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The GEOSCOPE Program: Progress and Challenges during the Past 30 Years

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Online material: Appendix 1—Station Information; Appendix 2—GEOSCOPE Roster 1982 to present; Appendix 3—complete acknowledgments; Figures S1–S8.

INTRODUCTION: THE EARLY DAYS OF LONG-PERIOD SEISMOLOGY

The Institut de Physique du Globe in Paris (IPGP) has a solid tradition in long-period seismology and instrumentation. The IPGP Seismological Laboratory designed handmade instruments from 1952 to 1982, mainly to study the Earth tide tilt. After several attempts, the first prototype of a tiltmeter was constructed in 1957 by P.A. Blum (Blum and Jobert 1959; Blum *et al.* 1964). This sensor was a horizontal mechanical seismograph with classical Zöllner suspension (Zöllner 1869), made of fused silica working under vacuum (Figure 1A). Optical amplification and photographic recording at a velocity of 1 cm/h were used. Earthquakes were then visible only as a thickening of the recording line. The recording of the large event of 22 May 1960 in Chile, however, clearly showed long-period waves lasting several minutes (Figures 1B and 1C) and raised the question of the usefulness of tiltmeter records for earthquake studies. At that time and during the following decade, the study of large earthquakes, such as those in Chile in 1960 or Alaska in 1964, involved processing time series longer than 24 hours at each station. This data processing took several months due to the tedious procedure of digitization, which introduced additional errors (Cifuentes and Silver 1989).

In the 1960s, there were no digitization tables, and access to computers was very limited. The long-period seismological team of that time performed laborious hand digitization and analog Fourier transforms that took more than several hours to complete. After the large Chile event of 1960, IPG seismologists were invited by the Caltech Seismological Laboratory to digitize Blum tiltmeter records at a 5-minute sampling rate and to compute the corresponding spectra (Connes *et al.* 1962; Gaulon 1971; Blum and Gaulon1971). The spectral analysis performed on the east–west component of the Blum recording (Figure 1D) shows the quality of the gravest normal modes recordings (<1 mHz). The theoretical spheroidal and toroidal eigenfrequencies computed for the Gutenberg continental model (Gutenberg 1948) are indicated by vertical lines. Although theoretical computations of the free oscillations of an elastic sphere date back to Poisson (1829) for the radial modes and to Jaerisch (1880), Lamb (1881), and Jaerisch (1893) for the other modes, the first observation of free oscillations was made by Benioff (1958) after the large Kamchatka event of 4 November 1952. This late observation may explain the late interest of seismologists in very-long-period observations (Benioff *et al.* 1961). Unfortunately, the original and digitized Blum records have been lost, and only some published records are left.

The tiltmeters built for tide studies at IPGP thus appeared to be appropriate for studying the horizontal motion due to earthquakes as well (Jobert *et al.* 1977, 1979). Some attempts were made to build vertical seismographs, also of fused silica, but these attempts did not fully succeed. This is one of the reasons why the Blum tiltmeters were not chosen when GEOSCOPE was launched a few years later. In France, the first attempt to use computers for recording and pre-processing long-period seismological data was made by the Strasbourg group in the early 1970s at the location of the present ECH (Echery) GEOSCOPE station, a site located in an old mine gallery. A prototype Schlumberger analog-to-digital (A/D) converter, driven by a Digital Equipment Corporation PDP8 computer and associated with a nine-track magnetic tape recorder for data storage, was operated there and could be controlled via the telephone network (Trifilief 1974). At about the same time, the group headed by Nelly Jobert in Paris installed

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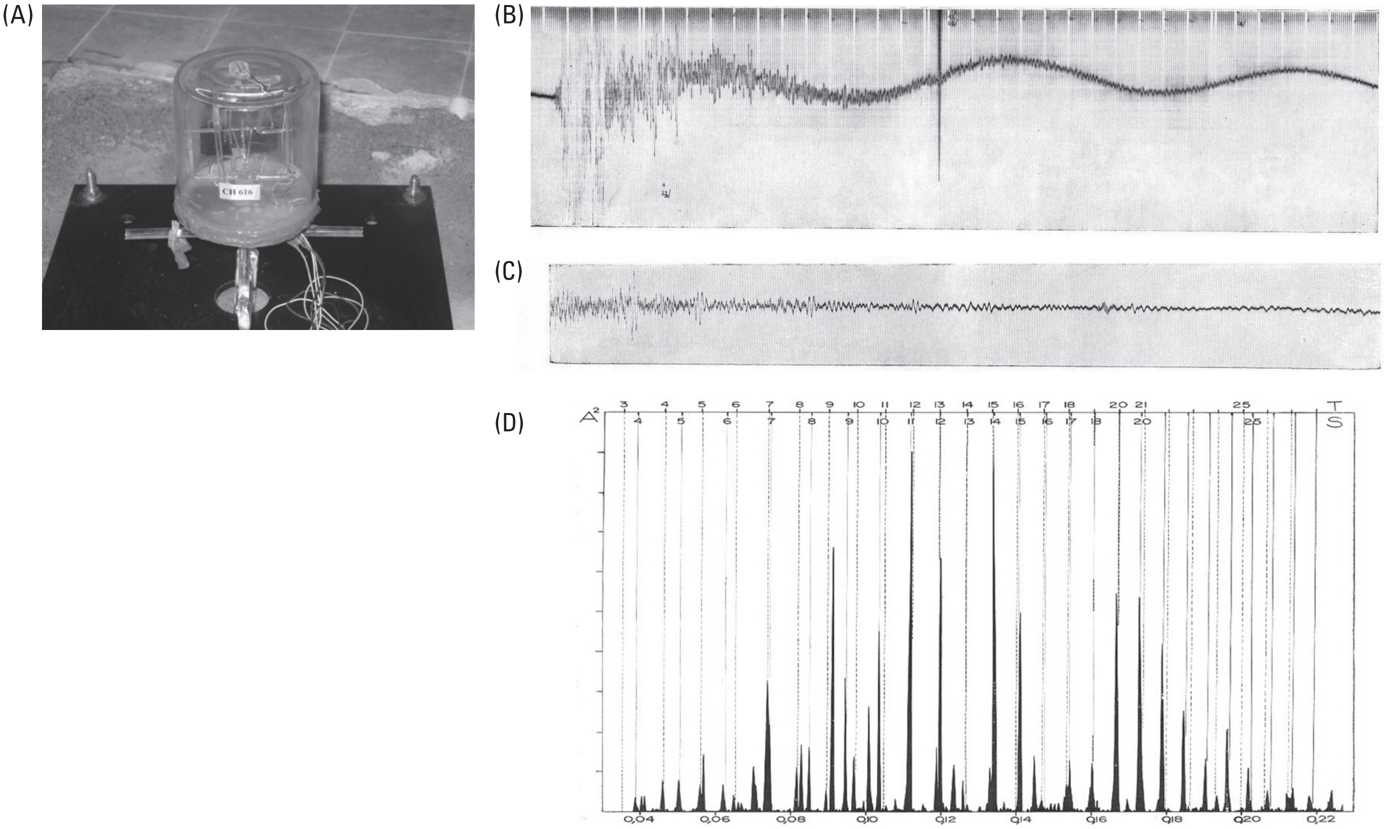


▲ **Figure 1.** Recordings of the giant Chile event of 22 May 1960 by fused-silica tiltmeters installed at the Astronomical Institute in Paris (Blum and Jobert 1959). A) Example of fused-silica Blum horizontal sensor. B) East–west component. C) North–south component. D) Spectral analysis using a Fourier transform performed on the east–west component record of the previous Figure 1B. The theoretical spheroidal and toroidal eigenfrequencies computed for the Gutenberg continental model (Gutenberg 1948) are indicated by vertical lines on the energy spectrum. The abscissa corresponds to cycles per hour.

very-long-period seismometers at several sites, and in particular at two sites in the Pacific Ocean, Pamatai (Tahiti) and Kipapa (Hawaii). The records of these two stations were extensively used for studying the upper mantle structure of the Pacific Ocean (Jobert *et al.* 1979; Montagner and Jobert 1981, 1983).

Three decades ago, it was clear to the IPGP group that easy access to data and standardized sensors distributed on a worldwide scale were necessary to make original contributions to seismology. Despite of the quality of the IPGP tiltmeters, it was not realistic to install them worldwide because of the problems involved in transporting these excessively fragile instruments and the difficulties involved in calibrating them (each tiltmeter had its own transfer function). A high-quality observation requires homogeneous and standardized station equipment. This concept was pioneered by the World-Wide Standard Seismograph Network (WWSSN), launched in 1961, for which standardized seismographic equipment (three-component long-period [LP] and short-period [SP] sensors and an accurate clock) was deployed at more than 120 sites worldwide (Oliver and Murphy 1971) under the responsibility of the Albuquerque Seismological Laboratory (ASL). The sensors, with a free period close to 30 s (later reduced to 15 s for stability reasons), provided calibrated records in the frequency band 15–100 s. In the 1960s, free distribution of WWSSN microfilm seismograms was the means by which short-period and long-period three-component seismograms were collected by the users. Although the primary goal of the network was the monitoring of underground nuclear explosions, the analysis of microfilms allowed many seismologists to work on various fundamental Earth sciences questions. Seismology's contribution to our understanding of plate tectonics is one of the important results that emerged from the WWSSN data. Loss due to improper preservation makes the remaining recordings and microfilm collections very precious today. Selected events from 1960 to 1985 have been preserved and saved through the International Digital Earthquake Archive Project (IDEA; Lee 1994) and can still be used by seismologists today (see Dziewonski and Romanowicz 2009 for additional details).

As mentioned above, the transition from analog to numerical recording became possible in the early 1970s in France. The digital Seismic Research Observatories (SRO) and Associated Seismic Research Observatories (ASRO) network deployments (Peterson and Orsini 1976; Peterson *et al.* 1976) represented a great improvement on the analog WWSSN network. The SRO network, a key part of the Global Digital Seismic Network (GDSN), was set up with the main purpose of discriminating between earthquakes and nuclear explosions. SRO provided numerical recordings from worldwide standardized stations for the first time, allowing studies of the Earth's background noise at long periods (Murphy and Savino 1975).

The need for instruments capable of recording seismic signal at periods up to several thousands of seconds was addressed by the leaders of the International Deployment of Accelerometers (IDA) project (Agnew *et al.* 1976; Agnew and Berger 1978). Many Lacoste-Romberg Earth-tide gravimeters basically derived from ET19 (Lacoste 1934) were installed at a global scale and were of considerable interest to the scientific community. Both tide and long-period channels allowed extensive studies after the Sumbawa event of 19 August 1977 (Roult 1982). Data from the IDA network (Agnew *et al.* 1976) stimulated research toward the determination of source parameters for large earthquakes using long-period observations. A simple inversion method for the fundamental mode Rayleigh wave spectra (Kanamori and Given 1981) permitted rapid estimation of the mechanism and seismic moment of events large enough to excite several successive mantle wave trains. This method is still applied successfully at IPGP to all large events. IDA data also permitted a detailed study of the frequency variation of the seismic moment of the largest events (Silver and Jordan 1981), opening new perspectives for estimating the energy and dimensions of large seismic sources and recovering the rupture propagation process.

SRO and IDA networks were the first global networks to provide digital recordings on magnetic tapes. The first 3-D models of the Earth are a spectacular result of these early times (Masters *et al.* 1982; Woodhouse and Dziewonski 1984a,b; Nataf *et al.* 1984). The analysis required to construct these models involved several thousand seismic records—a prohibitive task with classical analogic instrumentation. Despite the improvements listed above, the global networks of 1981 lagged behind advances in theoretical seismology, and exhibited strong shortcomings:

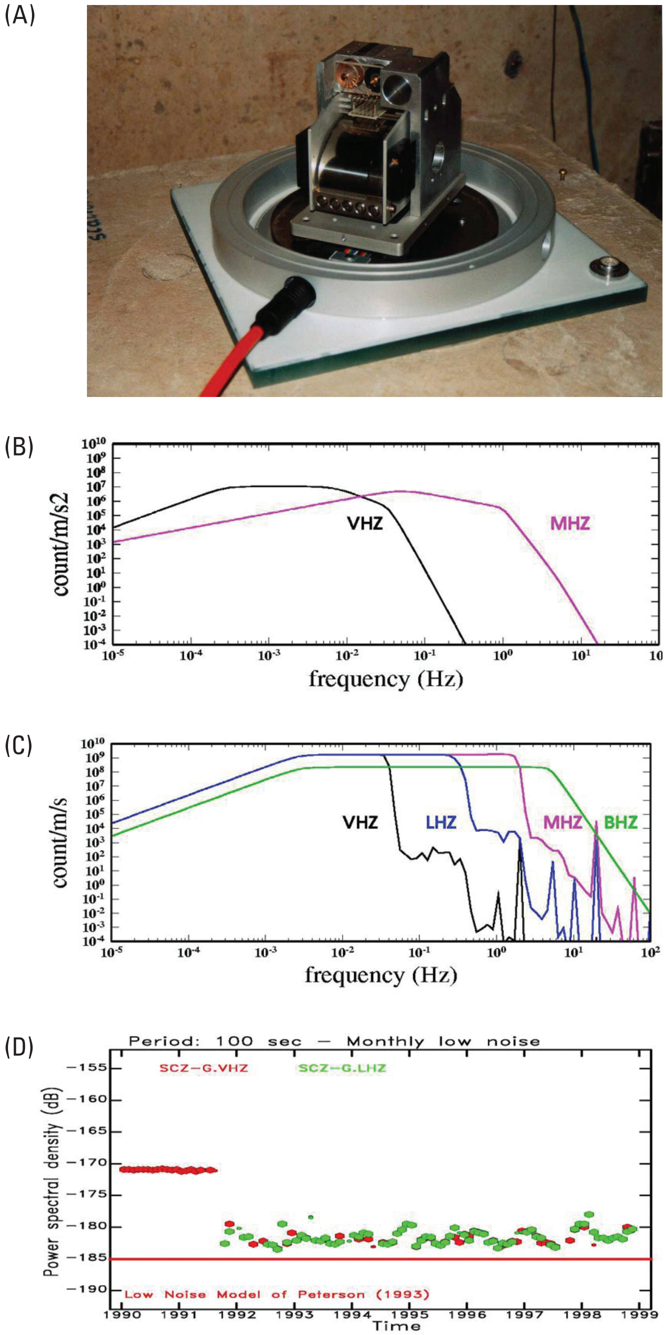
1. The IDA network was limited by its narrow frequency band and by the fact that it recorded only the vertical component of motion. The dynamic range was insufficient for large events and the geographical distribution of its 20 stations was uneven.
2. In the 1–100 s broadband domain, the GDSN instrumentation was plagued by nonlinearity and instrumental responses not well suited to the needs of seismologists in terms of long-period recording. Indeed, the SRO network, which made up a large part of GDSN, was specifically designed for nuclear discrimination purposes, which do not require very broadband signals.
3. The recordings were still made with analog recorders on magnetic tapes, and their analysis was still tedious and time-consuming.
4. More generally, the need for three-component stations was evident. For example, in the very-long-period frequency band (100 s–1 h), recording only the vertical component of ground motion gives no information on the Love surface waves and toroidal modes of the Earth. At shorter periods, the simultaneous recording of different body wave data (*S*, multiple *S*, *SKS*, *ScS*, etc.) on three components improves the depth resolution of *S* velocity heterogeneities. New observations, like the "X phase" observed by Jobert *et al.* (1977), which is made of higher modes strongly excited on the horizontal components (Jobert 1978), required the recording of the three components. It was also shown at the same time that to better constrain the moment tensor parameters and anisotropy, Love and Rayleigh surface wave trains including the fundamental and higher modes must be analyzed simultaneously (Cara *et al.* 1980). Very-long-period data on three components provide examples of mantle waves that do not respect the laws of geometrical optics, as illustrated by amplitude anomalies and mixing of Love and Rayleigh waves on the longitudinal and transverse components (Roult and Romanowicz 1984).

In addition to the need for three-component recording, it was also deemed necessary to broaden the seismometer bandwidth and increase its dynamic range. The technical solution came from the use of broadband feedback sensors, which had been pioneered in the late 1960s (Plesinger 1973; Plesinger and Horalek 1976). In the mid 1970s the first STS-1 seismometers (Figure 2A; Figure S1A, online material), characterized by a large dynamic range, a broadband frequency range, and a feedback system, were installed in Switzerland and in Erlangen in Germany (Wielandt 1975; Mitronivas and Wielandt 1975; Wielandt and Mitronivas 1976; Wielandt and Streckeisen 1982; Wielandt 1983; Streckeisen 1983). Large-dynamic-range instruments operating on the concept of mass-balance feedback have been a major step forward in seismology. The Seismological Laboratory at IPGP quickly adopted the STS-1 sensor and installed a vertical one at SSB (Saint-Sauveur Badole). Characterized by a large dynamic range (140 db) in a broad frequency range 20 Hz–1 mHz, the STS-1 sensor was able to fill the traditional gap between short-period seismology (periods < 1 s) and long-period seismology (periods > 50 s) and to record both fairly large and small regional earthquakes accurately. Records of seismic signals in the very noisy microseismic band (1–12 s) also demonstrated the superior capabilities of this new sensor.

In the early 1980s, the scientific context was very favorable for launching a new global broadband network. The GEOSCOPE program, supported by Institut des Sciences de l' Univers (INSU) as early as 1981, was formulated in this context and was based upon three important motivations (Romanowicz *et al.* 1984):

The long experience at IPG in Paris and Strasbourg with long-period instrumentation, and their expertise in long period-seismological research, thanks to the work of Nelly Jobert and her colleagues (*e.g.* Blum and Jobert 1959; Blum and Gaulon 1971; Jobert and Roult 1976; Jobert *et al.* 1977, 1978; Jobert 1978).

The availability of the new high-performance STS-1 instrument (Figure 2A), which, as described above, solved several key problems in long-period seismometry (three components, high dynamic range, and large frequency band). Although the STS-1 provided a 140-db dynamic range on its analog output, there were no 140-db digital recorders at that



▲ **Figure 2.** A) Photograph of the STS-1, first generation vertical sensor (Wielandt and Streckeisen 1982). B) Transfer function curves at SCZ (Santa Cruz station, USA) in a BB configuration corresponding to ground acceleration VH recordings and ground velocity MH recordings, with responses respectively flat in the period domain 3,600 s–150s and 20 s–1s. C) Same as (B) after September 1991 in a VBB configuration corresponding to ground velocity physical parameters and a flat response of the BH channel in the period domain 360 s–0.02s. D) Background noise level at SCZ as a function of time, estimated by Ekström *et al.* (2001). Monthly noise of the power spectral density is represented in dB for the vertical component (channel VHZ), at the period T = 100 s. The red horizontal line illustrates the low noise model of Peterson (1993) at period 100 s.

time. The first digitizers installed were therefore 12 bit with gain-ranging.

A long-lasting tradition of cooperation between IPG Paris and IPG Strasbourg (now the Ecole et Observatoire des Sciences de la Terre, EOST) and other French institutions such as Institut de Recherche pour le Développement (IRD) (formerly Office de la Recherche Scientifique et Technique Outre-Mer [ORSTOM]) and the Institut Paul-Emile Victor (IPEV), which had access to isolated sites worldwide, as well as with seismology institutes in many countries. These partnerships facilitated access to several geographic sites and contributed to the GEOSCOPE objective of a global network.

1981–1984: BIRTH OF GEOSCOPE AND EARLY DEVELOPMENTS

The GEOSCOPE project came to life in 1981 with the installation of STS-1 seismometers at Saint-Sauveur Badole (SSB) in central France (Figure 2A). For comparison purposes, an IDA instrument was run parallel with the STS-1 for one year starting in October 1981, showing that comparable noise levels were to be expected on the vertical component, with the advantage of a wider dynamic range for the STS-1. A second station—which marked the official launch of GEOSCOPE as a network—was installed at La Reunion island in 1982 (PCR), followed by Port aux Français (PAF, Kerguelen Island) and Tamanrasset (TAM, Algeria) in 1983 and Westford (WFM, Massachusetts) in collaboration with MIT in 1984.

One of the most important challenges of the GEOSCOPE program was to instrument some isolated sites to achieve homogeneous geographical coverage. Accessing these remote areas was, and still is, difficult. The EOST group in Strasbourg played an important role here from the very beginning, owing to their involvement in the permanent scientific bases for the observation of global-scale geophysical processes in the Austral French territories and in Antarctica (Terres Australes et Antarctiques Françaises [TAAF]). The first seismological observations started in 1950 in Terre Adélie (Port Martin station, moved to Dumont D'Urville [DRV] in 1957; see Souriau 1964) and in 1953 in Kerguelen Island (Pointe Molloy station; see Baltenberger *et al.* 1959; the station was moved to Port aux Français [PAF] in 1965). EOST installed and managed three of the first GEOSCOPE stations: PAF in 1983 (Romanowicz *et al.* 1984; Wajeman and Souriau 1987) and CRZF (Crozet Islands) and DRV in 1986 (Cantin *et al.* 1990; Pillet *et al.* 1990). The French national center for overseas research (ORSTOM, now IRD) was invited to participate in GEOSCOPE, helping to finance and install two stations in cooperation with the Strasbourg team: NOC (Nouméa, New Caledonia) and MBO (M'Bour, Senegal), both in 1985, and BNG (Bangui, Central African Republic) in 1987.

In 1981, GEOSCOPE's goal was to install 25 stations (Romanowicz *et al.* 1984). Selection of a new site was generally preceded by field measurements of the background noise levels. Sensors installed on solid basement rock were preferred, since they are less sensitive to potential sources of noise. Use of existing vaults or tunnels, or construction of vaults according to specifications, were then the essential criteria, as was access to a power supply. Specific agreements were made with the institutions hosting instruments for routine operation and prompt access to data (sending magnetic tapes by mail in the initial stage). Close working relationships were established between local operators and IPGP or IPGS. Local personnel were trained in the use of the equipment, data processing techniques and given a foundation in the science. The operators in charge of the stations on the South Indian Ocean islands and in Antarctica are changed every year and are trained at EOST for two months before traveling to the remote bases.

At the very beginning, only the very-long-period (VLP) channel was recorded. This channel became the VH channel in further SEED naming system (see http://www.iris.washington.edu/manuals for a comprehensive description of SEED format; see also Ahern *et al.* 1986; Halbert *et al.* 1996). This channel presented a flat response to ground acceleration in the 3,600 s–60 s period-range. The data acquisition system was of a gain-ranging kind (12 bit of mantissa and 8 bit of gain) with continuous recording at 0.1 sps. At that time IPGS developed another digital acquisition system allowing a continuous recording of the high-gain long-period channel (HGLP) at 1sps. Later in 1985, for large earthquake studies, GEOSCOPE started recording an additional triggered channel, the BRB channel (BRoadBand channel or MH in SEED naming), characterized by a flat response to ground velocity in the 1–200 s period-range, at a sampling rate of 5 sps. The corresponding transfer functions of the sensors for that time are shown in Figure 2B. At the end of 1982 the network had consisted of only two stations: SSB in France and RER in La Reunion Island; the number of stations increased to 18 by 1987 and 23 by 1991. The data, stored locally on magnetic tapes at the stations, were sent to France by airmail about every two–four weeks, except for the remote stations located in Antarctica and in the South Indian Ocean (these went by ship once a year and later, twice a year). All raw data were centralized at the Data Processing Centre of Saint-Maur des Fossés, near Paris, where they were transferred onto nine-track tapes for archiving and distribution. The data format was a specific "homemade" format. There were two different clocks in stations, an internal homemade "atomic" clock and an external clock providing the absolute time dispatched by the OMEGA system with an accuracy of 50 ms, except at PAF (Kerguelen) and DRV (Terre Adélie), where the external clock was a specific local atomic (rubidium) one. The internal clock drift was significant. Checking and application of time corrections was done at the Data Processing Centre after collection of the data tapes and was very time consuming. Starting in the early 1990s, OMEGA was progressively replaced by more accurate GPS clocks.

The first results using GEOSCOPE data were very promising for normal mode studies (Roult and Romanowicz 1984; Romanowicz and Roult 1986), for the observation of anomalous surface wave behavior (Roult *et al.* 1986), and for the development of 3-D velocity models (Montagner 1986; Roult *et al.* 1987). The evidence of degree-2 upper mantle discovered by Masters *et al.* (1982) was also reported in the first analysis of the free oscillations of the Earth from the GEOSCOPE data by Romanowicz *et al.* (1987) and Roult *et al.* (1990).

1985: THE FDSN LAUNCH, AN INTERNATIONAL INITIATIVE

GEOSCOPE was soon followed by national initiatives in other countries. The establishment of the Incorporated Research Institutions for Seismology (IRIS) in 1984 and, in particular, the development of the IRIS Global Seismographic Network (GSN) in the United States in 1986 were important steps forward that underscored the need for standardized digital equipment on a global scale (IRIS 1984, 1985; Smith 1986, 1987; Butler *et al.* 2004).

With the start of the Centroid Moment Tensor (CMT) project (Dziewonski *et al.* 1981; Ekström *et al.* 1986) and the first global 3-D models (Dziewonski and Woodhouse 1986), most seismologists became convinced that a global distribution of high-quality broadband seismological stations was necessary to make progress on the dynamics of the deep Earth (Souriau and Woodhouse 1985).

The need for international coordination led to the formation of the Federation of Digital Seismographic Networks (FDSN) in 1985 (Romanowicz and Dziewonski 1986), of which GEOSCOPE, IRIS/GSN, and the U.S. Geological Survey (USGS) were founding members. Several other countries with burgeoning efforts in broadband station installations were soon invited to join (China, Germany, Australia, Italy, and the Soviet Union).

The first task of the FDSN was to define broadband instrumentation standards, which remain in force to this day (see http://www.fdsn.org). To be a member of the FDSN, each network had to fulfill several criteria. The seismometers had to be broadband (which in practice at that time meant they were STS-1s), recording digitally with high dynamic range, and seismic data had to be freely accessible. In addition, the FDSN defined siting standards; to qualify as "FDSN," a station had to be installed at least 2,000 km away from another FDSN station.

A standardized data distribution system became a necessity, and the GEOSCOPE team participated in the FDSN efforts to design the SEED format, which was adopted at a meeting of the FDSN chaired by Ray Buland of the USGS in Albuquerque, New Mexico, in December 1987. The choice of a unique format for describing so many geophysical parameters was a challenging task. The chosen format had to satisfy the traditional short-period seismic network operators, focused on event-oriented formats, and also the long-period research community, who promoted continuous data recordings. After more than 20 years, the SEED format is still a universal standard format in seismology, which shows how important it was to adopt a format that network operators and the whole seismological community could use. Another advantage of the SEED format was to provide a method of data compression that substantially reduced the volume of data to be archived and distributed

(Wielandt and Steim 1986; Steim 1986). The FDSN played and is still playing a key role in promoting and coordinating broadband seismology projects in many countries. The standardization of sensors, acquisition systems, and data distribution format, together with the sharing of experience in order to avoid the duplication of national efforts, led to a great improvement of the global coverage by digital broadband seismic stations (Presgrave *et al.* 1985). In 2008, more than 50 countries and 30 networks participated in the FDSN (http://www.fdsn.org).

GEOSCOPE 1985–1990: FROM BB CONFIGURATION TO VBB CONFIGURATION

Several important upgrades were implemented at GEOSCOPE in accordance with the highest FDSN standards (Romanowicz *et al.* 1991) between 1985 and 1990.

Progressive Transformation from Broadband to Very Broadband Configuration

After the success of the first-generation STS-1 sensor (Figure 2A), Steim (1986) and Wielandt and Steim (1986) introduced the VBB version of the seismometer, which provided a single channel recording over the entire frequency band, rather than the VLP and BRB channels of the original instrument, and also widened the frequency band to 10 Hz (rather than the original 5 Hz). This was accompanied in practice by continuous recording at 20 sps, which improved the accuracy of short-period teleseismic body wave studies. The switch from the broadband configuration (BB) to the very broadband one (VBB) was made progressively at all GEOSCOPE stations. By the end of 1990, 13 stations were in the VBB configuration and six remained in the former configuration. Figure 2C illustrates the instrument responses to ground velocity of the four channels recorded in the VBB configuration, compared to the two previous ones (in acceleration), at station SCZ (Santa Cruz, California) (Figure 2B). The channels commonly used are described in the Appendix (online material).

Because the BH (or MH) channel was still event-triggered, a significant part of the signal was lost. Figure 2D shows the background noise level at SCZ station as a function of time, estimated by Ekström *et al.* (2001). Monthly power spectral density is estimated and plotted in dB for the vertical component (channel VHZ) at a period of T = 100 s. The upgrade from BB to VBB corresponds to a spectacular decrease in the noise level. Figures 3A and 3B summarize the evolution of the network from 1982 to 2000. At the end of 1990, the network counted 21 stations.

The Particular Case of the HGLP Channel

In order not to lose data in case of hardware failure in the most remote stations, two digital acquisition systems were installed at each station. In the broadband configuration, two channels were recorded with a flat response to ground acceleration, the LP channel (1 sps) and the VH channel (0.1 sps). The LP channel, called HGLP (high-gain long-period) at that time, was characterized at 20-s period by a magnification 50 times larger than the VH amplification (Streckeisen 1983). Data collected from HGLP channels contributed significantly to the construction of the first 3-D group velocity, phase-velocity, and attenuation models of Antarctica (Rouland and Roult 1992; Roult *et al.* 1994; Billien 1999; Billien *et al.* 2000). HGLP records also contribute to our understanding of how the polarization of Rayleigh waves could be due to anisotropic structures (Pettersen and Maupin 2002).

Remote Daily Quality Control

In the first three years of GEOSCOPE, data were recorded locally on magnetic cartridges, regularly sent to France by mail. In 1985, station computers were upgraded and equipped, wherever phone lines were available, with a Minitel system (French Telecom ancestor to Internet) to allow retrieval of data from the station computer via telephone. At the more remote stations, an ARGOS antenna was installed, allowing the daily telemetry of state of health data, which greatly facilitated quality control. Processes were also set up to retrieve 24 hours of VLP data by telemetry immediately following the largest earthquakes (J.-F. Karczewski, personal communication, 1987).

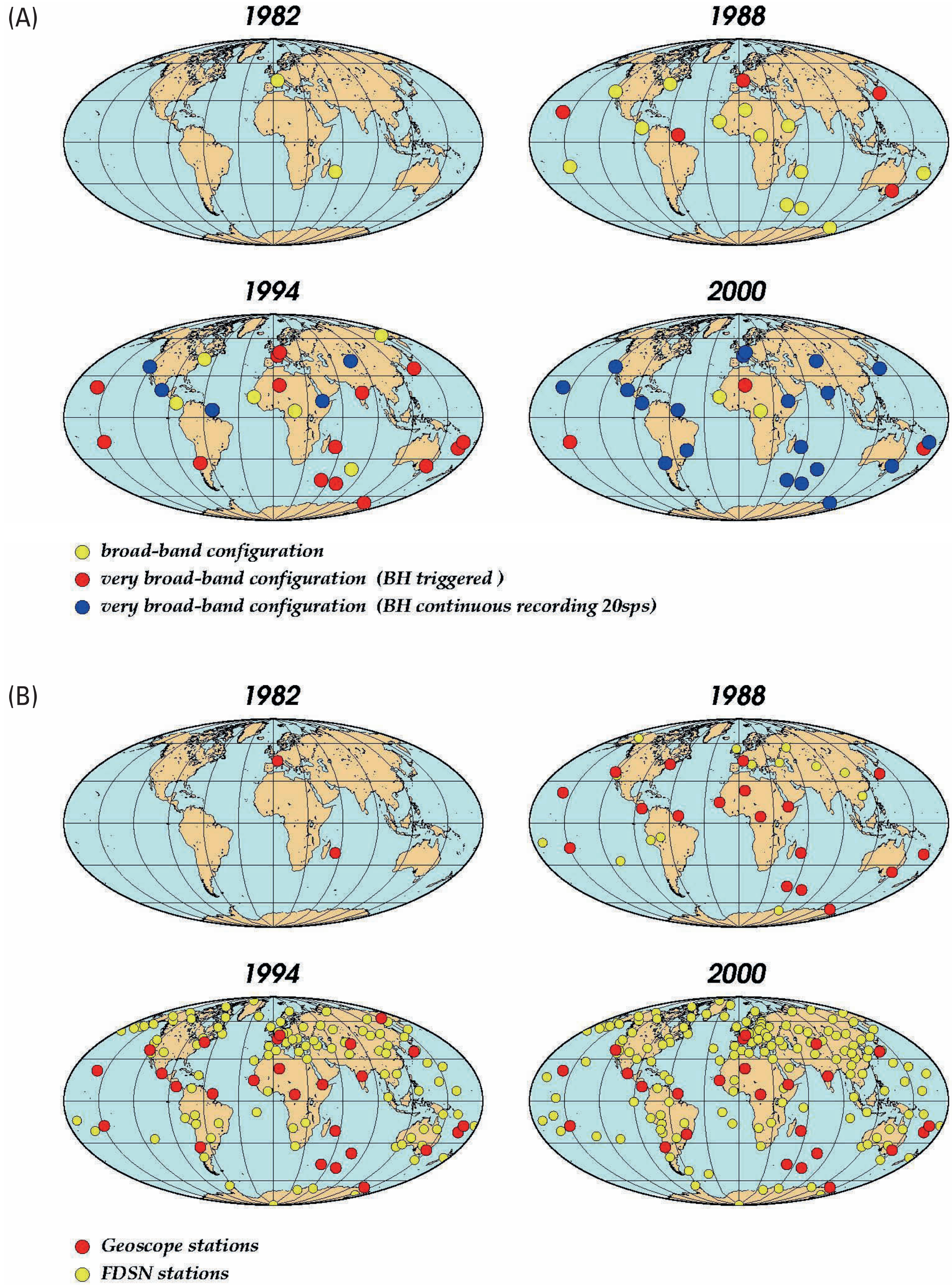
Improvement of the Triggered Recording System

The earlier STA/LTA ratio (short time average/long time average) algorithm (Vanderkulk *et al.* 1965), originally designed for short-period body wave detections and used for triggering on the MH channel (5 samples per second), was not well adapted to teleseismic earthquake recordings (Rouland *et al.* 1987). Many intermediate-size events, body waves of large events, and signals of long durations were often missed. A new event detection algorithm developed by Rouland *et al.* (1989) was progressively integrated in the digital recording systems (Pillet *et al.* 1990).

The four channels of the VBB configuration were commonly used for source studies (Monfret and Romanowicz 1986; Monfret 1988; Dufumier 1995), as well as for waveform modeling at different wavelengths, to provide 3-D regional or global models (Montagner 1986) and for the study of normal modes (*e.g.*, Romanowicz *et al.* 1987; Roult *et al.* 1990).

Data Distribution

At the inception of the network, IPGP and EOST developed different homemade formats, which made it difficult to operate a common data center. Nevertheless, it was decided to construct a single GEOSCOPE data archive at IPGP, which would manage the data and coordinate its distribution to the international scientific community. The main time-consuming tasks were checking the timing information (clock set by the operator, leap seconds correction, clock jumps) and applying the required time correction to the data. The first mode of data distribution to the wide scientific community was on magnetic tape and later on magnetic cartridges, upon request. In 1988, GEOSCOPE installed its first data "juke-box" and initiated an effort toward systematic data distribution on CD-ROMs (Figure S2A, online material). The GEOSCOPE Data Center further developed its capabilities in the 1990s to respond to the high volume of data requests from the scientific community and to take advantage of technological improvements, such



▲ **Figure 3.** A) Evolution of the number of GEOSCOPE stations as a function of time, from 1982 to 2000, with information related to three different steps of the acquisition chain configuration (BB, VBB with BH channel triggered, VBB with BH continuous recordings at 20 sps). B) Simultaneous evolution of the GEOSCOPE network and the FDSN stations.

as the development of the Internet. These developments were completed according to FDSN guidelines and in cooperation with the IRIS Data Center (Ahern 1994).

GEOSCOPE 1990–1998: A PERIOD OF VARIOUS EXPERIMENTS

The key role played by FDSN (Ahern 1994) helped the GEOSCOPE network to set priorities in instrumental development (Romanowicz *et al.* 1991; Roult and Montagner 1994). Two important improvements were made in the early 1990s: the development of multiparameter recording and the reduction of the time delay for collecting the data (some stations were still providing data by mail with delays up to one year). In September 1992 a meeting was held in Paris to celebrate the 10th anniversary of the GEOSCOPE program. Station operators, data center managers, and scientists met to discuss the state of the art in broadband seismology and its new challenges. Several changes in operational procedures resulted from the meeting, as described below.

A New Calibration Method

The seismometer transfer function is commonly obtained from the instrument "sensitivity," itself routinely determined on tilt tables by the manufacturers and assumed to be reliable with a nominal accuracy of 1%. This nominal accuracy ignores sensitivity to transportation, site conditions, and aging of equipment. Bernard *et al.* (1991) developed a method of in situ absolute calibration termed "G-calibration," which is easy to perform at the station site. They concluded that it is possible to achieve an accuracy of 1% for the vertical components and a few percent for the horizontal components, but only if the tilt perturbation is completely eliminated.

A New Original Design Concept

The importance of auxiliary channels was recognized very early on. It was obvious that we could benefit from recording other physical parameters as well as the seismic components. The GEOSCOPE stations were all equipped with three STS-1 seismometers. Some of them also had auxiliary channels (temperature, microbarometric pressure, tilt). The first microbarometers installed were designed and provided by Streckeisen. The response was flat in the frequency range from DC to 0.03 Hz, and the accuracy was better than .1 μbar (10^{-2}Pa). The thermometers were PT100 or PT1000 probes manufactured by the technical team at Saint-Maur-des-Fossés**.** The transfer function was flat from DC to 0.03 Hz with a dynamic range adjusted to ± 30°C corresponding to ± 10V. The sensitivity was better than 0.1 mK. Unfortunately, all auxiliary data before the year 2000 have been lost.

In 1990, two microbarometers were added to the two sets of STS-1 seismometers already operational at the GEOSCOPE reference station SSB (Saint-Sauveur Badole, France). The observations illustrated an obvious correlation between the atmospheric pressure and the horizontal component seismic noise signals (Figure 4A; Beauduin, R., J.-P. Montagner *et al.* 1996; Beauduin, Lognonné *et al.* 1996). Seismic noise in the vertical component is less correlated with pressure, and only at periods larger than 500 s. These results are in agreement with Zürn and Widmer (1995), who note that local atmospheric pressure is not systematically correlated to the seismic signal, but that the correlation largely depends upon the quality of the sensor installation. This result is particularly important for future installations in hostile environments where human intervention is very difficult and even impossible, such as the ocean floor and other planets.

The IPGP Data Center

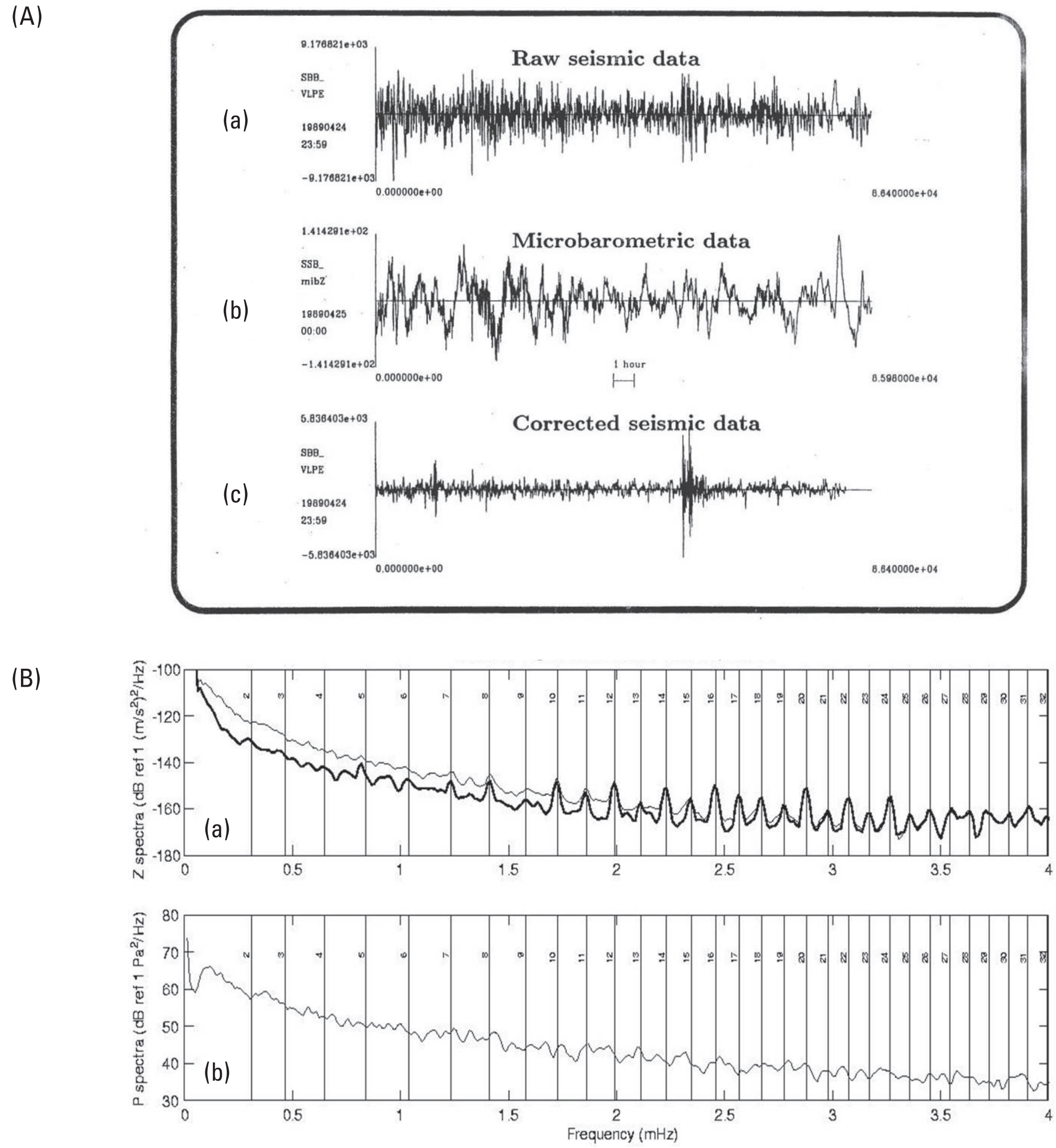
In 1989 GEOSCOPE signed a cooperation agreement with CEA/DASE (the department of the Commissariat à l'Energie Atomique in charge of seismic detection) to write data on optical disks. In 1990, GEOSCOPE data were archived in a homemade "database" format, and the sheer volume of data made distribution on magnetic tapes impractical. GEOSCOPE aligned itself with the FDSN standards regarding 1) the systematic determination of the transfer function, 2) the editing of a "station book," and 3) worldwide data distribution through various procedures.

Transfer Functions

Any processing of seismological data now requires accurate transfer functions (Holcomb 1989, 1992). In the SEED format, amplification factors and the poles and zeros characterizing the transfer function are summarized in a file named "DATALESS," described in the SEED manual (see, for example, Scherbaum 1996). To compute the instrument responses, the different elements of the acquisition chain for each station component and channel have to be known accurately. The instrument responses change with time, and changes in the analogic and numerical filters and in the dynamic range of the acquisition chain (12 bit, 12 bit gain-ranged, 16 bit, 20 bit, 21 bit, 24 bit) have to be documented. As an example, for the VH channel of station SSB in France, the present DATALESS volume includes 23 different transfer functions corresponding to successive upgrades of the acquisition chains. To check and validate the polarities of the channels, the component azimuths, and the instrument responses, we computed synthetic seismograms after each large event. To collect and check all the technical information took several years.

Station Book Editing

At the 1992 FDSN meeting, a resolution promoted the systematic publication of comprehensive "station books" using a standardized template, with each network operator responsible for its station book (FDSN 1994). The first GEOSCOPE station book was a printed document (Morand and Roult 1994), followed two years later by a more comprehensive and upgraded version (Morand and Roult 1996). The station book had to present the "history" of each station, its network affiliation (name and address), the network instrumentation, the station site with its geographical coordinates and its geology, the different channels with their sensitivities and dates of operation,



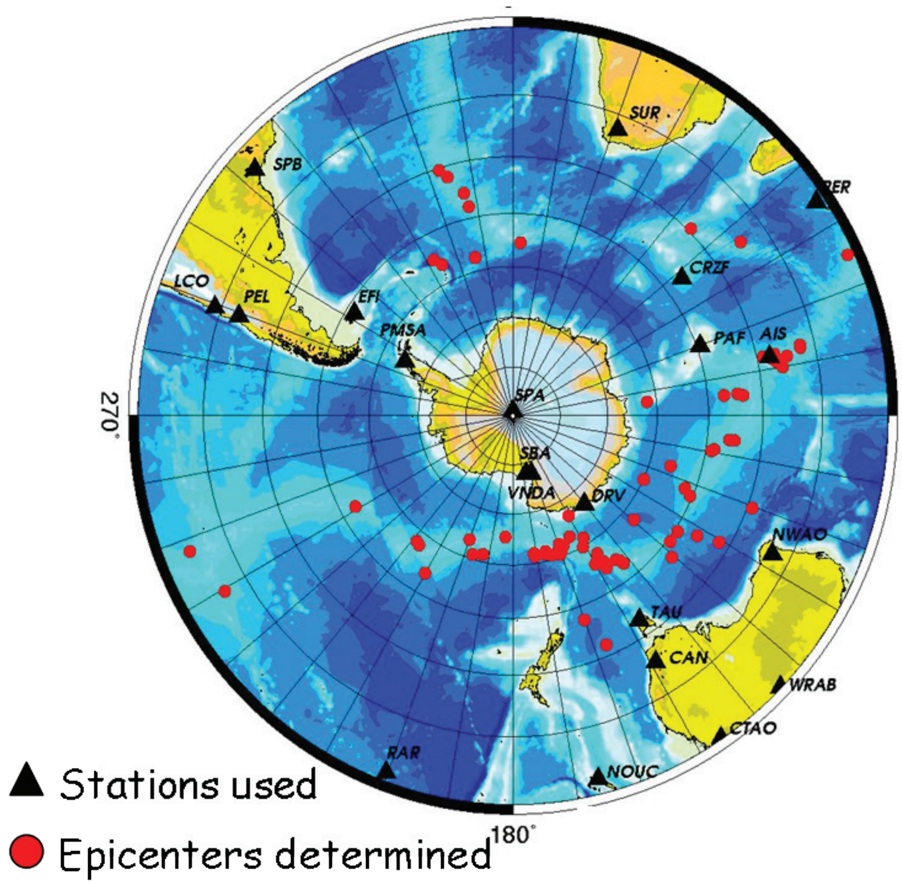
▲ **Figure 4.** A) Importance of recording the atmospheric pressure data (Beauduin, Lognonné *et al.* 1996). The simultaneous recording of microbarometer data (b) allowed to correct the raw data (a) from the atmospheric pressure effect and to obtain a seismic signal data (c) with a better signal-to-noise ratio. B) Interest in recording the local atmospheric pressure (Roult and Crawford 2000). Example at TAM station in 1998, from day 51 to day 68, after the large event on day 48 (February 19th) in the New Guinea area (Ms = 8.1). The vertical lines indicate the angular order l of the free oscillations of the Earth in the PREM model: (a) Power spectral density in acceleration before pressure effect correction (thin line) and after pressure atmospheric effect subtraction (thick line); (b) Atmospheric pressure power spectral density.

the instrumental transfer function plots, and photographs of sites. Each modification of the station has to be integrated in a new DATALESS volume and transmitted to the FDSN/IRIS Data Center, which gathers all station books provided by the different FDSN networks. Each FDSN meeting offers the opportunity for carefully upgrading the station books.

Distribution of Data

1. On CD-Rom

To ensure the long-term preservation and distribution of data, the GEOSCOPE Data Center was equipped in 1990 with a "juke-box" of 300 Gbytes capacity. All incoming data were then stored on the juke-box after time corrections had been applied. All data from March 1982 (82.061) to July 1992 (92.189) were written on CD-Rom in SEED format, and the whole collection (36 CD-Roms) was freely distributed worldwide to about 200 users during the period 1989–1997. The first CD-Rom (number 00) contained five years of data, but due to the increasing number of stations and channels recorded, the last CD-Rom (number 34) contained only eight days of data, as shown in Figure S2A (online material). It was difficult with the CD-Rom distribution to inform data users of upgrades or changes made at the stations. To inform all users, each new CD-Rom had to contain data for its time span and also cor-



▲ **Figure 5.** GEOSCOPE and FDSN stations (black triangles) used to identify and locate all "overlooked" earthquakes (red dots) in the Southern Hemisphere for the year 1999 (Rouland *et al.* 2003).

rections for errors on the previously distributed CD-Rom. The system became a nightmare. In 1997, CD-Rom production was stopped. At the same time, the rapid expansion of the Internet allowed us to provide direct access to the data archive through anonymous *ftp* requests (Figure S2B, online material).

2. Via Anonymous ftp

The GEOSCOPE Web site was developed in 1993. All data from recent earthquakes with magnitudes larger than 6.3, or of particular interest because of their locations or depths, were transmitted to the Data Processing Center at Saint-Maur des Fossés. For 11 stations, these data were transmitted through phone lines at very high cost. Approximately one event per week was transmitted this way. These data were made available at the Data Center in Paris through a specific procedure created in 1999 and were also made available to the scientific community through the GEOSCOPE Web server or through anonymous *ftp* one or two days after the event, in accordance with the FDSN requirements (Roult *et al.* 1999). Distribution through the AutoDRM procedure described by Kradolfer (1993, 2000) was implemented by the GEOSCOPE Data center starting in 1998.

Contribution to Earthquake Catalogs

Contributing to earthquake catalogues was not, at the outset, one of the scientific objectives of the GEOSCOPE network, but the sites at high latitude in the Southern Hemisphere provided interesting recordings of "overlooked" events that could then be localized.

Earthquake catalogs (such as the International Seismological Centre [ISC] catalog or USGS Preliminary Determination of Epicenters [PDE] catalog) are more and more complete because of the increasing number of stations installed worldwide in the last decades-even in deserts and other hostile areas. Although the development of worldwide seismological networks by various countries has been significant, there is still a lack of stations in the Southern Hemisphere. Very few earthquakes occur far away from plate boundaries, and the limited number of good-quality stations in the Southern Hemisphere results in a large number of missed intermediate-magnitude events. The comparison between the number of events of magnitude below and above 4.2 located in the Northern and Southern hemispheres underlines evidence that standard global earthquake catalogs are incomplete in their reporting of *Mw* 4.2–5.0 events in the Southern Hemisphere. The lack of stations in the Southern Hemisphere causes, on average, 100 earthquakes per year to be overlooked in the Southern Hemisphere and unlisted in global seismic activity catalogs. Rouland *et al.* (1992) inspected the continuous records collected at PAF, CRZF, DRV, and NOC stations during 1986 and checked the arrival times of the observed seismic waves with those of Rayleigh waves calculated for the epicenters reported in the U.S. National Earthquake Information Center (NEIC) monthly listings. They could locate only 23 previously undetected events by using the arrival time of the well-identified Rayleigh waves. Later, the use of both GEOSCOPE and IRIS stations in the Southern Hemisphere enabled a better identification of these events and the localization of half of those that occurred in 1999 (Rouland *et al.* 2003). To locate these events, the authors used Rayleigh wave trains visible on the vertical records filtered in the 20–100 s period range where the noise level is lowest. Figure 5 indicates the geographical location of the GEOSCOPE and IRIS stations used in this study as well as the 88 "overlooked" earthquakes from 1999. These "overlooked" events range in magnitude from 3.7 to 5.2.

GEOSCOPE 1998–2002: TOWARD MULTIPARAMETER OBSERVATORIES

The increasing numbers of GEOSCOPE and FDSN stations from 1982 to 2000 are compared in Figures 3A and 3B. The importance of GEOSCOPE within FDSN lies in the fact that 80% of its stations are equipped with STS-1 (Figures S1A, S3, online material). These instruments have a flat response to ground velocity up to 360 s, which provides better performances than the STS-2 (Figure S1B, online material), whose flat response extends only to 120 s. The fact that STS-1 seismometers are presently no longer manufactured makes those that are operational particularly precious for very-low-frequency studies, in particular for free oscillation studies. The initial priority for the GEOSCOPE network was to increase the number of stations and to improve their quality. A subsequent challenge was to record environmental parameters along with seismic signals (Montagner *et al.* 1998) and to increase accessibility and rapid availability of data using telephones and the Internet. The development of multiparameter observatories enabled monitoring of environmental parameters such as atmospheric pressure and temperature, and the investigation of the coherence between these parameters and the seismic signal (Figure 4).

Multiparameter Stations

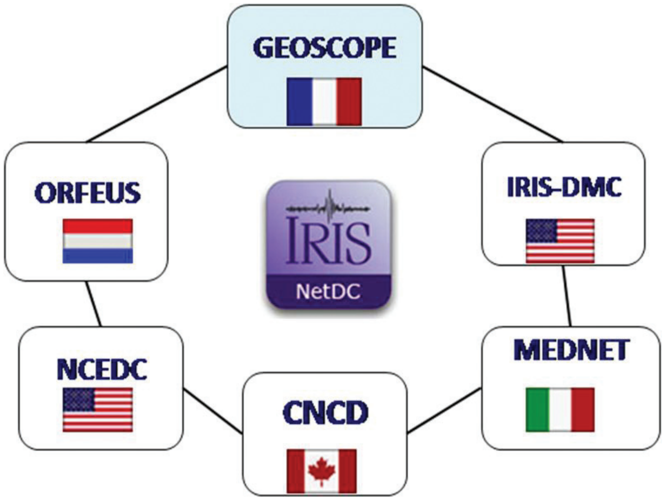
An instrumentation effort focused on the progressive upgrade of the equipment at the GEOSCOPE stations, particularly the analog-to-digital converters (ADC), and on the transformation of the stations into multiparameter observatories by adding microbarometers and thermometers. This effort had two different purposes: 1) to improve the signal-to-noise ratio, and 2) to investigate possible correlations between seismic and environmental physical parameters. GEOSCOPE decided to transform every seismic station into a multiparameter geophysical station. At that time, the concept of the multiparameter station was already widely accepted. Beauduin (1996), Zürn and Widmer (1995), and Beauduin, Lognonné *et al.* (1996) demonstrated the interest of deconvolving seismic data with pressure data, especially at frequencies lower than 2 mHz (Figure 4A). Spectra from large events were found to show a better identification of the frequencies of free oscillations of the Earth if the atmospheric pressure effect was taken into account. In 1998, several authors reported evidence of excitation of continuous free oscillations of the Earth even in seismically quiet periods of time. That weak signal of about 0.4 nanogals, now named seismic "hum," was found in all records from stations equipped with STS-1 seismometers (Suda *et al.* 1998; Nawa *et al.* 1998; Kobayashi and Nishida 1998; Tanimoto *et al.* 1998; Tanimoto and Um 1999). Observation of the "hum" is considerably enhanced when the atmospheric pressure is also recorded and subtracted, significantly increasing the signal-to-noise ratio (Roult and Crawford 2000). Figure 4B illustrates the utility of subtracting the pressure signal P from seismic Z data. Spectra were directly calculated after the large earthquake of 17 February 1998 near New Guinea. Subtracting the local atmospheric pressure effect clearly improves the spectra. The stacked Z–P spectrum shows low frequency peaks absent from the raw stacked spectra, in particular in the angular order range 2–15, making it possible to study very-low-frequency modes such as ${}_0S_2$ to ${}_0S_{15}$ that often are undetected due to the noise level.

The AGECODAGIS Experiment

In the late 1990s, a digitizer built by the French company AGECODAGIS and called "GEOSCOPE2000," seemed to compete with the Quanterra ones. It provided six 24-bit seismic channels (three BH channels and three LM channels) as well as 16 16-bit channels for recording various other parameters (atmospheric pressure, temperature, tiltmeters, GPS, etc.). One such digitizer was installed at the GRC station (Garchy, France) in June 2000 for two years (Roult and the GEOSCOPE team 2003). This was also the time when the Q4120 was being widely installed worldwide, and when Quanterra started to develop the Q330 (Figure S1C, online material). The AGECODAGIS and QUANTERRA systems were tested side by side by IPGP, which finally chose the Q330 to progressively replace the data loggers in all stations in the GEOSCOPE project to ensure better standardization with the FDSN station equipment.

The NetDC Procedure

In 1999, the GEOSCOPE Data Center was reorganized to better manage the increase in data volume and prepare for future real-time data. All GEOSCOPE data were moved into a relational database of metadata and stored in an efficient and secured system. In 1999 the GEOSCOPE Data Center became one of the Networked Data Centers (NetDC) nodes. This method of accessing the data was planned within the FDSN framework and installed at the IPGP Data Center with the help of the IRIS group. Within NetDC user requests are routed toward the appropriate networked data centers through an application layer that wraps operations and coordinates the data delivery. Compiling the datasets from various networks and sending them is transparent to the users, as shown in Figure 6.



▲ **Figure 6.** GEOSCOPE data availability and present operating diagram of the NetDC procedure with data centers and countries involved. In 1999, NCEDC, ORFEUS, and GEOSCOPE were the first networks to install the NetDC procedure, with IRIS help. Every NetDC node acts as a hub data center.

GEOSCOPE 2002–2007— A NEW CHALLENGE: TOWARD REAL-TIME STATIONS

In 2002, during a "Scientific Committee" attended by all French seismological authorities, delegates of FDSN and the European Data Center ORFEUS, French scientists, and GEOSCOPE data users, the objectives of GEOSCOPE were clearly redefined: increased cooperation with French and foreign partners, installation of sites at high latitudes, modernization and standardization of the data-acquisition chain, transformation of seismological stations into multiparameter observatories, and data transmission in near real time at all stations. At that time all permanent networks were focusing their efforts toward real-time data transmission (Hanka *et al.* 2000; Ahern 2003; Romanowicz and Giardini 2001; Giardini *et al.* 2002).

Increased Cooperation with French and Foreign Institutions

Since 2002 the GEOSCOPE program has developed increasingly active collaboration with French and foreign institutions regarding the upgrade and maintenance of its stations (Figure S4A, online material). The cooperation agreements became more numerous and efficient, thanks to the increasing interest of seismologists for real-time data recording in order to accelerate data processing and scientific research. GEOSCOPE continued to seek local partners to streamline maintenance and upgrading of remote stations. More responsibility was given to local universities or agencies that hosted its stations. Priority was given to original sites in the Southern Hemisphere, as well as to special sites at high latitude in both the Southern and Northern hemispheres.

Installation of Sites at High Latitude

The installation/upgrade of two stations at high latitudes in the Northern Hemisphere has been planned for several years to provide more polar paths for improved investigation of Earth's inner core (Souriau 1998). GEOSCOPE wished to instrument a new site, VOR (Vorkuta, Russia), near Novaya Zemlya and to upgrade the existing station SEY (Seymchan, Russia). The STS-1 sensors of SEY will be moved in the near future to another site, KAM, in the northern part of Kamchatka. These two locations are really original and scientifically interesting, thanks to their high latitude (Figure S4B, online material). These two stations are under the joint responsibility of IPGP and the Geophysical Survey of the Russian Academy of Sciences (GSRAS). In the Southern Hemisphere, the EOST group was involved in an International Polar Year (IPY) experiment and the installation of the CONCORDIA permanent station (Figure S4C, online material), in cooperation with Italy's Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome.

Standardization of the Data Acquisition Chains

The installation of modern standardized analog-to-digital converters is a top-priority step toward data transmission in near real time. Starting in 1997 with station AIS in the Indian Ocean (and 1998 at PAF, DRV, and CRZF), stations have been progressively equipped with Quanterra ADCs, first with the Q4120 series and then with the Q330 series. The Q330-HR matches the Q4120 and the Q330 performances. It provides three 26-bit channels, three 24-bit channels, and four 16-bit auxiliary channels. Its lower cost and its user-friendliness are very attractive (Figure S1C, online material). In 2006, a few stations maintained by EOST in the Indian Ocean were equipped with a Q330-HR in parallel with the existing Q4120 within the framework of the Centre National d'Alerte aux Tsunamis dans l'Océan Indien (CNATOI), as detailed later in the section on GEOSCOPE involvement in other programs. The present status is given in Table 1.

Data Transmission in Real Time

The near-real-time data transmission system was time consuming for the operators of the Data Center since time corrections had to be applied and soon became obsolete. Figure S5 (online material) lists the stations in year 2000. New developments made by GeoForschungsZentrum Potsdam led to freely available software, allowing easy data transmission (Hanka *et al.* 2000). All communication is based on the Seedlink protocol, which provides continuous data streams from remote stations (A. Heinloo, personal communication, 2001). Since 2002, the GEOSCOPE program has undergone a major change, with important upgrades in its transmission procedures to the IPGP Data Center (Roult and the GEOSCOPE team 2002). Each station requires a customized solution. For example, Figure S6 (online material) describes the detailed procedure that has been followed at RER (La Réunion Island) since June 2004. More than 3.5 km of optic fiber carry the signal from the shelter tunnel to an ethernet bridge. A radio link then allows us

TABLE 1
The GEOSCOPE stations: geographical coordinates, seismic sensors (STS-1 or STS-2) and environmental sensors (*P* pressure, T_{re} temperature), information on the different upgrades (VH recording, MH triggered recording, VBB configuration, Real-Time, etc.) and indication of the responsible institution (Resp. 1. IPGP; 2. EOST; 3. CEA; 4. GSN; 5. CTBTO; 6. ANU; 7. ERI).

Station	Location	Latitude	Longitude	Elev m	VH m/s^2	VH – MH m/s^2 m/s	BH – VH m/s	RT since	P	T_{re}	STS	Resp
AIS	Amsterdam Island	−37.797	+77.569	36		25 Dec 1993	7 Jan 1999	Oct 2009			1Z+2	2
ATD	Arta tunnel, Djibouti	+11.531	+42.847	610			7 Jul 1993	Sep 2005			2	5
CAN	Canberra, Australia	−35.319	+148.996	700			27 Nov 1987	Dec2006			1	1,6
CLF	Chambon la Forêt, France	+48.026	+2.260	145			10 Jul 2008	Jul 2008	X		2	1
COYC	Cohyaique, Chile	−45.573	−72.081	235			17 Dec 2004	Internet			1	1
CRZF	Port Alfred, Crozet Islands	−46.431	+51.855	140	13 Mar 1986	27 Jul 1988	28 Nov 1993	Dec 2008			1	2
DRV	Dumont d'Urville, Antarctica	−66.665	+140.002	40	1 Feb 1986	1 Feb 1988	25 Jan 1991				1	2
DZM	Dzumac, New Caledonia	−22.072	+166.444	878			1 Sep 2003	Sep 2003	X		2	3,5
ECH	Echery, France	+48.216	+7.159	580			8 Nov 1990	Dec 2006			1	2
FDF	Fort de France, West Indies	+14.735	−61.146	467			25 Nov 1998	Nov 2002	X	X	2	1
FOMA	Fort-Dauphin, Madagascar	−24.976	+46.979	28			1 Sep 2008	Sep 2008	X		2	1
HDC	Heredia, Costa Rica	+10.002	−84.111	1186			8 Mar 1997	Oct 2008	X	X	2	1
HYB	Hyderabad, India	+17.419	+78.552	510			15 Jan 1989			X	1	1
INU	Inuyama, Japan	+35.350	+137.029	132			4 Mar 1987	May 2007			1	7,1
KIP	Kipapa, Hawaii, USA	+21.423	−158.015	70		17 Apr 1986	26 May 1988	Apr 2004	X		1	4
MBO	Mbour, Senegal	+14.392	−16.955	3	1 Sep 1985	30 Nov 1987	5 Nov 2002				1Z+2	2
MPG	Montagne des Pères, Fr. Guiana	+5.110	−52.644	147			3 Jul 2000	RA		X	2	1
NOUC	Port Laguerre, New Caledonia	−22.101	+166.303	112	21 Mar 1988	8 May 1989	2 Nov 1992	RA			1	1
PAF	Port aux Français, Kerguelen	−49.350	+70.211	17	1 Jan 1983	28 Jan 1988	28 Dec 1992	Dec 2006			1	2
PEL	Peldehue, Chile	−33.144	−70.675	660			4 Oct 1995	Internet		X	1	1
PPTF	Papeete, Tahiti	−17.590	−149.565	705			25 Apr 2009	Apr 2009	X	X	1	1,3
RER	Rivière de l'Est, La Réunion I.	−21.171	+55.741	834		10 Feb 1986	4 Jul 1990	Apr 2004	X		1	1
SCZ	Santa Cruz, California, USA	+36.599	−121.405	261	11 Jun 1986	27 Sep 1987	27 Sep 1991	Internet	X	X	1	1
SPB	Sao Paulo, Brazil	−23.593	−47.427	647			17 Jun 1996	Nov 2006	X	X	1	1
SSB	Saint Sauveur Badol, France	+45.279	+4.542	700	2 May 1982	14 Jan 1985	22 Apr 1987	Apr 2004	X	X	1	1
TAM	Tamanrasset, Algeria	+22.791	+5.528	1410	16 Nov 1983		11 Mar 1990	Dec 2006	X	X	1	1
TAOE	Marquesas I., France	−8.855	−140.148	800			15 Jun 2005	Oct 2005	X		2	1,3
TRIS	Tristan Da Cunha, UK	−37.068	−12.315	57			3 Mar 2004	Mar 2004			1Z+2	4
UNM	Unam, Mexico city, Mexico	+19.329	−99.178	2280			6 Jun 1990	Jul 2008	X	X	1	1
WUS	Wushi, Xinjiang, China	+41.199	+79.218	1457			31 Oct 1988		X	X	1	1

TABLE 1 (continued)
The GEOSCOPE stations: geographical coordinates, seismic sensors (STS-1 or STS-2) and environmental sensors (*P* pressure, T_{re} temperature), information on the different upgrades (VH recording, MH triggered recording, VBB configuration, Real-Time, etc.) and indication of the responsible institution (Resp. 1. IPGP; 2. EOST; 3. CEA; 4. GSN; 5. CTBTO; 6. ANU; 7. ERI).

Decommissioned Stations					Started			Stopped
Station	**Location**	**Latitude**	**Longitude**		**VH m/s/s**	**VH – MH m/s/s – m/s**	**BH – VH m/s – m/s**	
AGD	Arta Grotte, Djibouti	+11.529	+42.824	450	9 Mar 1985	6 Aug 1987		9 Dec 1990
BNG	Bangui, Centrafrica	+4.435	+18.547	378	11 Dec 1987	12 Sep 1988		01 Dec 2001
CAY	Cayenne, French Guiana	+4.948	–52.317	25	22 Jul 1985	9 Dec 1985		28 Sep 1991
EVO	Evora, Portugal	+38.532	–8.013	0			7 Feb 1996	30 Jun 1997
GRC	Garchy, France	+47.295	+3.074	191			21 Jun 2000	19 Dec 2002
HDC2	Heredia, Costa Rica	+10.027	–84.117	1253		25 Sep 1987		1 Mar 1989
KOG	Kourou, French Guiana	+5.207	–52.732	10			2 Jul 1994	19 Dec 2000
NOC	Noumea, New Caledonia	–22.284	+166.432	5	8 Dec 1985			27 Oct 1987
PCR	Plaine des Cafres, Réunion	–21.196	+55.578	1520	25 Jul 1982			9 Feb 1986
PPT	Papeete, Tahiti, France	–17.569	–149.576	340	31 May 1986	24 Nov 1986	5 Oct 1991	25 Mar 2009
PVC	Port Vila, Vanuatu I.	–17.740	+168.312	8		01 Jun 1994	23 Mar 1995	01 Apr 2004
SEY	Seymchan, Russia	+62.933	+152.373	206			21 Sep 1990	2 Feb 1994
WFM	Westford, Massach., USA	+42.611	–71.491	87	17 May 1984	9 Apr 1986		27 Apr 1994

Planned Station	Location	Latitude	Longitude
KAM	Kamchatka	~+61.0	~164.0
RODM	Rodrigues, Mauritius	~–19.7	~+63.4
VOR	Vorkuta, Russia	~+65.0	~+75.0

to send the signal to the roof of Saint Benoit city high school 12.5 km away, where a fast connection to Internet is available. Figure 7 shows the data stream for a current standard GEOSCOPE station, with eight different channels (three seismic channels, three boom positions, one microbarometer, and one thermometer). Automatic controls enable rapid detection of dysfunctions and transmission of error messages in order to trigger appropriate reactions.

GEOSCOPE IN 2009, STATE OF THE ART

The strong points of the GEOSCOPE network in 2009 are:

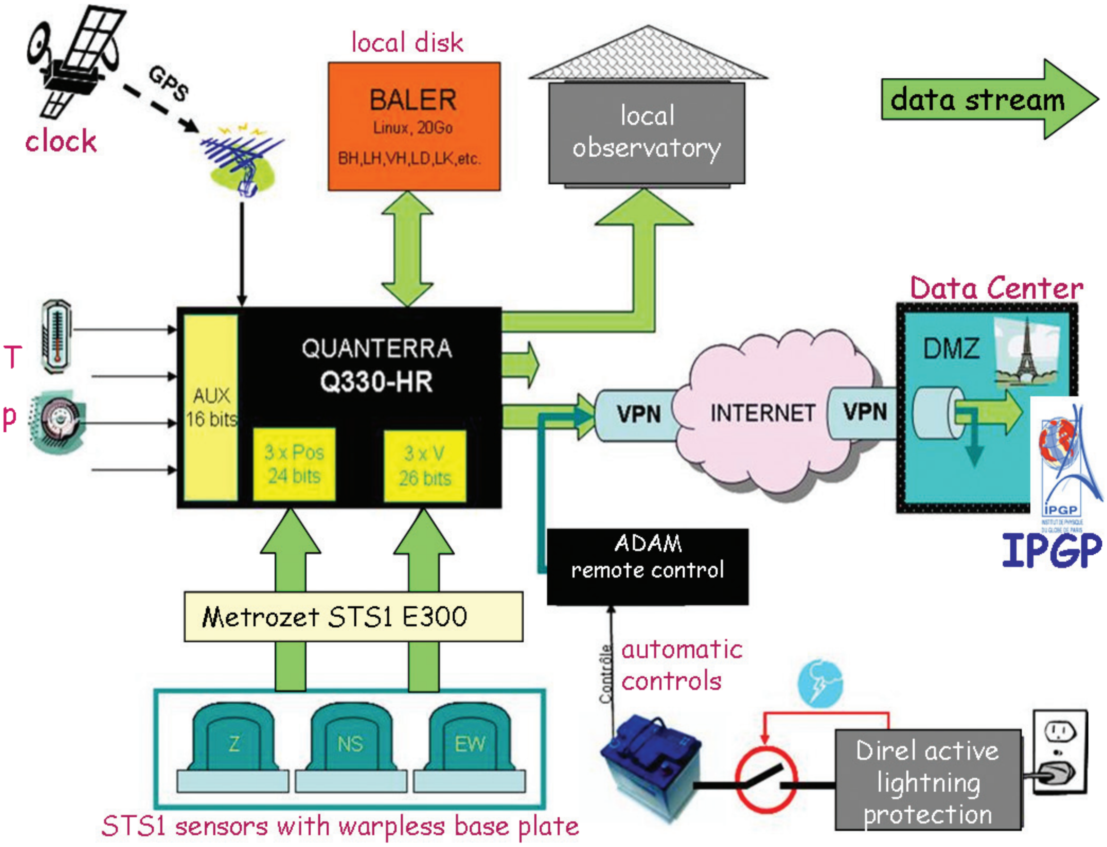
1. the network offers a unique distribution of stations in Africa and in the Indian Ocean with a good coverage of the Southern Hemisphere in general;
2. most sensors are very broadband seismometers (22 stations with STS-1, eight with STS-2);
3. the noise levels are among the lowest of all FDSN stations;
4. real-time data are now available from 21 (out of 30) stations; and
5. noise levels are estimated and plotted in quasi real time.

At the end of 2009, the network consisted of 30 stations (Figure 8A), with four stations in the northern part of Africa and eight stations in or close to the Indian Ocean. The stations are equally divided between the Northern and Southern hemispheres and are mainly equipped with STS-1 sensors (Figure S3, online material). Table 1 gives different informative parameters on the evolution of the stations, their start and end dates, their geographical coordinates, the start of the different channels (VH, BH), the station equipment (sensors and dataloggers), the data transmission state (RT: real-time, NRT: near real time, RA: remotely accessible by phone line or via Internet). Clearly, GEOSCOPE has reached and exceeded its original design goals.

Stations Operating at the End of 2009 (Figure 8, Table 1)

As of the end of 2009, 30 stations are operational. Their maintenance is performed in situ by CEA/DASE, CNES (Centre National d' Etudes Spatiales), EOST, IPGP, IPEV, IRD, GSN/USGS, and local universities and research institutes.

- Seventeen stations are under the responsibility of IPGP, in the VBB configuration: CLF, COYC, FDF, FOMA, HDC, HYB, MPG, NOUC, RER, PEL, PPTF, SCZ, SPB, SSB, TAM, UNM, and WUS.
- Six stations operate under the responsibility of EOST (Strasbourg) in the VBB configuration: AIS, CRZF, DRV, ECH, MBO, and PAF.
- Two stations are under the joint responsibility of CEA/DASE (at Bruyères-le-Châtel): DZM in New Caledonia and TAOE in the Marquesas Islands.
- Two stations are under the joint responsibility of GSN/IRIS/USGS (United States): KIP in Kipapa, Hawaii, and TRIS in Tristan Da Cunha, U.K.
- One station is under the joint responsibility of CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization) and IPGP: ATD (Arta, Djibuti).



▲ **Figure 7.** Present operating diagram of a GEOSCOPE real-time station.

- One station is under the joint responsibility of the Australian National Institute (ANU) and Geosciences Australia (GA): CAN in Canberra, Australia.
- One station is under the joint responsibility of the Earthquake Research Institute (ERI): INU in Inuyama, Japan.

Almost all stations are multiparameter observatories (Figure 8B). Information on instrumentation in stations (seismic and auxiliary sensors, dataloggers) is given in detail in Appendix 1 (online material) and on the GEOSCOPE Web site (http://geoscope.ipgp.fr).

Channel Specifications

The three seismic components (vertical, north–south, east–west) of ground velocity are recorded. For each STS-1 component, eight channels are continuously recorded, the three channels VH, LH, and BH according to the sampling rate, the three streams corresponding to the boom position (outputs recommended for tide studies, LM channel), the atmospheric pressure (LDI/LDO channels), and the temperature (LKI channel), as detailed in Appendix 1 (online material). The data are released in SEED format (Ahern *et al.* 1986; Halbert *et al.* 1996).

The IRIS Data Management Center (DMC) in Seattle collects data from different FDSN sources (more than 50 networks), archives them in a reliable high-capacity system, and distributes seismic waveform data very quickly (Malone 1996, 1997, 2002). All GEOSCOPE real-time (RT) data are part of the real-time data available through the buffer of uniform data at the IRIS DMC. The GEOSCOPE RT data are also available at the IPGP Data Center (http://geoscope.ipgp.fr) and can easily be downloaded. Data are in mini-seed format; the transfer functions are available through the associated DATALESS volume.

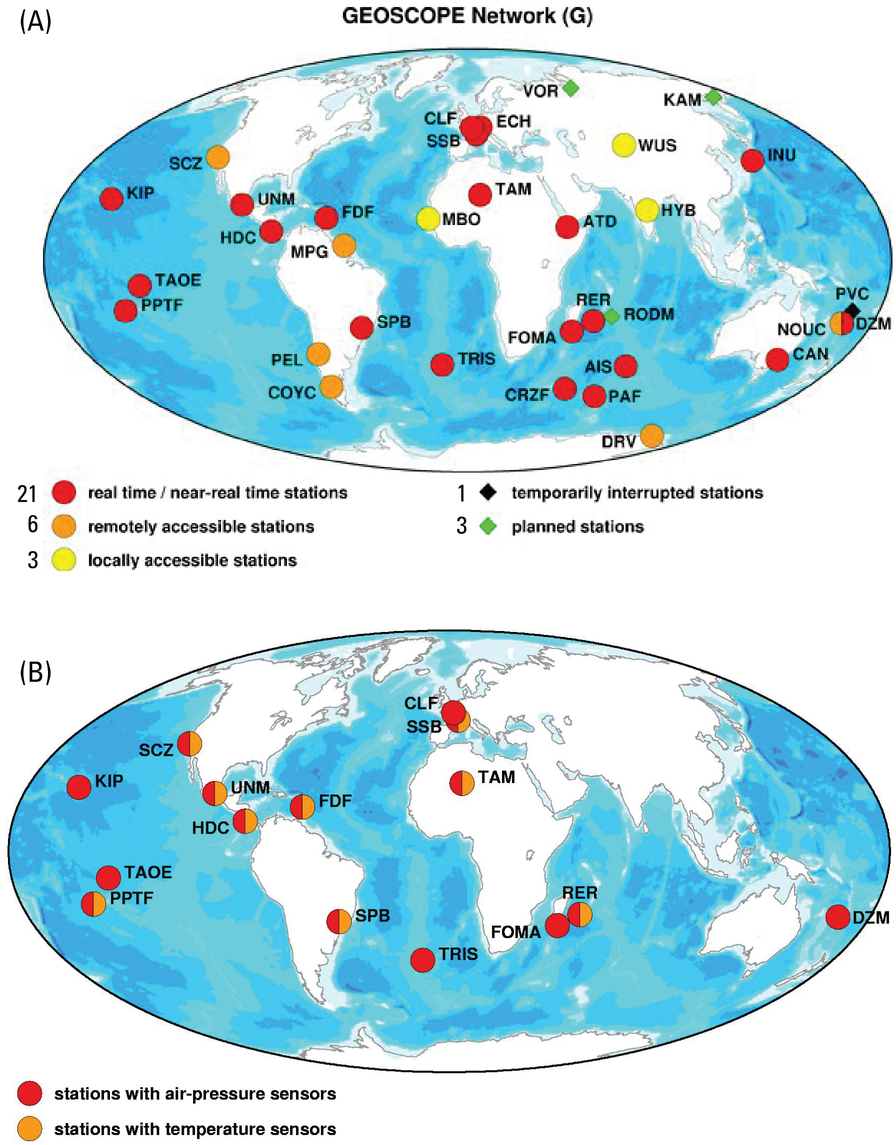
Twenty-one Stations in Real Time at the End of 2009

Data are available at the GEOSCOPE Data Center in real time (<1 mn) for 15 stations maintained by IPGP (ATD, CAN, CLF, FDF, FOMA, HDC, INU, KIP, PEL, PPTF, RER, SSB, SPB, TRIS, UNM) and in near real time (<2 h) for two stations maintained by CEA (DZM and TAOE) (Table 1). Data from four stations monitored by EOST (AIS, CRZF, PAF, ECH) are available in real time as well. There remains a significant time delay for the other stations, which still depend on mailed magneto-optical disks (about every month).

Figures S2C and S2D (online material) illustrate the increasing amount of data archived with time and the volume of the distributed data, with indication of the different distribution procedures (CDRom, *ftp*, Web, NetDC) as a function of time.

Data Quality Control

Murphy and Savino (1975) and Webb (1998) describe possible causes of seismic noise. A better understanding of the origin of seismic noise is fundamental for enhancing the signal-to-noise ratio of the data. The correlation between atmospheric pressure

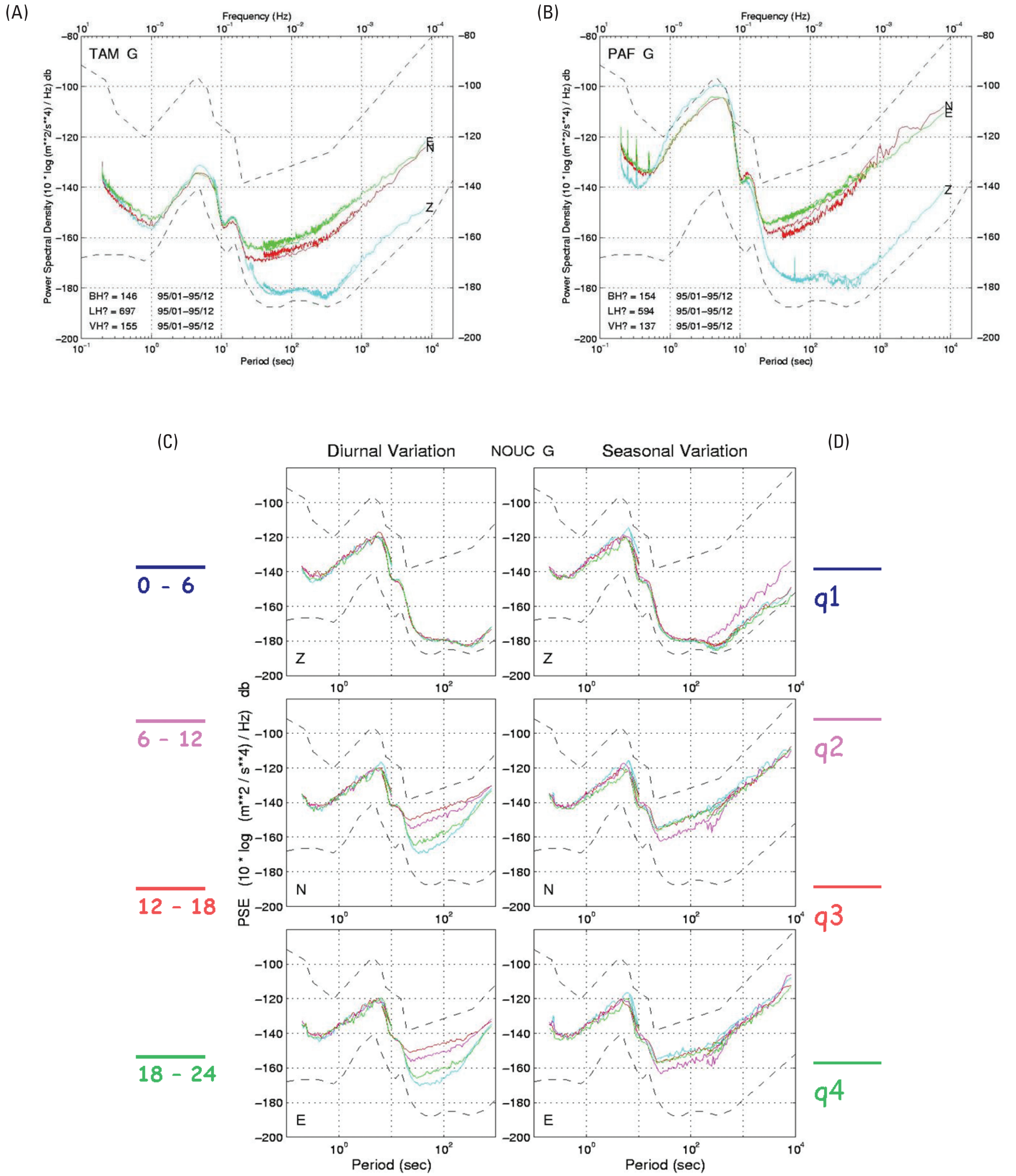


▲ **Figure 8.** The GEOSCOPE network as of January 2010 as it moves toward real-time and multiparameter observatories A) Network status: 21 real-time/near-real-time stations, six remotely accessible stations through Internet or phone lines, and three locally accessible stations. B) More and more seismological stations are equipped with microbarometers and microthermometers participating in the global efforts for multiparameter observatories concept.

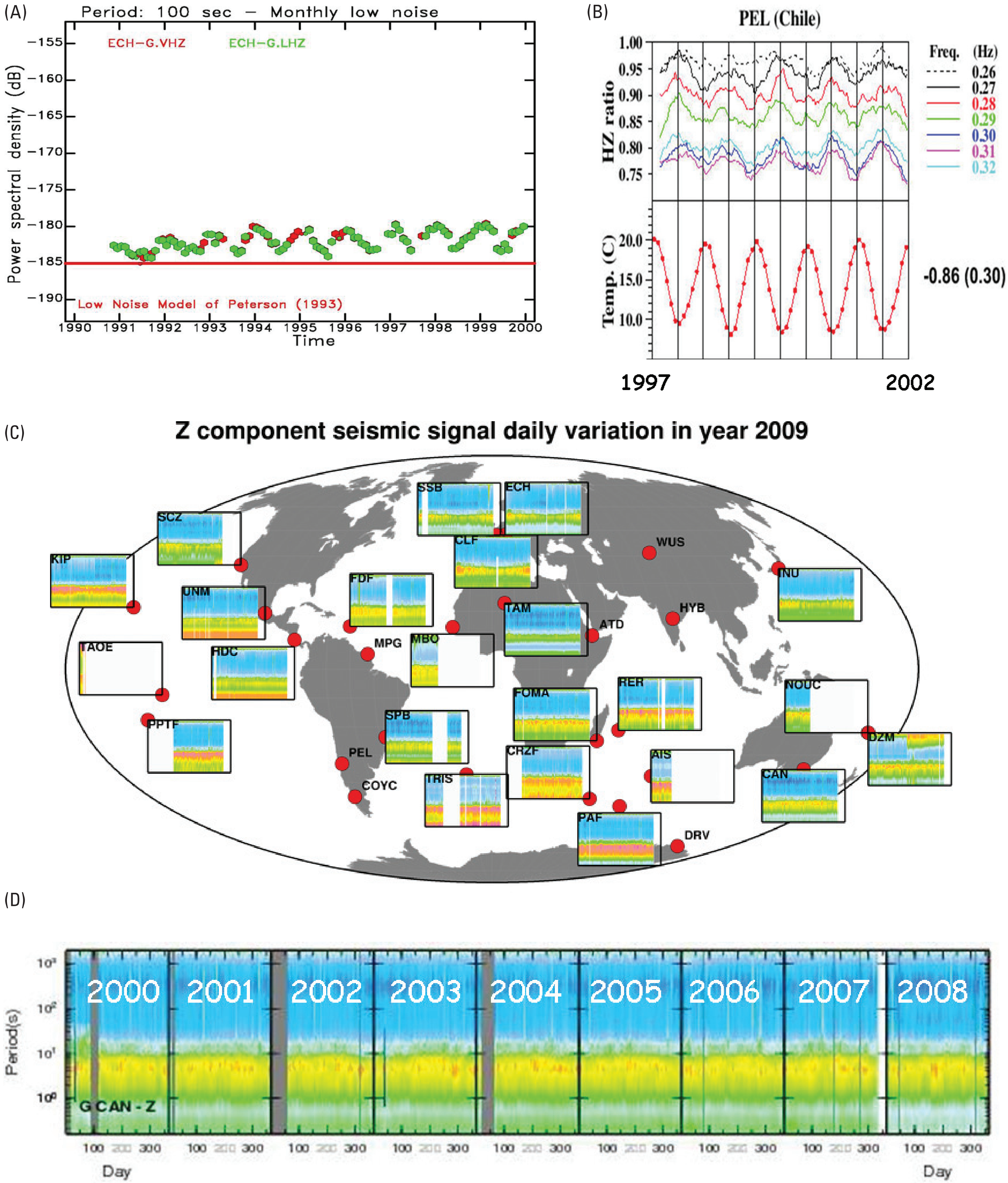
and seismic noise in the seismic period band can be used for land stations (Beauduin, Lognonné *et al.* 1996). Crawford *et al.* (1991) developed a new technique for noise reduction by using the coherence between ocean-bottom seismic data and the local pressure changes under the loading of long-period ocean waves.

Analysis of the power spectral density (PSD) noise level at one station, calculated according to the Chave *et al.* (1987) procedure, shows systematically higher noise for the horizontal components than the vertical ones, as illustrated by Figures 9A and 9B (Stutzmann *et al.* 2000). As already observed by Berger *et al.* (2004), the lowest horizontal component noise levels are observed at stations where STS-1 seismometers (not STS-2) are located in very well-isolated vaults or long tunnels. Thermally induced tilts and local atmospheric pressure fluctuations may contribute to seismic noise (Bradner and Reichle 1973). Rotational effects can be induced by tilts and have to be taken into account (Pillet and Virieux 2007). Cavity effects are not negligible on the horizontal components, as demonstrated by Lambotte (2007).

All GEOSCOPE stations exhibit low average noise compared to the average over the entire set of the FDSN stations (Stutzmann *et al.* 2000), and some GEOSCOPE stations are amongst the least noisy of the FDSN stations (WUS in China, TAM in Algeria). As expected at short periods, the horizontal component noise level is lower at TAM station, located in a continental area (Figure 9A), than at PAF station, located in an island area (Figure 9B). Most coastal stations located at distances less than 150 km away from the coast have a higher noise level than continental stations. Island stations have a similar



▲ **Figure 9.** Top: Power spectral density plots at two Geoscope stations. A) At a continental quiet one (TAM, Tamanrasset). B) At a coastal one (PAF, Port aux Français, Kerguelen Island, Indian Ocean) with respect to the low noise model (LNM) of Peterson (1993) (dashed lines). Bottom: Daily and seasonal variations of the power spectral density at NOUC (Nouméa, New Caledonia) station, estimated for the three components. C) Diurnal variations of seismic noise as a function of period. Local time windows are 0–6 hours (blue), 6–12 hours (pink), 12–18 hours (red), and 18–24 hours (green). D) Seasonal variations of the seismic noise. Term windows are from January to March (q1, in blue), April to June (q2, in pink), July to September (q3, in red), and October to December (q4, in green).



▲ **Figure 10.** A) Power spectral density (PSD in dB) variation from 1990 to 2000 at the ECH station on the vertical component at a period T = 100 s (Ekström *et al.* 2001). B) Interest in recording the temperature: there is a clear negative correlation between the H/Z ratio (horizontal component versus vertical component) and the temperature versus time, from 1997 to 2002 (Tanimoto *et al.* 2006), at different frequencies in the microseismic frequency band, at the same station. C) The noise level plots are estimated every year, at all stations (example for year 2009). D) Noise level plots from 2000 to 2008 (example for CAN station).

noise level at long periods as coastal stations, but a higher noise level at periods shorter than 20 s, particularly within the period range of the microseismic peaks. For periods longer than 20 s, noise on the horizontal components varies, in most stations, as a function of local time, and is higher during the day than during the night (Figure 9C). There is no evidence for systematic seasonal variations of short-period seismic noise (periods lower than 7 s). Some stations exhibit seasonal variations in the 7-s microseismic peak amplitude, with higher peak amplitude in fall and winter than in spring and summer; that peak is also shifted toward longer periods in fall and winter (Figure 9D). The explanations can be found in the increase of large oceanic storms in fall and winter. Long-period seismic noise (periods greater than 30 s) also varies with the season in some stations, but no systematic characteristics have been observed.

Figure 10A illustrates the seasonal variation of the noise level at ECH station (Echery, France) from 1990 to 2000 (Ekström *et al.* 2001). The noise level seems to increase slightly with increasing time. A possible explanation of such a trend is the aging of the STS-1 sensors, a phenomenon that is carefully evaluated by STS-1 users. The interest in installing thermometers at the site is illustrated by Tanimoto *et al.* (2006), who observed seasonality in the particle motion of microseisms (HZ horizontal/vertical ratio) at PEL station (Peldehue, Chile) and found a high coherence with the temperature signal (Figure 10B).

In 2006, automatic quality control of the data available in real time was implemented at the GEOSCOPE Data Center to speed up the archiving process. This quality control consists of a search for anomalies, in time or amplitude, as well as in the validation of transfer functions. Daily, monthly, and yearly plots of the seismic signal power spectral estimates are displayed on the GEOSCOPE Web site (Figures 10C and 10D).

CMT Determination

Since the beginning of the GEOSCOPE program, one of the priorities was to determine the focal mechanisms of all large events (Monfret and Romanowicz 1986; Monfret 1988; Dufumier 1995; Gouget 1996). The source parameters of large earthquakes are now systematically studied in the regional tectonic context (Clévédé *et al.* 2004). The data used are three-component long-period seismic signals of the GEOSCOPE stations and a few additional FDSN ones, in the 1–10 mHz frequency range. The accurate determination of source mechanism and rupture process is performed by comparing results derived from body waves of shorter periods. The centroid parameters and the source duration are estimated by an exploration over a space-time grid (longitude, latitude, depth, source duration). When the centroid is supposed to be known and fixed, the relationship between the moment tensor and the data is linear. Then, for each point of the centroid parameter space, a moment tensor can be obtained by linear inversion in the complex spectral domain for the different source durations. The best solution corresponds to the best data fit.

The GEOSCOPE CMT solution (source mechanism) is systematically calculated in the week following a large earthquake. Figure S7 (online material) gives the geographical location of all earthquakes in 2009. These centroid solutions are published on the GEOSCOPE Web site (http://geoscope.ipgp.fr) and are also available on the European-Mediterranean Seismological Centre (EMSC) Web site (http://www.emsc-csem.org/index.php?page=home).

GEOSCOPE INVOLVEMENT IN OTHER PROGRAMS

GEOSCOPE shares with the seismological community at large its expertise and experience in seismological instrumentation and data distribution. The GEOSCOPE program has launched a number of initiatives and has played a key role in related fields.

Ocean-bottom Observatories and Pilot Experiments

A large part of the oceanic area (two-thirds of the surface of the Earth) is devoid of permanent geophysical sensors. The international community has long recognized the need for long-term observations on the ocean floor, which provide the geoscientific community with global, regional, and local-scale observations in real time when the infrastructure allows data transmission (Purdy and Dziewonski 1988). A recommendation of all future strategy workshops has been to promote the installation of long-term oceanic seismographic stations or even better, geophysical stations and observatories. Since its inception, the GEOSCOPE group has since its inception promoted the extension of BB stations in the oceans.

The installation of a network of geophysical ocean bottom observatories (named GOBO) represents a formidable technological challenge for the new century. Several pilot experiments have been carried out to unravel the different technical issues. Preliminary experiments focused on the installation of permanent seismic stations were initiated in the early 1990s (Dziewonski *et al.* 1992).

In March 1991, a set of borehole broadband CMG3 seismometers was successfully placed in Ocean Drilling Project (ODP) hole 843B in the Japan Sea, but was not recovered (Suyehiro *et al.* 1992). Teleseismic events were recorded on this instrument and the broadband seismic noise spectrum (0.03 s–200 s) was obtained after recovering the data (Kanazawa *et al.* 1992). In May 1992, the French pilot experiment Observatoire Fond de Mer/Seismological Ocean Bottom Seismometer (OFM/SISMOBS) was successfully conducted in the north Atlantic Ocean at the location of the Deep Sea Drilling Project (DSDP) hole 396B (23°N, 43.3°W). Two sets of CMG3 broadband seismometers were installed, operated over a week, and recovered (Montagner, Romanowicz, and Karczewski *et al.* 1994). The first set of CMG3 seismometers (sea floor seismometers called OFM) was installed on the sea floor at 20 m from the hole and was half-buried within the sediments. The second set of CMG3 seismometers (downhole seismometers named OFP) was installed in the hole at 296 m below the sea floor. After the installation of both sets of seismometers, seismic signals were continuously recorded during eight days for OFM and five days for OFP, at a sampling rate of 5 samples per second. The instruments were successfully recovered at the end of the experiment.

All the logistical support was provided by Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER). From a technological point of view, this experiment was a complete success. The most important scientific results are described by Montagner *et al.* (1994). The seismic noise is lower in the period range 4–30 s for both OFM and OFP compared to a typical broadband continental FDSN station such as SSB (France, GEOSCOPE), and it is still lower than the noise at SSB up to 600 s for OFM (Beauduin *et al.*1996b). This low level of seismic noise implied a low detection threshold, and teleseismic earthquakes of magnitude as small as 5.2 are correctly recorded. This experiment demonstrated, for the first time, that a broadband seismometer carefully installed and half-buried on the sea floor can present an excellent signal/noise ratio and provide useful seismic data. This result was confirmed during the comprehensive ocean seismic network pilot experiment OSN1 close to Hawaii (Collins *et al.* 1998).

Following these successful pilot experiments, the international scientific community decided to launch a new organization, International Ocean Networks (ION), in 1993, with the same technical specifications and similar scientific objectives as FDSN but for ocean-bottom seismic stations. ION is affiliated with the International Association of Seismology and the Physics of the Earth's Interior (IASPEI) and the International Union of Geodesy and Geophysics (IUGG).

As a result of the first international workshop of ION in Marseilles in 1995 (Purdy and Dziewonski 1995; Montagner and Romanowicz 1995; Montagner and Lancelot 1995), IPGP, Université de Bretagne Occidentale Brest (UBO Brest), the Monterey Bay Aquarium Research Institute (MBARI), and the University of California at Berkeley launched a cooperative multiparameter project to test the feasibility of installing, operating, and recovering different geophysical sensors (primarily broadband seismometers, electro-magnetometers, and environmental sensors) on the sea floor. The MOISE (Monterey Bay Instrumental Seismic Experiment) experiment was conducted from June to September 1997 off the California coast in Monterey Bay on sea-floor sediments at a depth of 1,015 m. The geophysical instruments were deployed by MBARI's remotely operated vehicle Ventana, and the seismometer package was half buried in the sediments (Stutzmann *et al.* 2001; Stakes *et al.* 2002). The results presented in Romanowicz *et al.* (1998) demonstrated a strong correlation between seismic noise and deep water currents.

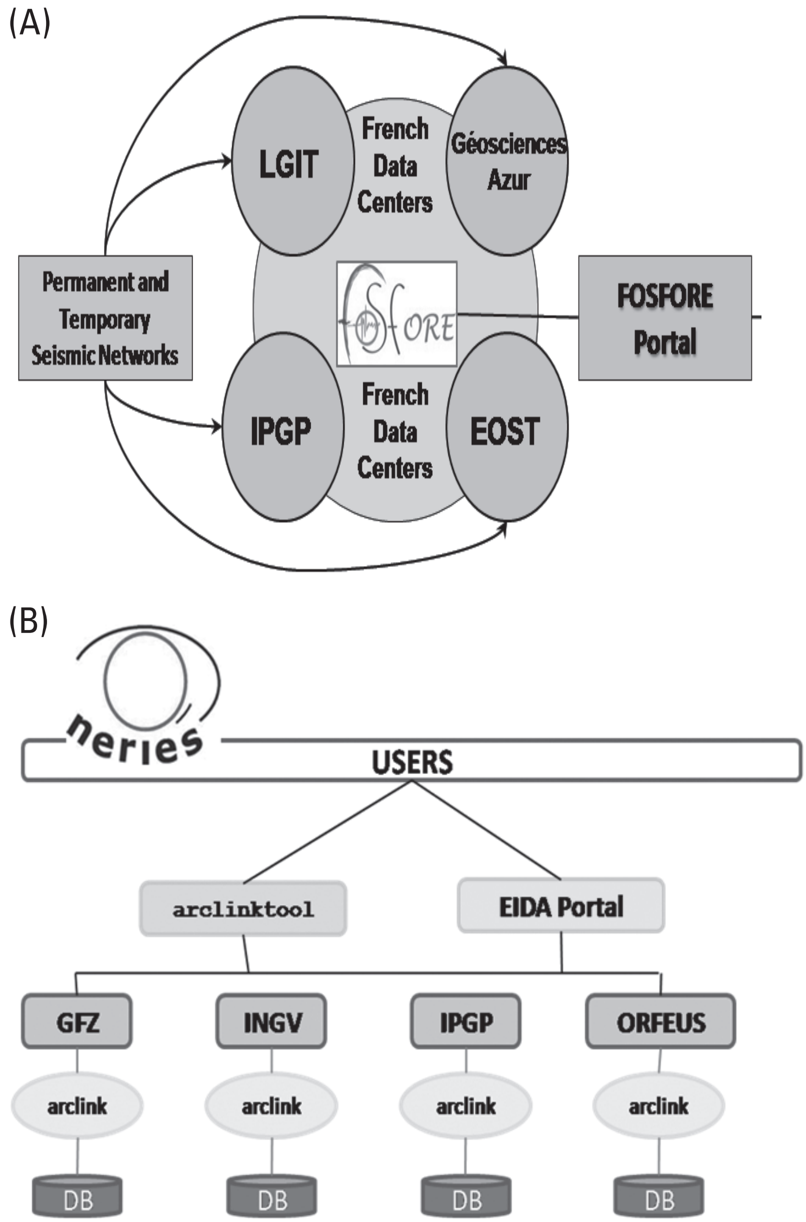
In the framework of ION and the Integrated Ocean Drilling program, IPGP, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and IFREMER initiated an international cooperative project and plan to install an ocean-bottom observatory at the Ninety East Ridge Observatory (NERO) site along the Ninety East Ridge in the Indian Ocean (18°S–88°E). The hole was drilled in 1998 and has since been awaiting geophysical instrumentation.

Pilot experiments have demonstrated that the installation of GOBOs is technically feasible at some particular sites (Montagner *et al.* 2002). However, the problem of long-term maintenance has not been solved. Other countries are faced with the same problem of long-term operation of GOBOs and, except in the case of Japan, which installed several GOBOs (WP1, WP2, JT1, JT2), the entire ION observatory program is stalled pending future funding. Another exception is the autonomous broadband ocean floor station MOBB (Monterey ocean bottom broadband observatory), installed in 2002 by UC Berkeley Seismological Laboratory and MBARI and built on the lessons learned during the MOISE experiment, which was still operational as of 2009. An ambitious new program led by Japanese groups was launched in March 2008 and might revive ION and the whole ocean-bottom observatory initiative. The development of portable broadband ocean-bottom stations is a successful alternative, proven by the Japanese program, to permanent ION observatories and is starting to efficiently complement permanent land-based networks such as GEOSCOPE.

GEOSCOPE AND TSUNAMI WARNING

The giant Sumatra event of 26 December 2004 and its tragic consequences had a major impact on the seismology community and on society in general. The French government decided to participate in a tsunami warning system in the Indian Ocean named SATOI (Système d'Alerte aux Tsunamis dans l'Océan Indien) and provided funds to the national meteorological center (MétéoFrance) to collect all the data necessary for tsunami warnings, through the French organization for tsunami warning in the Indian Ocean, the Centre National d'Alerte aux Tsunamis dans l'Océan Indien (CNATOI). Seven GEOSCOPE stations were upgraded for that purpose: ATD (Djibouti), HYB (India), RER (La Réunion Island), CAN (Australia), PAF (Kerguelen), AIS (Amsterdam Island), and CRZF (Crozet Island). By the end of 2009 seven stations (some but not all the same stations as CNATOI) were transmitting data to SATOI (AIS, ATD, CAN, CRZF, FOMA, RER, and PAF). Due to the restrictions of the Indian government on real-time access to HYB (Hyderabad, India) station data, the French institutions have decided to install two new stations in the Indian Ocean, the first one south of Madagascar (FOMA, Fort-Dauphin, Madagascar) and the second one at Rodrigues Island, Mauritius (RODM). All field operations are conducted jointly by IPGP and the Institut et Observatoire de Géophysique d' Antananarivo (IOGA) in Madagascar and by IPGP and Mauritius Meteorological Services (MMS) at Rodrigues Island.

Data from the GEOSCOPE/CNATOI stations are sent to the IPGP Data Center and made available to all existing and operational international tsunami warning centers and tsunami information centers (Pacific Tsunami Warning Center, Japan Meteorological Agency/Earthquake and Tsunami Observations, German-Indonesian Tsunami Warning Center, Australian Tsunami Warning System, International Tsunami Information Center) according to Figure S8 (online material). All information disseminated from the tsunami warning/information centers goes to the relevant authorities and is used for the mitigation of tsunami disasters. The centers send the information over the Global Telecommunication System (GTS).



▲ **Figure 11.** A) In France: in 2006, FFOSL moves to FOSFORE. The main purpose was to link the different French networks and the various institutes (Grenoble, Nice, Paris, Strasbourg) into one French portal, following a "Data Centers"–oriented concept. B) In Europe: GEOSCOPE and NERIES. The EIDA project corresponds to four European nodes—the ORFEUS Data Center in the Netherlands, GFZ in Germany, INGV in Italy, and IPGP in France.

More Facilities for Accessing Seismological Data

FOSFORE (France)

In 2002, the GEOSCOPE team at IPGP, regional agencies (Figure 11A), and INSU decided to federate the French contributors of broadband data and the operators of permanent networks and portable arrays and initiated a French federation called FFOSL (Federation Française de l'Observation Sismologique Large-Bande). In 2006 the federation fell under the sponsorship of INSU under a new name, the Federation de l'Observation Sismologique Française—Observatoire de Recherche en Environnement (FOSFORE) and was expanded to include also short-period networks as well as temporary networks. The main goals of the federation were to make all data accessible to the international community in SEED format and through a national portal (http://www.fosfore.ipgp.fr). By the end of 2009, the GEOSCOPE Data Center at IPGP was a primary data provider, together with the other data centers in Grenoble, Nice, and Strasbourg.

NERIES (Network of Research Infrastructures for European Seismology)

GEOSCOPE and IPGP have been a part of the European initiative ORFEUS (Observatories and Research Facilities for

European Seismology) since its founding in 1987 (Nolet *et al.* 1986). ORFEUS coordinates different European projects (Van Eck *et al.* 2001, 2002; Giardini *et al.* 2002) such as the Network of Research Infrastructures for European Seismology (NERIES). The objective is to create the core of a pan-European infrastructure that will serve the current and future needs of the scientific community. NERIES is a consortium of 25 universities and research centers, each of which contributes its expertise and infrastructure (Giardini 2002). NERIES responds to the needs of the seismological research and surveillance communities; its priorities are monitoring and understanding the earthquake processes. Its activities are related to data exchange, data archiving, and technology transfer. The GEOSCOPE program is involved in the European integrated waveform data archive (EIDA) subproject, which aims to create a unique European data portal called as shown in Figure 11B.

CONCLUSION AND PERSPECTIVES

We present the historical context in which GEOSCOPE was born and how it developed driven by scientific priorities (Appendix 2, online material). We describe the evolution, major steps, and challenges in the development of GEOSCOPE, emphasizing not only its successes in the international context but also the major difficulties encountered on the way.

GEOSCOPE was the first global three-component "broadband" seismic network, pioneering a new era in digital seismology. The GEOSCOPE program started in 1982 as the French component, and it was a founding members of global broadband seismic networks. GEOSCOPE played a key role, and its technical developments have always been closely associated with the scientific objectives of the international broadband community and coordinated by the FDSN. Over the years, GEOSCOPE station configurations and methods of data acquisition and data transmission have been upgraded whenever possible.

GEOSCOPE data are extensively used by the seismological community to investigate seismic sources and to construct 3-D models (tomography) of the interior of our planet. The products derived from GEOSCOPE observations range from the evaluation and follow-up of seismic risk to a deeper understanding of the internal dynamics of the planet; from studies of subducting plates and mantle heterogeneities to the behavior of terrestrial materials. The network participates in the earthquake source parameterization for the whole Earth. Real-time GEOSCOPE station data are used for global CMT estimates (Dziewonski *et al.* 1981) as well as for the routine IPGP determination of CMT parameters. The GEOSCOPE network has evolved from a basic global seismic network to a global multiparameter real-time monitoring network associated with the development of international monitoring systems, in particular for risks related to tsunamis in the Indian Ocean and the French West Indies.

Solid Earth, ocean, and atmospheric studies are an increasingly important part of GEOSCOPE's function. Earth scientists are more and more interested in time-dependent seismology (4-D seismology); they need data for very long time-series to develop research on long-period phenomena. The operation of the GEOSCOPE network on a long-term basis is essential for these emerging fields, including environmental seismology.

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