Study Provides Data on Active Plate Tectonics in Southeast Asia Region

A major geodynamic study has provided significant new information about the location of active plate boundaries in and around Southeast Asia, as well as deformation processes in the Sulawesi region of Indonesia and tectonic activity in the Philippine archipelago. Results also have confirmed the existence of the so-called Sunda Block, which appears to be rotating with respect to adjacent plates.

The study, known as the Geodynamics of South and South-East Asia (GEODYSSEA) project, has been a joint venture of the European Commission and the Association of South-East Asian Nations. It began in 1991 and involved a large team of European and Asian scientists and technicians studying the complex geodynamic processes and natural hazards of the region from the Southeast Asia mainland to the Philippines to northern Australia. Earthquakes, volcanic eruptions, tsunamis, and tectonically induced landslides endanger the lives of millions of people in the region, and the tectonic activity behind these natural hazards results from the convergence and collision of the Eurasian, Philippine, and Indo-Australian Plates at relative velocities of up to 10 cm per year.

Locations of the project’s 42 new GPS stations are indicated on the tectonic map in Figure 1. Two major observation campaigns were conducted and a third is planned for November 1998. GEODYSSEA’s most important results are presented in Figures 2 and 3. The recovered velocities of several stations in the more stable interior parts of the plates are in close agreement with the motions predicted by the NUVEL-1A global plate tectonic model, an indication of the quality of the results. However, there are also significant differences, which form the basis for some important new discoveries.

The Sunda Block

Closer analysis of the velocity vectors of 12 of the westerly stations reveals that there is a gradient in the magnitude of the velocities, showing an increase from south to north (Figures 3 and 4). It was possible to fit these results accurately with a model and thereby determine the Sunda Block’s pole of rotation and rate. These westerly stations are all situated on the Sunda Block, the existence of which had already been inferred from geological and paleomagnetic data. The block appears to be rigid, deformations within it being less than 5 ppb per year. The study provides the first direct evidence that this block exhibits distinct relative motion with respect to Eurasia at a rate of about 2 cm/yr (Figure 4).

The Sunda Block’s rotation accommodates relative motions with respect to India (no more than 3.5 cm/yr of north-south opening in the Andaman Sea) and to China (no more than 1.5 cm/yr of right lateral slip along the Red River Fault). The pole of rotation is located in the South Australian Basin at -31.8°S latitude and 134°E longitude. The rotation (about 0.2°/Myr) permits the resolution of several problems: (1) Slip vector azimuths of interplate-subduction-related earthquakes along the Java Trench consistently show a 10° westward deviation with respect to the predicted NUVEL-1A Australia-Eurasia motion. This discrepancy is fully resolved if the Sunda Block’s motion is included. (2) In an India reference frame, the Sunda Block is moving to the south, so that the motion is pure dextral strike-slip north of Sumatra. The predicted velocity of India at the latitude of Myanmar is close to the rate of opening of the Andaman Sea, suggesting a low subduction rate along the Andaman front.

The kinematics observed are related to the motions of the Sunda Block and the Philippine and Indo-Australian Plates. The convergence between the Eurasian and the Philippine Plates is distributed across a 600-km-wide zone including the stretched continental margin and the Sulawesi-Luzon deformed volcanic belt.

Accretion to Australian Plate

The stations at the southern limit of the GEODYSSEA network indicated that Timor has been accreting to the Australian Plate [Genrich et al., 1994]. In fact, Timor, eastern Flores, the adjacent Indonesian islands to the east, and Irian Jaya all are currently accreting...
to the Australian Plate. The active margins of the plate now appear to run north of Irian Jaya, crossing the Banda Sea and Flores and joining the Jaya Trench south of the Nusa Tenggara Islands.

The triple junction region, located in the Molucca Sea near the island of Sulawesi, shows high velocities and complicated patterns of intense deformation and microblock rotations. The region shows both a northward extension of the Australian velocity field, affected by strong counterclockwise rotation, and a westward extension of the Philippine velocity field with accompanying clockwise rotation (see Walpersdorf et al. [1998] for discussion).

A significant problem is whether the measured velocities are indicative of the long-term tectonic velocities or are affected in part by the loading cycle in this highly seismic region. The most spectacular motion occurred at BIAK, which was displaced by more than 1.5 m (10 times the long-term rate) as the result of a M 8.2 subduction earthquake, which occurred 90 km from the station [Imamura et al., 1997] on February 17, 1996, between the two measurement campaigns.

(The GPS measurements took place from November 28 to December 2, 1994, and from April 18 to April 22, 1996. Anomalies in the results have been found to be related to earthquakes which occurred in the vicinity of individual stations during the interval between observations.) Several other points, such as in the Philippines and in southwestern Sumatra, are located adjacent to active margins and it is yet unknown whether they have been influenced by interseismic elastic loading [Michel et al., 1998]. Further measurements are required.

**Background**

A detailed geological description of the geodynamics of southeast Asia and the western Pacific can be found in Rangin et al. [1990]. Different investigators have used the Global Positioning System (GPS) in Southeast Asia both in regional and in more localized surveys designed to study specific geotectonic features such as the Sumatra Fault [Prawirodirdjo et al., 1998], the Java Trench [Tregoning et al., 1994], and Irian Jaya [Puntodewo et al., 1994]. However, all of these activities have been conducted under bilateral agreements restricted to a single national territory.

By contrast, GEODYSSEA’s scope involved tectonic motions across a 4000 x 4000 km network covering the entire region, using a common reference frame into which all detail networks can be fitted later.

The area studied covers the Malay Peninsula, Thailand, Vietnam, the Philippine and Indonesian archipelagoes, including Brunei, Christmas Island, and the Cocos Islands, and northwest Australia.

The geodetic network was designed to provide good coverage of all the major tectonic blocks in the region, while limiting the number of stations to manageable proportions. Besides data from the project’s 42 new observation sites, the Australian Survey and Land Information Group provided data from four stations on the Indo-Australian Plate (Cocos Island, Christmas Island, Karrahe, and Darwin). To facilitate the positioning of the network in a global reference frame, researchers included in the analyses data from five permanent stations of the global network of the International GPS Service for Geodynamics (IGS).

**GPS Data Analysis**

Four different analysis groups computed complete solutions for each dataset, each group using its choice of software and analysis strategy. The various solutions were then merged into a single combination solution. The four groups were from the Delft Institute for Earth-Oriented Space Research (DEOS),

Table 1. Repeatabilities of the daily coordinate solutions of each analysis group and the number of station-days accepted and rejected in the iterative editing process.

<table>
<thead>
<tr>
<th>Analysis group</th>
<th>Software used</th>
<th>#Stat.-Days accepted</th>
<th>#Stat.-Days rejected</th>
<th>North (mm)</th>
<th>East (mm)</th>
<th>Up (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEODYSSEA-94:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFZ (5 days)</td>
<td>EPOS</td>
<td>211</td>
<td>9</td>
<td>3.6</td>
<td>6.3</td>
<td>8.7</td>
</tr>
<tr>
<td>ENS (5 days)</td>
<td>GAMIT</td>
<td>217</td>
<td>12</td>
<td>3.5</td>
<td>4.9</td>
<td>8.8</td>
</tr>
<tr>
<td>DEOS (6 days)</td>
<td>GIPSY</td>
<td>245</td>
<td>25</td>
<td>3.2</td>
<td>6.9</td>
<td>9.5*</td>
</tr>
<tr>
<td>BKG (5 days)</td>
<td>BERNESE</td>
<td>215</td>
<td>16</td>
<td>4.0</td>
<td>6.9</td>
<td>10.3</td>
</tr>
<tr>
<td>Total rms</td>
<td></td>
<td></td>
<td></td>
<td>3.6</td>
<td>6.3</td>
<td>9.3</td>
</tr>
<tr>
<td>GEODYSSEA-96:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFZ (9 days)</td>
<td>EPOS</td>
<td>242</td>
<td>18</td>
<td>3.0</td>
<td>6.3</td>
<td>8.1</td>
</tr>
<tr>
<td>ENS (9 days)</td>
<td>GAMIT</td>
<td>260</td>
<td>23</td>
<td>3.3</td>
<td>6.0</td>
<td>8.5</td>
</tr>
<tr>
<td>DEOS (9 days)</td>
<td>GIPSY</td>
<td>289</td>
<td>33</td>
<td>3.2</td>
<td>6.7</td>
<td>10.1</td>
</tr>
<tr>
<td>BKG (5 days)</td>
<td>BERNESE</td>
<td>201</td>
<td>16</td>
<td>3.1</td>
<td>4.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Total rms</td>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
<td>6.0</td>
<td>9.1</td>
</tr>
</tbody>
</table>

*) including November 27, 1994, with partial network and less than 24-hour observations.
Delft, Netherlands, using GIPSY software; GeoForschungszentrum Potsdam (GFZ), Potsdam, Germany, using EPOS; Bundesamt für Kartographie und Geodäsie (BKG) (formerly known as the Institut für Angewandte Geodäsie (IfAG)), Frankfurt am Main, Germany, using Bernese; and École Normale Supérieure (ENS), Paris, France, using GAMIT. Also contributing to the data analysis were groups from the University of Newcastle upon Tyne, Newcastle, England; Observatoire Royal de Belgique, Brussels, Belgium; and the University of Bologna, Bologna, Italy.

Each of the main groups computed daily free-network solutions for all campaign days. These were accumulated into the final combined solution [Simons et al., 1998].

The softwares the groups selected are four of the most important state-of-the-art systems currently in use around the world. Each system applies different data reduction algorithms and modeling techniques, so the GEODYSSSEA project provided a unique opportunity to compare them. The performance indicators comprised the daily repeatabilities of the station coordinate solutions provided by the different groups. With repeatabilities (Table 1) ranging from 3 to 6 mm for the horizontal components and averaging about 9 mm in height, there is sufficient evidence that the various solutions are of similar quality. This shows that the internal precision of the GEODYSSSEA network solutions is at a level comparable to the IGS global network solutions for permanent stations. This is a remarkable result, in view of the fact that the stations are located in a region where large tropospheric and ionospheric variations are known to have a much larger effect on the GPS signals than at moderate temperate latitudes. Angermann et al. [1998] give more information on the individual analyses. Simons et al. [1998] give the complete set of station coordinates and velocities.

Project Goals

GEODYSSSEA involved field reconnaissance, identification, and monumentation of GPS observation points; geodetic measurements with GPS and subsequent analysis and interpretation; geological field mapping, sampling, laboratory analyses, and interpretation; computation of tomographic solutions from existing seismic data; and a feasibility study for improving observed seismic coverage of the region.

The prime objectives of the research were to obtain better estimates of the extent of the deformation zones associated with the triple junction of the Eurasian, Philippine, and Indo-Australian Plates; investigate the feasibility of using seismic tomography to obtain evidence of the mantle’s three-dimensional velocity structure; identify more precisely those areas in Southeast Asia which are genuinely susceptible to natural hazards such as earthquakes; and estimate the long-term slip rates in the triple junction area of Sulawesi from the displacement of geological or morphological features.

An important additional benefit to the region has been the derivation of precise three-dimensional coordinates of the GPS stations in a global reference frame. These points may now be used to connect the national geodetic networks in the various countries to the global reference frame and to integrate the results of other geodynamic projects into a common system.

Acknowledgments

The GEODYSSSEA Project was carried out under Contract No. C11-CT93-0337 between the European Commission and the GeoForschungszentrum (GFZ) Potsdam, in Potsdam, Germany, acting as the coordinating agency. Thanks and appreciation are extended to the European Commission, the Association of Southeast Asian Nations (ASEAN), and the hosting agencies for their strong support, and to the Australian Surveys and Land Information Group, Canberra, Australia, in recognition of its outstanding efforts and its spirit of cooperation. The project was funded to 50% by the European Commission and involved six European and eight ASEAN partners, with additional participants from Australia and Vietnam (at the time not eligible to participate as partners to a European community project). The fieldwork was organized jointly by GFZ Potsdam and BKG, Frankfurt am Main, in cooperation with the hosting agencies. Equipment and a large number of experienced observers to assist in the organization and execution of the field campaigns were supplied by GFZ Potsdam and BKG. National institutions in the host region have contributed to the project in various ways, including provision of field equipment, personnel, and logistical support.
countries contributed the majority of the field crews and assumed responsibility for most of the operational activities.

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FALL MEETING PREVIEW

Educators Infuse Science Programs with Enthusiasm and Currency

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Veronique Robigou, an oceanographer at the University of Washington School of Oceanography, says she is so thrilled about current research into submarine volcanoes and life forms associated with them that she has difficulty not expressing this fascination to others. Fortunately for Robigou, she is in a position to share her enthusiasm as codirector of project REVEL, "Research and Education: Volcanoes, Exploration and Life." REVEL teaches middle and high school science teachers about this emerging Earth and life sciences field that combines geology, physics, chemistry, and other disciplines. Robigou, along with project codirector and oceanography professor John Delaney, hitches teachers up with bona fide research cruises where they collaborate with scientists, sense some of the excitement and frustration of research, and view underwater ridges through the eyes of a robot.

The program, which began in 1996 and so far has brought 23 teachers on scientific cruises, bypasses textbooks to provide teachers with a first-hand experience they in turn share with students in the classroom and over the Internet (http://www.ocean.washington.edu/outreach/revel/missionframework.html).

The deep sea, deep Earth, distant galaxies, and geoscience arenas in between are the focus for a number of innovative geoscience and ocean science education and outreach projects that will be featured during several special sessions at the AGU Fall Meeting in December.

Robigou's presentation is part of the oral session on "Innovations in Ocean Science"
Fig. 1. Tectonic map of the GEODYSSSEA region and locations of the GFS stations.
Fig. 3. Enlargement of Figure 2, showing GEODYSSEA velocity field relative to ITRF-94.