

Configuration of the Seismographic Networks in Saudi Arabia

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INTRODUCTION

Saudi Arabia is tectonically part of the Arabian Plate, which consists of crystalline Precambrian basement overlain by low-dipping Phanerozoic sedimentary and volcanic rocks. The Arabian Plate came into existence 25–30 million years ago, when the rocks that comprise the Arabian Peninsula, Syria, Jordan, Iraq, and westernmost Iran began to separate from the African continent because of rifting along the margin of northeast Africa and the opening up of the Red Sea and Gulf of Aden (Johnson, 1998).

The Arabian Peninsula presents several interesting seismological problems. On the west rifting in the Red Sea has split a large Precambrian shield. Active rifting is responsible for the geometry of the plate margins in the west and southwest. To the south, similar rifting running in a more east-west direction through the Gulf of Aden has separated the Arabian Peninsula from Africa. In the northwest the Gulf of Aqabah forms the southernmost continuation of the Dead Sea transform. The northern and northeastern boundaries of the Arabian Plate are areas of continental collision, with the Arabian Plate colliding with the Eurasian Plate (Figure 1).

There has been only a modest amount of earthquake seismological work done in the Arabian Peninsula. Several countries either on or surrounding the Arabian Peninsula have seismograph stations, but most stations are equipped only with short-period vertical seismometers. In any event, the networks are sparse and often are poorly situated with respect to active areas. Broadband data required for analysis of teleseismic receiver functions are almost wholly lacking. Regional wave propagation from earthquakes and seismic wave attenuation have not been studied. Microseismicity is known to occur in many areas of the Arabian Peninsula, but the existing network of stations is inadequate for accurately defining spatial characteristics or determining focal mechanisms. Investigations of the seismicity and seismotectonics of the Arabian Peninsula and its bordering regions have repeatedly emphasized the need for establishing a digital seismic network to monitor seismic activity in this region in general and in Saudi

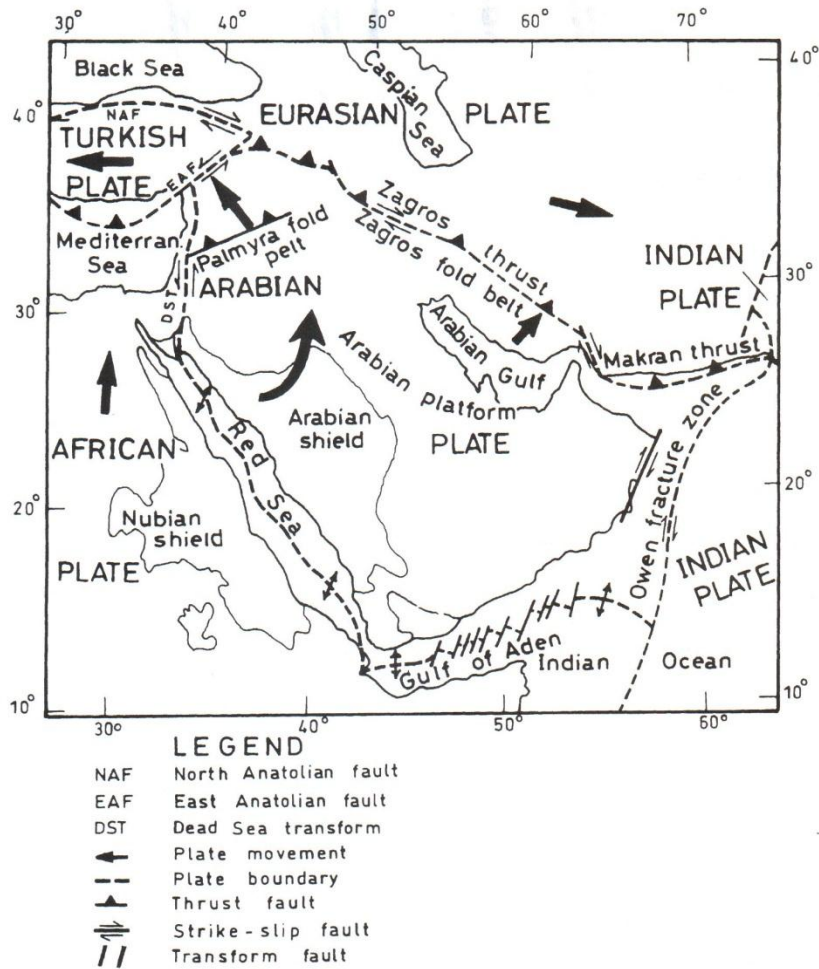
Arabia in particular. Such a need was further stressed by the relatively recent disastrous earthquakes that hit Yemen (1982), Egypt (1992), and the Gulf of Aqabah (1995).

Existing earthquake data and the low number of seismic stations do not allow evaluation of the degree of seismicity within the Arabian Peninsula at the present time. Hence, the objective of this paper is to evaluate the existing seismic facilities in Saudi Arabia and to describe the nature of the new national network and its hardware and software components. Detailed description of data flow, data archiving, and access to the network are presented. Upon completion of the new network, the regional monitoring capability in the Middle East in general and in the Arabian Peninsula in particular will be improved. Observations and characterization of the propagation of regional phases across the Arabian Shield over a broadband of frequencies will be possible. The network data also will be used to develop crustal structural models of the Arabian Peninsula.

SEISMOTECTONICS OF THE ARABIAN PENINSULA

The majority of earthquakes in the Arabian Peninsula are concentrated along three major belts. The first is the Zagros fold belt, which extends about 1,500 km in a northwesterly direction from Oman through west Iran and northeast Iraq to Turkey. The second belt expands from the central Red Sea region south to Afar and then east through the Gulf of Aden. The third belt extends from the northern tip of the Red Sea in a northeasterly direction through the Gulf of Aqabah, Dead Sea, Lebanon, and Syria, and terminates in southern Turkey. Analysis of the seismicity map of the Arabian Peninsula and adjacent regions (Figure 2) during the period from A.D. 112 to 1998 includes nearly 3,540 earthquakes ($3.5 < m_b < 7.0$), excluding some swarm activities of 1993 and 1995, which occurred in the Gulf of Aqabah region.

The Dead Sea transform system connects active spreading centers of the Red Sea to the area where the Arabian Plate is converging with Eurasia in southern Turkey. The Gulf of Aqabah in the southern portion of the rift system has experi-

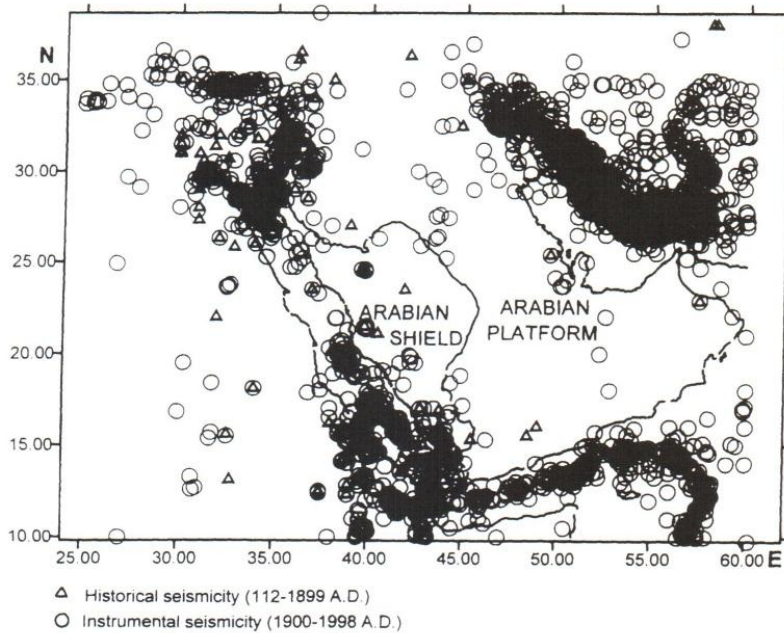


▲ Figure 1. Tectonic map of the Arabian Peninsula and adjacent areas (modified from Johnson, 1998).

enced left-lateral strike-slip faulting with a 110 km offset since early Tertiary. The seismicity of the Dead Sea transform is characterized by both swarm and mainshock-aftershock types of earthquake activity. The instrumental and historical seismic records indicate a seismic slip rate of 0.15–0.35 cm/yr during the last 1,000–1,500 years, while estimates of the average Pliocene-Pleistocene rate are 0.7–1.0 cm/yr (Ben-Menahem, 1979). Geologic and tectonic information attribute the swarms to subsurface magmatic activity and consequent isostatic adjustments in the Gulf of Aqabah region. Historically, the most significant earthquakes to hit the Gulf of Aqabah area were the events of 1068, 1759, 1822, and 1837, which caused the deaths of more than 30,000 people. Ben-Menahem (1979) indicated that about

26 major earthquakes ($6.1 < M_L < 7.3$) occurred in the southern Dead Sea region between 2100 B.C. and A.D. 1900.

In the 1980's and 1990's the occurrence of earthquake swarms in 1983, 1985, 1991, 1993, and 1995 in the Gulf of Aqabah clearly indicates that this segment is one of the most seismically active zones in the Dead Sea transform system. Probabilistic seismic hazard estimates of the Gulf of Aqabah have been reported by Al-Haddad *et al.* (1992). Peak ground accelerations (PGA) predicted for 10% probability of being exceeded in 50 and 100 years are about 0.20 g and 0.30 g, respectively. Earthquake locations provide evidence for continuation inland of the faulting regime from the Gulf north-eastward beneath thick sediments, suggesting that the northern portion of the Gulf is subject to more severe seis-



▲ **Figure 2.** Historical and instrumental seismicity map of the Arabian Peninsula and adjacent regions during the period from A.D. 112 to 1998. It includes nearly 3,540 earthquakes ($3.5 < m_b < 7.0$) and excludes some swarm activities of 1993 and 1995 that occurred in the Gulf of Aqabah region.

mic hazard compared to the southern portion (Al-Amri *et al.*, 1991).

To the south, the majority of earthquakes and tectonic activity in the Red Sea region is concentrated along a belt that extends from the central Red Sea region south to Afar and then east through the Gulf of Aden. There is little seismic activity in the northern part of the Red Sea, and only three earthquakes have been recorded north of latitude 25°N . Instrumental seismicity of the northern Red Sea shows that 68 earthquakes ($3.8 < m_b < 6.0$) are reported to have occurred in the period from 1964 to 1993 (Al-Amri, 1995a).

Historically, about ten earthquakes have occurred during the period 1913–1994 with surface-wave (M_s) magnitudes between 5.2 and 6.1. Some of these events were associated with earthquake swarms, long sequences of shocks and aftershocks (the earthquakes of 1941, 1955, 1967, and 1993). The occurrence of the January 11, 1941 earthquake (M_s 5.9) with an aftershock on February 4, 1941 (M_s 5.2), the earthquake of October 17, 1955 (M_s 4.8), and the 1982 Yemen earthquake of magnitude 6.0 highlight the hazards that may result from nearby seismic sources and demonstrate the vulnerability of northern Yemen to moderate-magnitude and larger earthquakes. Instrumental seismicity of the southern Red Sea shows that 170 earthquakes ($3.0 < m_b < 6.6$) are reported to have occurred in the period 1965–1994. The historical and instrumental records of strong shaking in the Arabian Shield (1832, 1845, 1941, 1982, and 1991) indi-

cate that the return period of severe earthquakes which affect the area is about 60 years (Al-Amri, 1995b).

The Arabian Plate boundary extends east-northeast from the Afar region through the Gulf of Aden and into the Arabian Sea and Zagros fold belt. The boundary is clearly delineated by teleseismic epicenters (Figure 2), although there are fewer epicenters bounding the eastern third of the Arabian Plate south of Oman. Most seismicity occurs in the crustal part of the Arabian Plate beneath the Zagros fold belt (Jackson and Fitch, 1981). The Zagros is a prolific source of large magnitude earthquakes with numerous magnitude 7+ events occurring in the last few decades.

The overall lack of seismicity in the interior of the Arabian Peninsula suggests that little internal deformation of the Arabian Plate is presently occurring. There is widespread Quaternary volcanism along the Red Sea coast, with at least one documented historical eruption in A.D. 1256 (Barazangi, 1981). Some seismicity was associated with that eruption. Seismicity may also be related to transform faults in the Red Sea continuing onto land as well as to other causes. To date, few on-land epicenters are accurately located and there are few focal mechanisms available.

ANALOG SEISMOGRAPHIC NETWORKS

There are two independent analog seismic telemetry networks in Saudi Arabia. The King Saud University (KSU)

network was established in 1985. A network run by King Abdulaziz City for Science and Technology (KACST) was established in 1993 with eleven stations.

KSU Seismographic Network

The King Saud University (KSU) seismological network was established in 1985 and includes the digital WWSSN station in Riyadh. Currently, the network consists of thirty stations with denser subnetworks in the Gulf of Aqabah region (twelve stations) and the southwestern part of Saudi Arabia (eight stations). The seismographic station in Riyadh is a 12-channel station and consists of three S-13 short-period and three SL-200 long-period seismometers. The seismometer outputs are amplified, filtered, and recorded in both analog and digital form. The filters allow recording in four different periods (SP wide band, SP narrow band, LP wide band, and LP narrow band). The total system response for the Riyadh station is broadband (0.01 to 33 Hz). Figure 3 shows the analog system response curves for some stations in the KSU network. Signals from the nine channels are also routed to a 12-bit A-to-D converter and recorded on 9-track magnetic tape. The other telemetered seismic stations are equipped with S-13 short-period seismometers connected to a field case housing an amplifier, a voltage-controlled oscillator (VCO), an automatic daily calibrator, and a telemetry interface.

Data processing and analysis of telemetered data are carried out using two computers. One is a MicroVAX II computer with an A-to-D converter used for real-time event detection and preliminary automated analysis. The other one is a VAX 750 used primarily for off-line interactive waveform analysis, event location, magnitude determination, and analysis of focal mechanism. Digital data transmitted by call-up mode are also analyzed using the VAX 750.

KACST Seismographic Network

In 1993 a seismological observatory was established at KACST. It consists of two subnetworks in the Gulf of Aqabah and the southwestern part of Saudi Arabia adjacent to the Yemen border. Each subnetwork consists of short-period vertical-component stations linked to the central recording station at Riyadh via dedicated telephone lines. The Riyadh station consists of two three-component (SP and LP) seismographs. All sixteen channels of incoming signals are input to a 16-bit PC-based data-acquisition system that provides triggered digital recording based on user-selected criteria. The PC is networked with a PC-based data analysis system for processing.

DIGITAL SEISMOGRAPHIC NETWORK

The Saudi Arabian National Digital Seismographic Network (SANDSN) of King Abdulaziz City for Science and Technology is being installed and will be operational by the middle of 1999, representing the third-generation seismic network and seismic information system. SANDSN utilizes state-of-the-art broadband sensors and 24-bit data loggers

combined with real-time telemetry to monitor local and regional seismicity in the Arabian Peninsula.

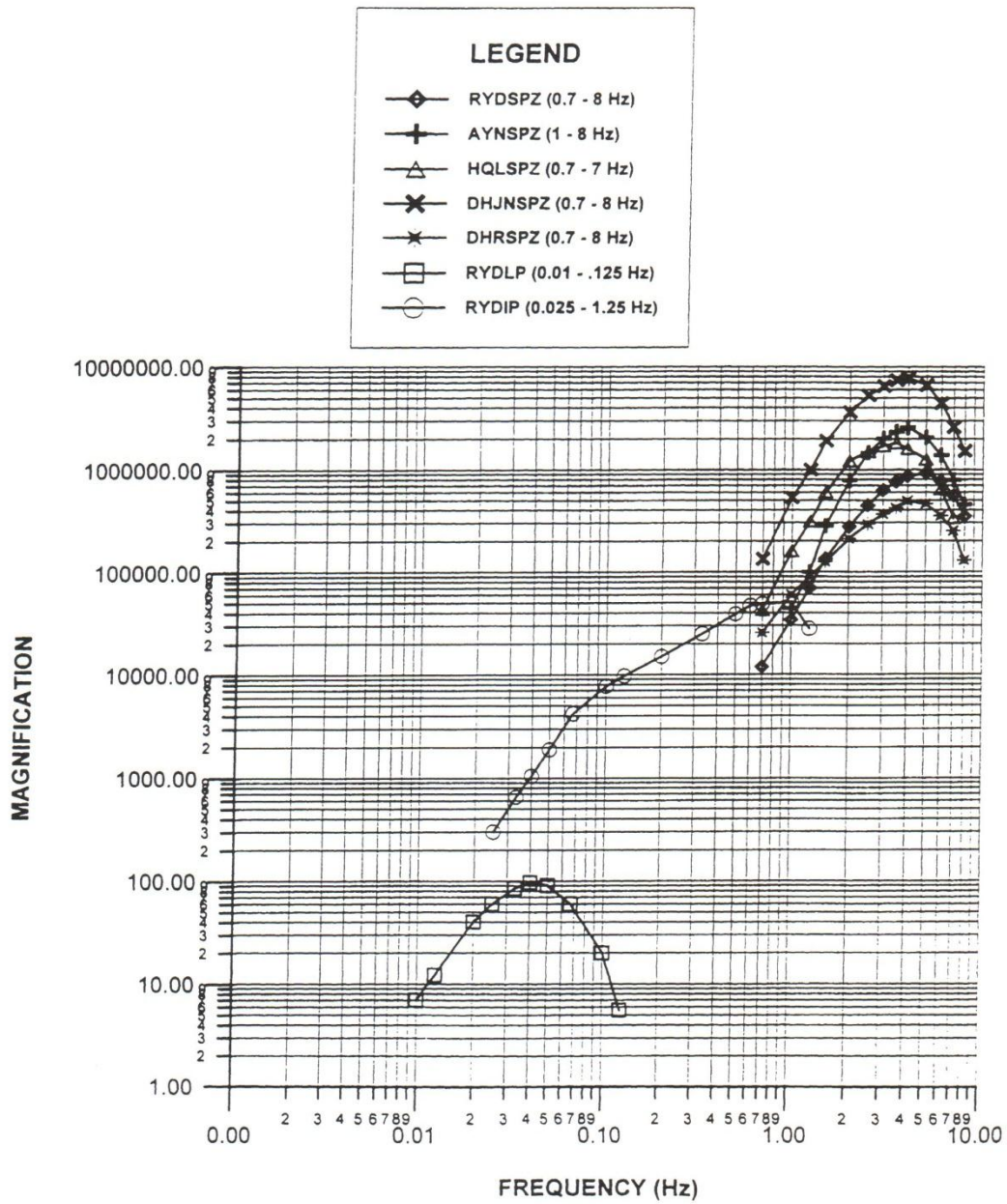
SANDSN consists of thirty-two seismic stations (Figure 4) equipped with twenty-one broadband and eleven short-period seismographs. The broadband STS-2 seismometers have a passband between 0.008–50 Hz, and the output will be recorded at a sampling rate of 100 sps by a 24-bit digitizer. The data will be transmitted via spread-spectrum transceiver links connecting 9.6 kbps leased telephone lines to the central recording site at KACST. The data analysis system has three Ultra SPARC-II stations which provide a high continuous data flow capacity of at least seven days for all channels on hard disk and at least 90 days using online mass storage. In addition, the system will provide automated event detection, arrival picking, and event location. Seven (six SP and one BB) of the thirty-two stations will be operated by King Abdulaziz University (KAU) and linked to KACST via a 64 kbps leased line.

Data Acquisition and Processing

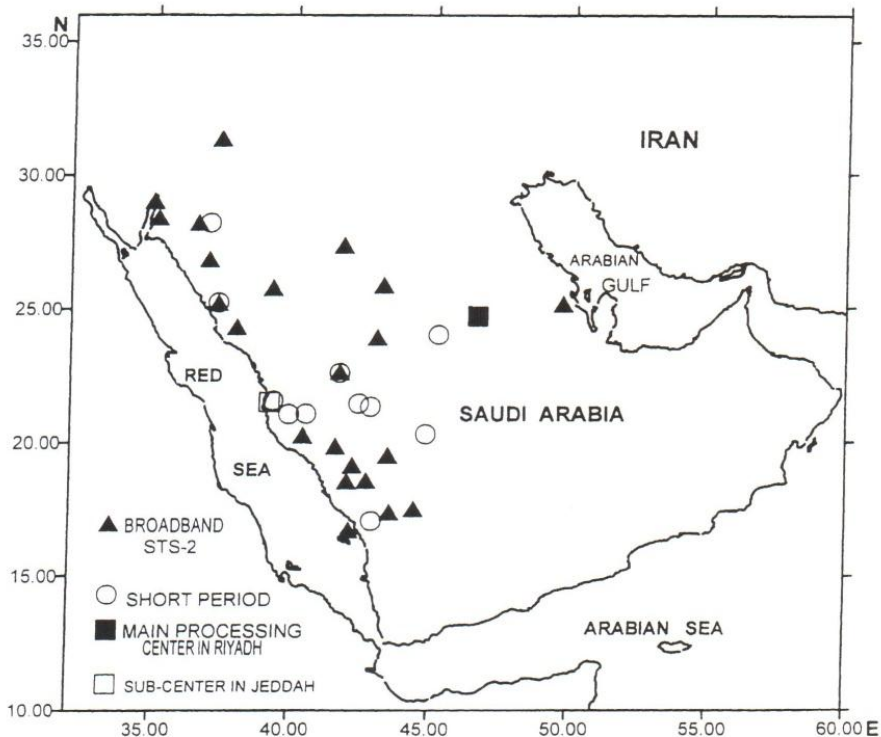
The central recording system hardware consists of the following components listed according to the logical data flow :

- A rack of TELEBIT analog leased line modems with RS 232 interface ports. This modem cabinet connects the telephone leased lines from the freefield stations to the main center.
- Two Sun Ultra-II workstations for real-time detection and analysis are connected to the TELEBIT NetBlazer through a 10BaseT Ethernet hub. The two computers are configured identically, each with dual CPU's, 256 MB of RAM, and a 4.2 GB internal disk. The two computers are connected to the LAN through the hub. An 8 mm tape drive is connected to the SCSI external connection of one machine. The SCSI line of the other machine is connected to a Sun Sparc storage device, which has a 7-slot DLT tape library.
- An additional Sun Sparc5 workstation for off-line analysis, with 64 MB RAM and an internal hard disk of 2.1GB. It has a 4 mm tape drive connected to the SCSI external connection.
- A Sun Sparc storage array 114 which has thirteen 4.1 GB disks formatted as RAID 5. This Sparc array is connected to the two Ultra-II machines.
- A True Time NTS-100 network time server (NTS) is connected to the 10 BaseT hub and a GPS antenna.

Complete data processing is accomplished from the individual digital signals to the final waveform and database archives using a UNIX-based object ring buffer package called the Antelope Real Time System (ARTS). ARTS collects the raw



▲ **Figure 3.** Analog system response curves for some stations in the KSU network.



▲ **Figure 4.** Location map of the twenty-one broadband and eleven short-period seismographic stations, and data acquisition and processing centers of the national digital network.

data and analyzes it through a series of processes that can be roughly divided into fifteen categories:

1. Field Interface Modules
2. Data Communications
3. Data and Information Buffering
4. Data and Information Flow
5. Automated Data Processing
6. Automated Data and Information Archiving
7. Real Time Data and Information, Distribution, and Sharing
8. Real Time System Monitoring and Control
9. Real Time Graphical User Interfaces
10. Automated Archive Management
11. Information System Functions
12. Interactive Review of Automated Processing
13. Batch Mode Processing
14. Graphical Displays of Archive Data and Information
15. Development Tools

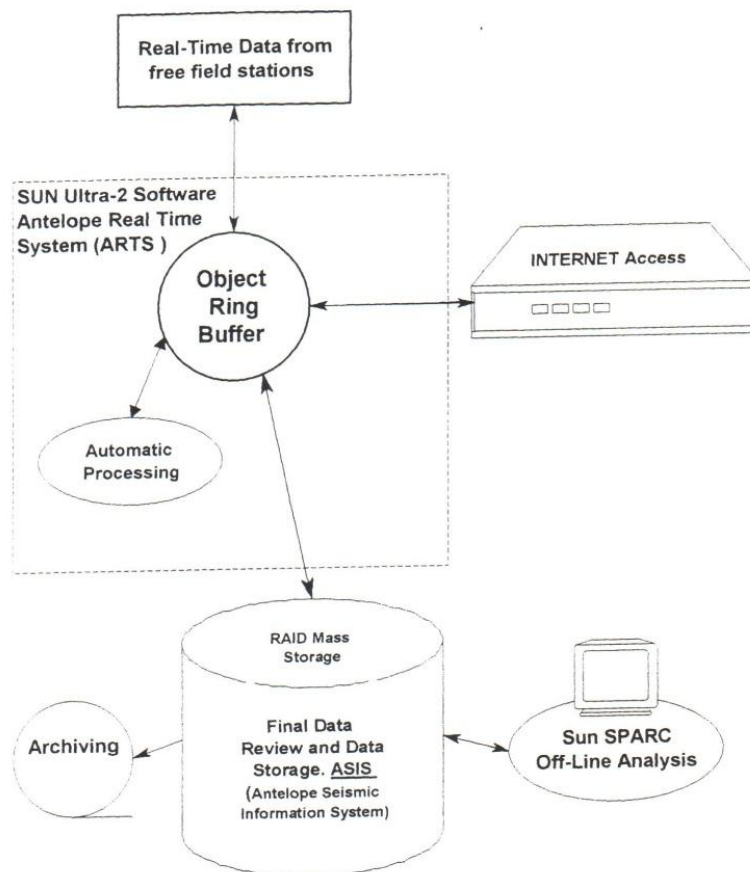
A diagram showing the data flow from the freefield stations through the Antelope Real Time System to the final data archiving is shown in Figure 5.

Dissemination of Information and Data

The complete digital waveform data set is stored off-line, and event segments are stored online in our RAID mass storage. These data are stored in the standard CSS 3.0 format including instrument responses. A data request will be satisfied through the Internet or by sending an 8 mm tape copy. At present we can provide data in the following formats: CSS 3.0, SAC, or SEED. We plan to get the necessary government permits to have the IRIS Data Management Center maintain a copy of our data archive.

We are currently developing a World Wide Web home page for the SANDS Network, <http://www.kacst.edu.sa/SANDSN/home.html>, which provides maps and information about our database, stations, and hardware configurations. In the near future it will be possible to display SANDSN waveforms through this interface, and we plan to provide interactive access to the waveform database in the near future.

The primary users of our data and results will be the educational institutions and governmental agencies in Saudi Arabia and the Arab states as well as the Saudi Arabia-based media through our home page. Furthermore, monthly published bulletins of all earthquake events and related



▲ **Figure 5.** A diagram showing data flow from the freefield stations through the Antelope Real Time System to the final data archiving and distribution via the Internet.

information will be posted on our Web site and will be sent electronically to all interested researchers and observations upon request by regular mail or e-mail.

OTHER SEISMIC FACILITIES

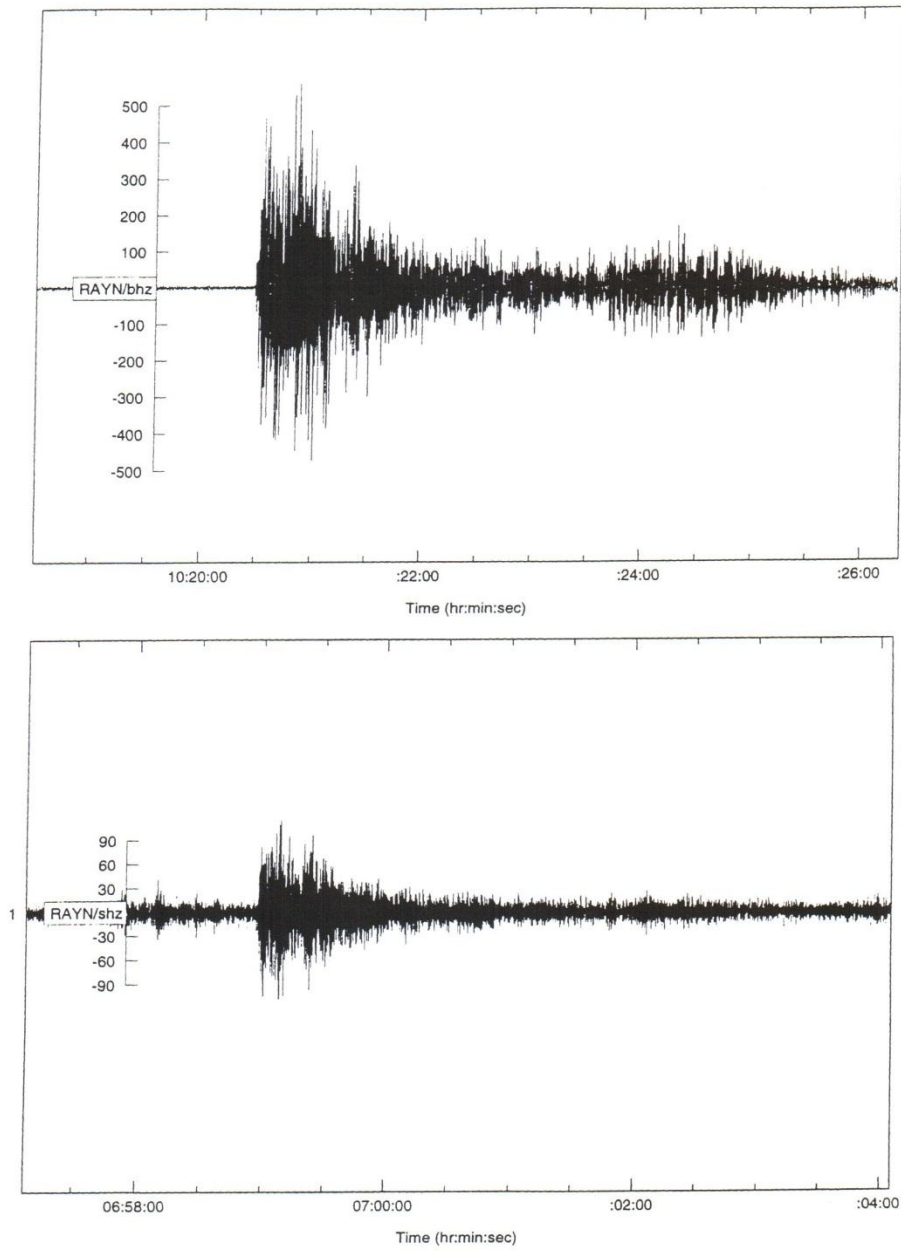
IRIS/IDA Station

RAYN is one of the newest stations in the IRIS/IDA global seismographic network. The seismic station at Ar Rayn (RAYN), Saudi Arabia was established in 1996 under a memorandum of understanding between KACST, the IRIS Consortium, and the University of California, San Diego (UCSD), with key support from the KSU Department of Geology.

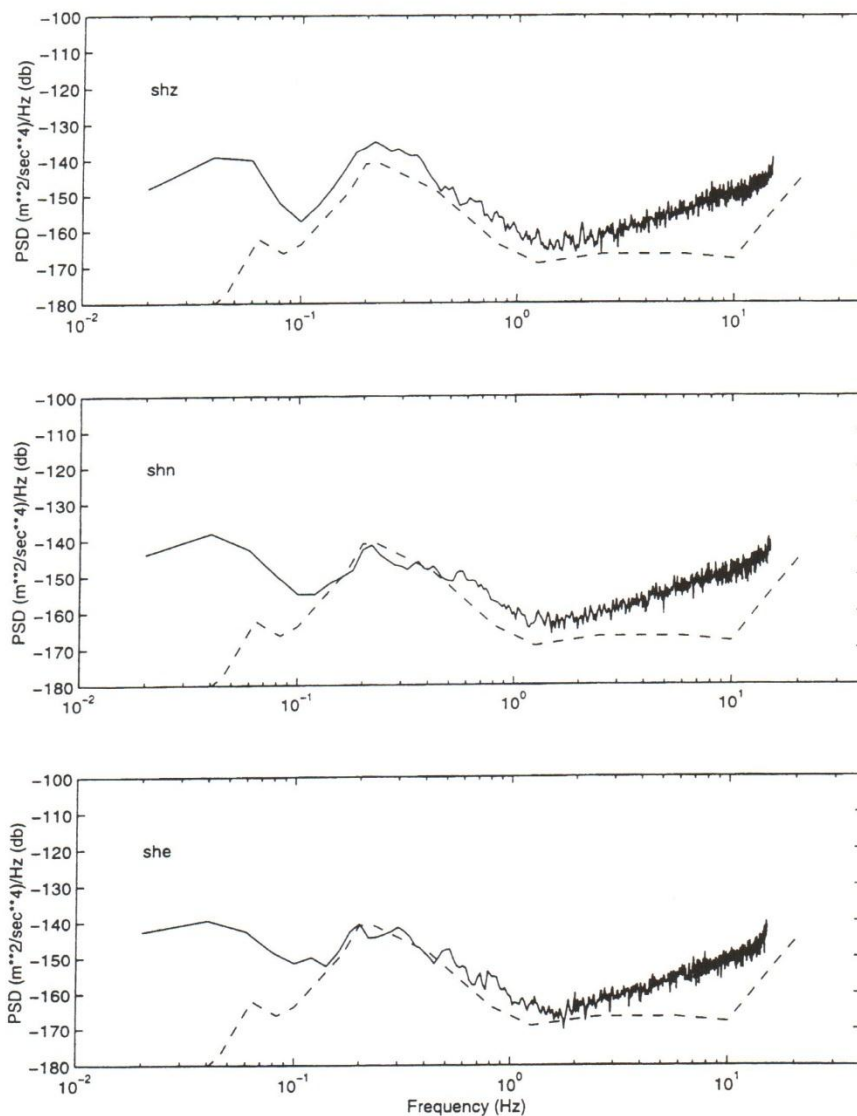
The RAYN station consists of an STS-2 three-component broadband seismometer (passband between 0.008 Hz and 50 Hz), a Kinematics FBA-23 strong motion accelerometer, and a Teledyne broadband KS-54000 (passband between

0.0003 Hz and 8 Hz). The KS-54000 is emplaced in a borehole at a depth of 100 meters to ensure the quietest possible recording environment. The purpose of installing the STS-2 is to provide much better coverage of high frequencies than would be possible with the KS-54000 alone. The FBA-23 is in place to record ground motion from earthquakes either too large or too close to be recorded on-scale by the KS-54000 and STS-2. All sensors are recorded on an IRIS-3 high-resolution data acquisition system (Given *et al.*, 1992).

Figure 6 shows recent seismograms for the two Pakistani nuclear tests recorded at RAYN. The first test, on May 28, 1998, occurred in the Chagai Hills and had a magnitude of $m_b = 4.8$. A number of phases are clearly visible in the wavetrain. The second Pakistani test of May 30 occurred approximately 100 km to the southwest of the May 28 test (Wallace, 1998) in the Ras Koh Range and had a magnitude of $m_b = 4.3$. These two events are very representative of the quality of data available.



▲ **Figure 6.** Seismograms of the two Pakistani nuclear tests recorded by RAYN broadband station. The first test of May 28, 1998 (at the top) occurred in Chagai Hills at lat. 28.96°N, long. 64.73°E, $m_b = 4.8$, and origin time 1998, 10:16:15. The second Pakistani nuclear test of May 30 (at the bottom) occurred in the Ras Koh Mountain Range at lat. 28.70°N, long. 64.04°E, $m_b = 4.3$, and origin time 1998, 06:54:56.



▲ **Figure 7.** Power spectral density in decibels relative to acceleration units of ambient ground noise at RAYN station from 0.01 to 30 Hz. The spectral density for a 500-sec long time series from the three components of the STS-2 seismometer. The dashed line represents the Peterson's Low Noise Model, based on a sample of stations worldwide.

RAYN has noise characteristics which place it among the quietest seismic stations in the world. Set upon the Arabian Shield far from sources of cultural noise, the sensors at the site routinely record background noise that approach Peterson's Low Noise Model (Peterson, 1993) over much of the seismic frequency band (Figure 7).

Broadband Seismic Experiment

In November, 1995 nine portable broadband stations were operated in the Arabian Shield in two linear arrays. The first linear array was pointed in the direction of high seismicity in the Zagros. These earthquakes are occurring in the Arabian Plate where it is colliding with the Eurasian Plate (Jackson

and Fitch, 1981). Seismic wave ray paths along this array from Zagros events should therefore have entirely intraplate paths. Stations were between 900 and 1,500 km from the nearest Zagros sources. The second linear array was pointed in the highly active area of the Afar triple junction in Africa, and events in the Caucasus were also generally aligned with this linear array. Each station had a STS-2 broadband seismometer. The output of the STS-2 was locally recorded at a sample rate of 40 sps by a 24-bit REFTEK data logger.

Generally, most of the experiment sites in the Arabian Shield were extremely quiet, with ground noise near or equal to the low noise model in the frequency band from 1–10 Hz. The low noise contributes to the very low detection threshold of events with $m_b > 3.5$ at distances from 10° to 100° . The Arabian Shield appears to be among the best sites in the world for the properties of detection thresholds and ground noise levels (Vernon and Berger, 1997; Mellors, 1998). ☒

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