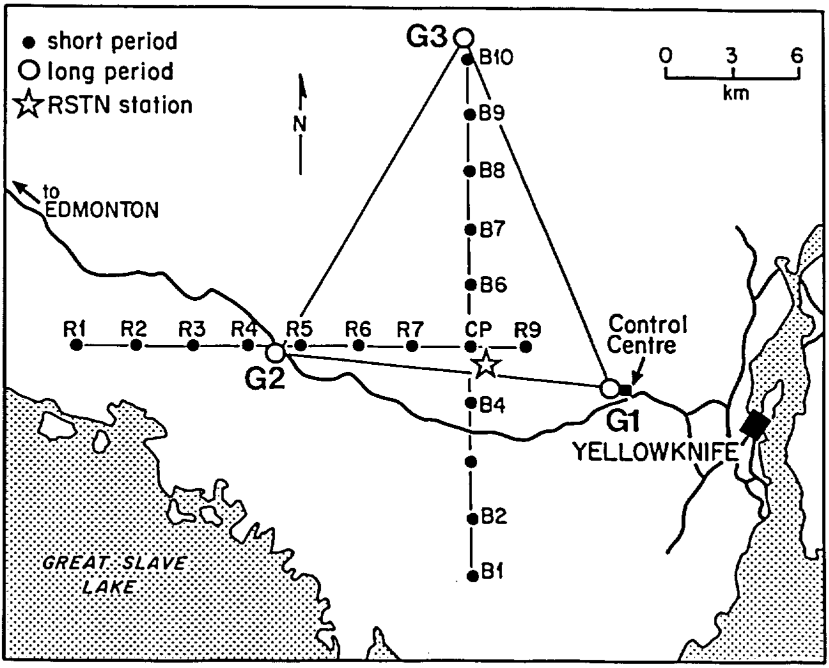
In the early 1960s the British built four of these arrays, all of which are still operating, in Scotland, India, Australia, and the Canadian Northwest Territories near Yellowknife. The Yellowknife array comprised 19 seismometers and had four arms, each about 10 kilometres long.

The original Yellowknife array was administered by the Canadian Defence Research Board until 1962, when responsibility was transferred to the Department of Energy, Mines and Resources. The array was much improved over the years and is now computerized. It forms a small but significant part of a continent-wide network of Canadian seismograph stations now numbering more than 100.

The scientific literature demonstrates that during those early years, the small Canadian group of experts made a substantial contribution to the general understanding of what reliable detection and identification of distant seismic events entails. During the past 10 years, the research of this group has become increasingly linked to the highly technical international discussions on verification of a test ban treaty. These are conducted mainly in Geneva, with scientists of Energy, Mines and Resources acting on behalf of the Department of External Affairs.

One indication of the Canadian interest in achieving an effective test ban treaty was our sponsorship in the United Nations General Assembly in the late 1960s of a key resolution asking all countries to deposit with the UN information about the capabilities of their respective seismic observatories. This was so that an assessment could be made of their capacity to contribute to a test ban moni-

Figure 10 Yellowknife seismograph array, N.W.T. The short period seismometers, separated by 2.5 km, form an irregular cross; the long-period seismometers form a triangle about 16 km on a side. Seismic data from the seismometers are transmitted to the Regional Seismic Test Network (RSTN) control centre in Albuquerque, New Mexico by radio telemetry.



toring network. Large volumes of material poured into the UN headquarters in New York and was analysed with Canadian help. A paper by Basham and Whitham of the Earth Physics Branch summed up the results and concluded that, with the network then existing, there was a 90 per cent probability of detecting any seismic event of Richter magnitude 4.5 in the northern hemisphere. However, there was much less confidence in the ability to identify correctly whether that same event was an earthquake or an explosion. An event of such magnitude would be equivalent to the detonation of a 3–10 kiloton explosive in a hardrock situation.

Capability for detection in the southern hemisphere, which is 85 per cent ocean, would be much less because of the paucity of good seismograph stations. The Canadian report contained a number of recommendations on how this detection capability might be improved and further papers addressed the question of how to improve estimations of the yield of remote events.

International Efforts

Chapter Four

International Efforts

In 1976 the Conference of the Committee on Disarmament in Geneva gave the Group of Scientific Experts its first mandate. The Group was asked to specify the technical features of a possible international seismic data exchange system and to provide factual results and analysis of data exchange methods.

The key words here are "international seismic data exchange." Equally important is an understanding of what the mandate does not encompass. The Group is not, for example, intended to design or develop an international system to monitor compliance with any hypothetical treaty. Rather, its objective is to facilitate verification by any interested state through a co-operative exchange of relevant seismic data.

In other words, what the Geneva Group has been doing since 1976 is discussing the technical and seismological means to achieve such an exchange of data among participating countries. The system, as now devised, would make data available to any participating country desiring it. Verification would remain a national responsibility.

Members of the Group of Scientific Experts meet in Geneva for two weeks twice each year. As a result of their initiatives, international experiments were conducted in 1980, 1981 and 1984 to test and improve a key element in worldwide monitoring, that of speedy international data exchange. By far the most important of these was the International Seismic Data Exchange experiment, conducted on a worldwide basis from October 15 to December 15, 1984.

Seismic Data Exchange

Chapter Five

Seismic Data Exchange

As in the case of the experiments sponsored by the Group of Scientific Experts in 1980 and 1981, the results of the 1984 International Seismic Data Exchange experiment emphasized the importance of reliable and speedy communication. The transmission network used was that of the World Meteorological Organization, known as the Global Telecommunications System. This data link was originally intended merely for the international exchange of weather data but for about 10 years the World Meteorological Organization has allowed it to be used for "other environmental data." Within this context, six or more countries have been making routine use of it for the exchange of seismic data for global earthquake monitoring.

In view of the quantity of data envisaged, some fears were expressed that the Global Telecommunications System would be brought to its knees by the flood of additional data involved in any comprehensive global seismic experiment. This did not occur, however, partly as a result of restricting seismic traffic to off-peak hours.

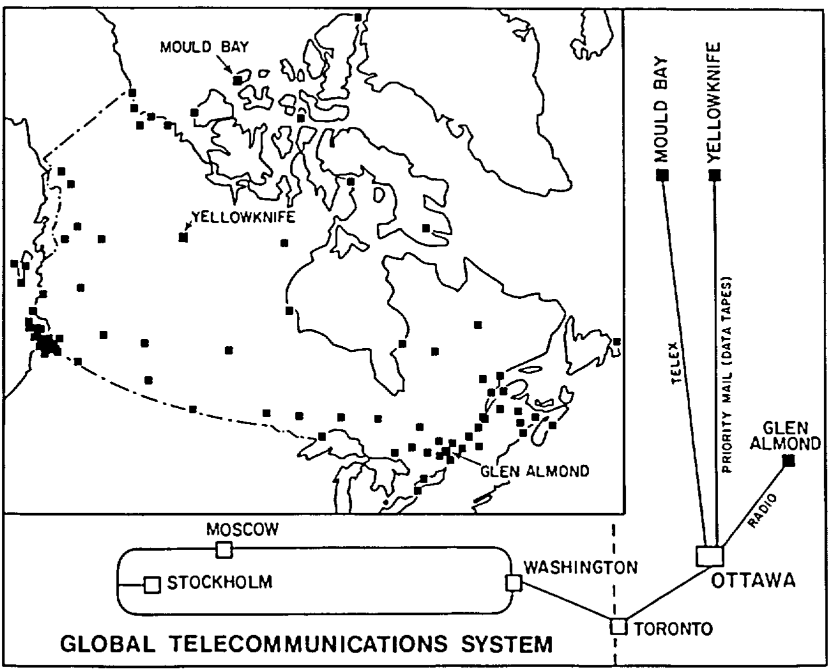
The program for the experiment was very well planned by the Group of Scientific Experts and an attempt was made to get as many countries as possible to take part. Three states, the USA, the USSR and Sweden, agreed to allow their national seismic computing facilities to act as experimental international data centres. More than 30 countries and 70 seismograph stations took part in the experiment.

Each station tried to measure certain agreed parameters recorded by their instruments for every seismic event. These data were then transmitted in a coded format via the Global Telecommunications System. International data centres in Washington, Moscow and Stockholm received the data and produced seismic event bulletins. These bulletins were transmitted to participating states within five days.

Of the more than 100 seismograph stations that Canada operates, three were chosen to take part: the Yellowknife array; Glen Almond, Quebec, about 50 kilometres north-east of Ottawa; and Mould Bay in the Canadian Arctic.

An important aim of the experiment was to determine how many of the data were circulated throughout the entire network and how many were lost. Canada compiled its own statistics on the experiment and took part in an international assess-

Figure 11 Global telecommunications system and Canadian participation in the 1984 International Seismic Data Exchange. Canadian seismograph stations are indicated in black; three stations shown on the right contributed to the data exchange experiment.



ment by the Group of Scientific Experts in Geneva. The extent of the overall Canadian contribution can be judged from the fact that its three stations provided between 10 and 15 per cent of the total data collected from some 70 stations.

Preliminary results of this large and highly successful operation show that while great strides have been made in the past 10 or 15 years, particularly in the real-time computerized analysis of data, there is still a long way to go in applying the latest data processing techniques to handle the huge quantities of information that would be generated on a day-to-day basis by an international data exchange system of this type.

Remaining Obstacles

Chapter Six

Remaining Obstacles

Evasion

The detection capability of a seismograph network in any area is heavily dependent on the strength of the signals received and the level of background Earth noise.

An additional concern is that the detection and identification of underground explosions can often be evaded or interfered with by several possible methods:

- Keeping seismic signals below the level of background Earth "noise";
- Testing in an earthquake-prone zone or creating seemingly "normal" noises at the same time to mask any explosion;
- Selecting a site so that the signal will pass through an absorbent region of the Earth's crust; or
- Partial or complete "de-coupling" of the explosion from its immediate solid surroundings, by detonating the device in a large artificial cavern.

Even assuming the establishment of an extensive seismograph network within the USSR, it must be accepted that the detonation of a device with a yield of 0.1 kiloton (which is equivalent to 100 tons of chemical explosive) will probably go unnoticed, even without resort to subterfuge. By suitable manipulation, such as cavity de-coupling mentioned above, that figure of 0.1 kiloton could be further increased by a factor of 50 to 100, making the test seem only one-hundredth as large as it is.

Cavity De-coupling

The USA was the first country to report the phenomenon of cavity de-coupling. In the 1960s the USA conducted large nuclear and chemical tests in underground salt domes, the results of which suggested that a cavity 50 metres in radius could fully muffle a five-kiloton explosion.

Such a technique might fully muffle an explosion several times larger if the cavity were created in a stiffer medium, such as granite. Although a single spherical underground cavity of so great a size would be difficult to excavate and might soon collapse because of damage to the surrounding rock, an alternate approach that has been used successfully is to increase the effective size of the chamber by connecting it to a tunnel network.

Figure 12 Cavity created by the United States Atomic Energy Commission (USAEC) test explosion (GNOME) detonated 1 200 feet underground on December 10, 1961. The cavity measured 160-170 feet in diameter and 60-80 feet deep, and was formed by a nuclear detonation with a yield of approximately three kilotons (courtesy of Lawrence Radiation Laboratory, Livermore, California).

Since satellite surveillance has been suggested by some countries as a complementary means of verifying compliance with a nuclear test ban treaty, it should be mentioned that the outward and visible signs of such an evasion operation may offer little of significance for a satellite to see. The accompanying aerial photograph of a surface facility used in a USA underground nuclear experiment shows that the surface installations for underground nuclear explosions are similar to those for conventional mining or other large-scale industrial activities.

The Problem of Discrimination

Once seismic waves have been detected, the source must be identified as an earthquake, a chemical explosion or a nuclear explosion. The decisive factors will include location and depth below the surface of the Earth, taking into account the fact that the limit of practical drilling capability at present is about 10–15 kilometres.

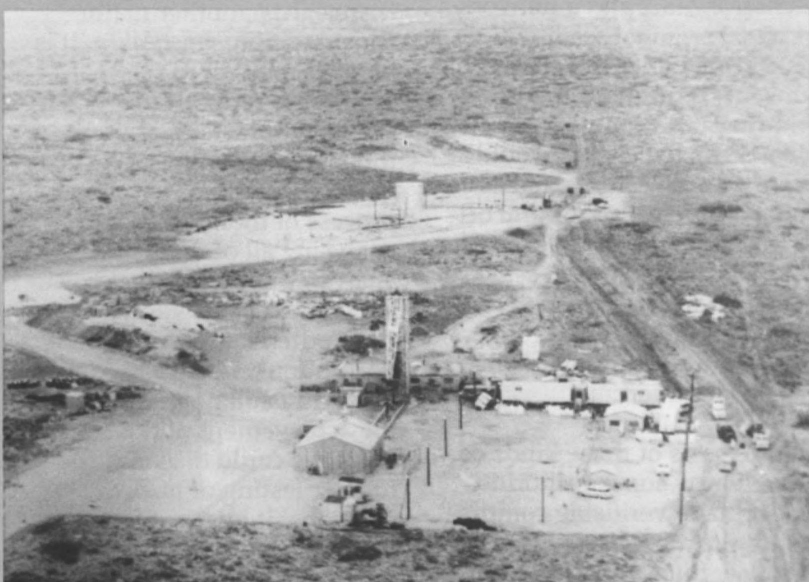
Surface location is also important: seismic events occurring in some locales, such as the ocean floor, are unlikely to be man-made explosions.

It must also be borne in mind that many areas may seem to be seismically inactive because high magnitude events may occur only rarely. However, those areas may be quite active in terms of events of lower magnitudes. Parts of Canada and the USA, for example, may register only one earthquake of Richter magnitude 4.5 in a decade, yet may sustain an average of one shock a day in the range of Richter magnitude 2.0–3.9 that would go unrecorded, except by local networks. The same is presumably true for the many granitic regions in the USSR.

10 000 Shocks a Year

Generally speaking, an additional Richter magnitude of 0.5 (equivalent to trebling the size of the shock, see Figure 14) is needed, above the detection threshold, before a pronouncement can be made that a specific event is an explosion. With some 10 000 earthquakes of magnitude greater than Richter 4 occurring around the world each year and countless thousands of smaller events, the challenge of identification is a formidable one.

Figure 13 Overall view of surface facilities at Ground Zero after test explosion, GNOME, December 11, 1961, Carlsbad, New Mexico (courtesy of Borden, Reynolds Electrical & Engineering Company Inc.).



The severity of a seismic event is usually expressed in terms of an open-ended scale, named after its inventor, Dr. Charles Richter, in which each successive number represents an additional factor of 10 in the size of the event.

For a hypothetical threshold of Richter 2.7–3.2 and a network of 25–30 regional seismograph stations deployed by common consent throughout the USA and the USSR, only 80 per cent of all recorded events would eventually be categorized as being of nuclear or natural origin. That leaves much scope for false alarms and the possibility that if nuclear tests of a very small or sub-kilotonne range were conducted, they might not be identified.

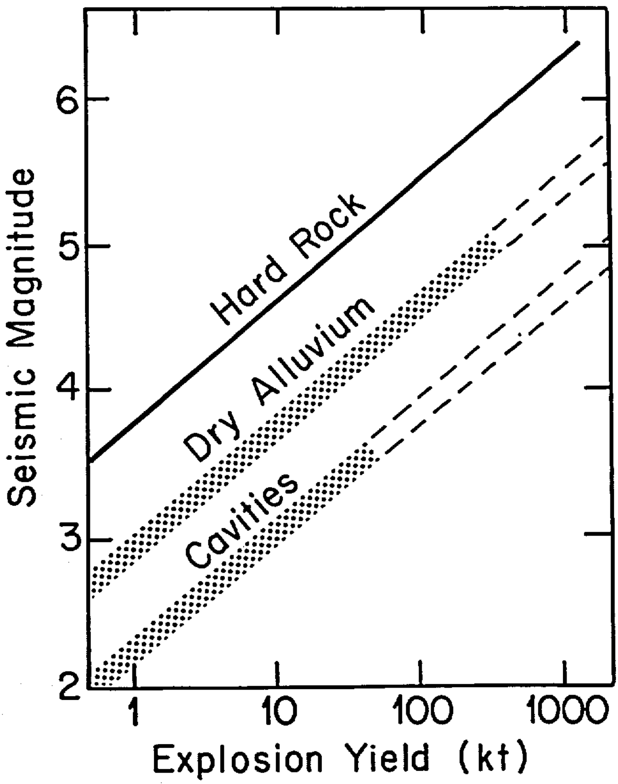
On the basis of these kinds of uncertainty, some authorities assert that a verifiable comprehensive test ban treaty is impossible. Such critics say that no monitoring technology currently foreseen can offer absolute assurance that very small-yield, illicit nuclear explosions would not go unnoticed.

This gap in the ability to detect and identify underground nuclear explosions emphasizes the need to press for adequate in-country detection networks and underlines the desirability of provisions for on-site inspections.

Practicality

Scientists are quick to stress that quite apart from detecting and identifying underground tests with a degree of precision, there exists another major consideration: *practicality*. It is no exaggeration to say that, within the range of any given seismograph station, many thousands of events will occur in the course of a year. The process of monitoring and analysing all of them and re-analysing suspicious events in the context of additional data from other sources would be horrendous, notes Dr. Basham. But many still point out that, if the achievement of this objective could discourage further testing of nuclear weapons, it might still be worthwhile.

Figure 14 Seismic magnitude as a function of explosion yield for different geological environments based on data from the Nevada Test Site. As the figure below illustrates, it takes approximately 10 times the explosion yield to produce a shock wave one unit greater on the Richter scale.



The Trend Towards Smaller Nuclear Weapons

The importance of effectively monitoring tests of small-yield devices must be viewed in relation to three important recent developments in advanced weapons technology:

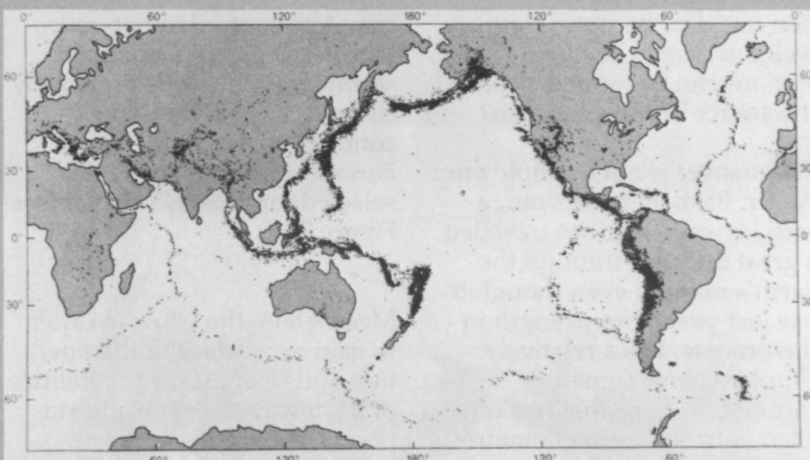
- The increasing accuracy achieved by nuclear missiles, which has reached a point where much smaller yields are thought capable of ensuring destruction of specific targets;
- The increasing attractiveness of very small nuclear weapons (equivalent to a few tons of chemical explosive) to those who would like to use nuclear weapons in a purely tactical battlefield situation, with minimal risk to civilians in the area and minimal environmental involvement; and
- The continuing search for smaller, more effective and more economic nuclear trigger mechanisms.

Although the military significance of these very small nuclear tests is a matter of continuing debate, most experts seem to agree that it would be relatively easy for any nation to test smaller weapons without fear of detection. It would be even easier to do so in those countries where information flow and movement are strictly controlled and where there are large, sparsely inhabited areas.

One Solution: Unmanned Stations for "Close-in" Data Gathering

The discussion and experiments that have been conducted each year since 1976 by the Group of Scientific Experts have always been based on the use of data generally available through the international seismic network. Discussions between the UK, the USA and the USSR during the period 1976–1980 indicated a willingness on the part of those countries to permit the placement of some unmanned devices, sometimes known as "black boxes", within their territories. Once the US and the USSR agreed in principle to the establishment of unmanned stations within each other's borders, American scientists started designing a prototype unmanned station that would be able to continuously transmit data back to the USA by satellite.

Figure 15 Earthquake occurrence worldwide (above magnitude 4.5) for a seven-year period.



The use of such unmanned stations changes the whole nature of the monitoring problem. It also brings into focus Canada's potential role in developing technologies appropriate to this new situation. The key question has now become: How well can events be monitored if stations can be located close to the source of the explosion?

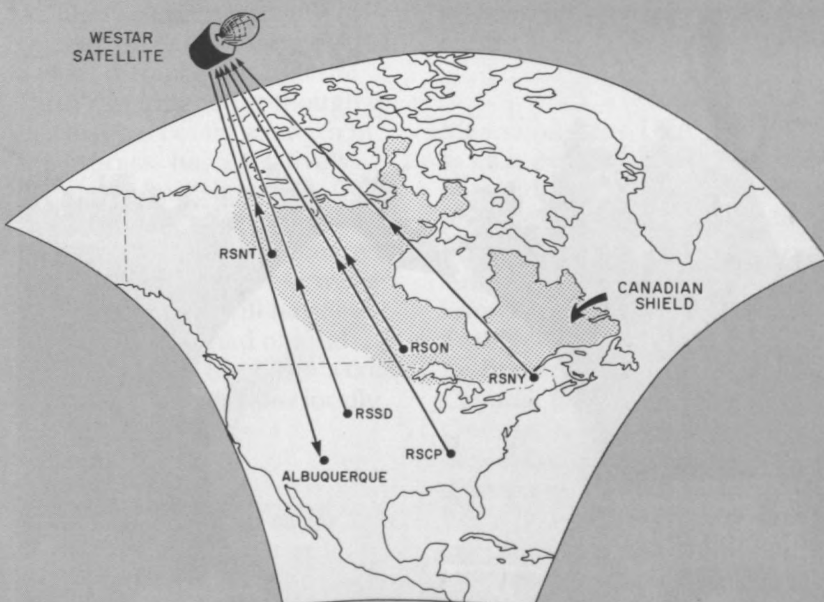
The answer is not a simple one. As Dr. Basham points out, a seismic wave that has travelled a great distance through the Earth's mantle, even though it has lost part of its strength in the process, has a relatively simple seismic signature. By contrast, a shock that has travelled only 500–1000 kilometres may be very complex in wave form, because it will have encountered a myriad of local complexities in the Earth's crust that generate weak but locally recordable signals.

Canada is important so far as on-going research into unmanned seismic stations is concerned. This is because most of Canada sits on a huge ancient rock mass, known as the Precambrian Shield, which is geologically similar to the great continental rock masses that underlie much of Europe and Asia. Canada, thus, in a geophysical sense, resembles the USSR and is therefore a testing ground where a great deal can be learned about close-in seismological techniques that might be applicable to a remotely controlled network within the USSR. Canadian seismographs are also relatively close to, and on the same continental mass as, the Nevada Test Site, the region selected for most USA tests (see Figure 3).

Meanwhile, the USA, in order to gain experience in the operation and operational capabilities of its new remote sensing stations, has installed a North American network of five units, known as the Regional Seismic Test Network. Two of these, by mutual arrangement, are in Canada. One is at Red Lake, Ontario, and the second is near Yellowknife, close to the Canadian array. It will thus be possible to compare the performances of the two, quite different, Yellowknife stations.

Figure 16 Prototype of unmanned United States surface seismograph station in the Adirondack Mountains, containing transmitting and receiving equipment and an antenna for communication via satellite with the RSTN system (see Figure 17) (courtesy of Sandia National Laboratories, Albuquerque, New Mexico).

Figure 17 Regional Seismic Test Network (RSTN). Stations on the Canadian Shield at Yellowknife (RSNT) and Red Lake, Ontario (RSON) are operated in a co-operative project between the Canadian Department of Energy, Mines and Resources and the United States Department of Energy. Seismic data are transmitted by WESTAR satellite to Albuquerque, New Mexico.



The Road Ahead

Chapter Seven

The Road Ahead

This type of close-in data may be a key to increasing our ability to identify smaller events. At present, seismologists do not know very much about how higher frequency energy waves propagate through the Earth's crust. One of the matters they will therefore be looking into is the possibility that P-type body waves of much higher frequency than have been used before, may be used to identify low energy nuclear events, even though these waves tend to weaken rapidly over distance.

Dr. North stresses that no nuclear detonations or deliberate detonations of conventional explosives will be needed in the course of this Canadian research. There are many little earthquakes, mine blasts and rock bursts from various sources that can be used.

One fact that is not in dispute is that the task of verification, already complex enough, will be even greater if more close-in data must also be analysed.

The Bottom Line

What is the bottom line? Most scientists who have studied these matters agree that, from a technical point of view, any treaty to ban nuclear tests must be based on a genuine desire by all parties to make it work. It would be extremely easy for any nation in almost any part of the world to test a sub-kiloton nuclear device without fear of detection, even if international sensors were to be deployed within its own territory. Whether a factor of this sort stands in the way of successfully negotiating a ban on underground nuclear testing is a matter that politicians and diplomats, rather than scientists, will be in a better position to decide.

Figure 18 Highlights of international negotiations and initiatives aimed at banning and regulating the use of nuclear weapons.

1946	* USA Baruch Plan for ensuring that atomic weapons are used only for peaceful purposes.
1955	*USSR plan for general and complete disarmament and a ban on all testing of nuclear weapons.
1958 (summer)	*First meeting of seismic experts in Geneva makes recommendations for a global seismographic network and an on-site inspection system.
1958 (autumn)	*Trilateral negotiations (USA, UK, USSR) concerning a test ban treaty leads to an agreement on a moratorium on nuclear testing.
1959	*France, USA, UK and USSR sign a treaty (now subscribed to by 32 countries) banning nuclear tests in Antarctica.
1961	*Nuclear testing moratorium ends with the detonation of the largest-ever nuclear explosive (58 megatons) by USSR.

1963	*India, UK, USA and USSR sign the Partial Test Ban Treaty (now subscribed to by 111 countries) prohibiting nuclear testing in the oceans, the atmosphere and outer space.
1967	*France, India, UK, USA, and USSR sign the Outer Space Treaty (now subscribed to by 92 countries) banning the stationing of nuclear weapons or other weapons of mass destruction in space.
1967	*Twenty-nine Latin American countries sign the Treaty of Tlatelolco prohibiting nuclear weapons in Latin America.
1968	*UK, USA, and USSR sign the Nuclear Non-Proliferation Treaty (now subscribed to by over 127 countries) to prevent an increase in the number of nuclear weapons and to discourage their distribution to other countries.

1971	*UK, USA, and USSR sign the Sea-bed Treaty (now subscribed to by 81 countries) prohibiting the placement of nuclear weapons on the sea-bed.
1974	*USA and USSR sign the Threshold Test Ban Treaty (not ratified) banning underground nuclear testing with yields of more than 150 kilotons.
1976	*US and USSR sign a treaty on Peaceful Nuclear Explosions (not ratified) in order to establish appropriate rules governing underground explosions for peaceful purposes.

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