

#### Mission

To conduct fundamental research on earthquakes, volcanic eruptions, tsunami and climate change in and around Southeast Asia, for safer and more sustainable communities

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# DESIRED OUTCOMES & PERFORMANCE GOALS

#### A. Attract, retain and support world-class scientists in Singapore

Goal 1: Build a team of outstanding, collaborative researchers

#### B. Position the host university as a centre of excellence in education

**Goal 2:** Build an outstanding infrastructure in support of research

**Goal 3:** Expand earth science education at NTU and in Singapore

#### C. Create new knowledge in science and technology

**Goal 4:** Acquire significant new knowledge about earthquakes, volcanoes, tsunami, and climate change in keeping with our mission

**Goal 5:** Promote uptake of EOS research amongst key users



Before the Sumatra-Andaman earthquake and Indian Ocean tsunami in 2004, few people, in Singapore and elsewhere in the region, were aware of the possibility that Nature could be capable of destruction on such an enormous scale. Thanks to the far-sightedness of our Singapore funders, the National Research Foundation, the Ministry of Education, and our generous host university, Nanyang Technological University, the Earth Observatory of Singapore (EOS) is well placed to fundamentally and systematically address a wide spectrum of natural hazards that pose major threats to our societies in and around Southeast Asia

In the short history of our species, and the even shorter history of our civilization, human progress will depend on how successfully we meet the challenges and adapt to the limits of the natural world. Resources are becoming scarcer while populations expand into naturally dynamic and dangerous environments, and climate is changing more strikingly than at any time since humans invented agriculture. In this context of civilization in peril, the field of earth sciences has never been more relevant.

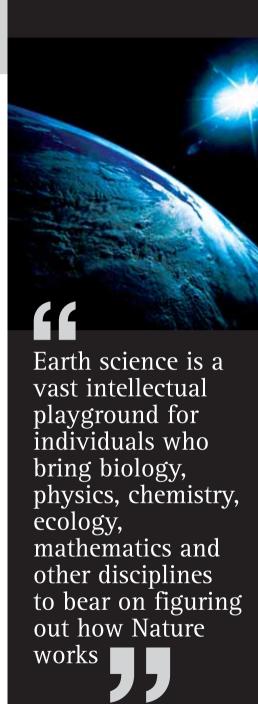
Earth science is a vast intellectual playground for individuals who bring biology, physics, chemistry, ecology, mathematics and other disciplines to bear on figuring out how Nature works. For example, recent forecasts of future great earthquakes and tsunamis in western Sumatra have come from deciphering the growth bands of corals and the layers of plankton-rich swamp muds, Great tectonic rendings of the ground during recent large earthquakes in Tibet, Pakistan and Turkey have been figured out by the manipulation of electronic data collected by satellites before and after the earthquakes. Volcanoes attract scientists who enjoy tracking and forecasting the

journey of molten rock through subterranean plumbing and out onto the surface and high into the atmosphere. That exploration requires not only sophisticated scientific capabilities, but seismic and geodetic and chemical instruments as well. Scientists trying to forecast sea level rise over the next century will be making sensible mathematical, physical and chemical super-computed models of the behavior of the biosphere, oceans, atmosphere and ice sheets, based on collections of data from all these environments.

The EOS is clearly science-driven, but it is also community-driven. EOS is committed to fostering a new generation of young scientists and an earth scienceliterate public. In Singapore, we have embarked on an energetic Education & Outreach program targeted at schools to grow earth sciences as a new field of study. Here, in our home at NTU, we have just set up a Division of Earth Sciences, under the School of Physical and Mathematical Sciences. We can also play a vital role in helping and partnering with neighbouring countries to conduct fundamental research and share knowledge on natural hazards.

In this report on EOS activities in 2009, our first full year of operations, you will read about our overarching strategy and goals, recruitment of the first of a critical mass of talented earth scientists and other specialists from around the world, and about nearly thirty ongoing and emerging research projects in collaboration with our colleagues in the region and beyond.

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## COVERNING BOARD MEMBERS

#### Tan Gee Paw

Chairman, Public Utilities Board and Chairman, EOS Governing Board

#### Lawrence Koe

Director (Projects), National Research Foundation

#### Tan Gee Keow

Director, Higher Education, Ministry of Education

#### **Foong Chee Leong**

Director-General, Meteorological Services, National Environment Agency

#### Lam Chuan Leong

Ambassador-at-Large, Ministry of Foreign Affairs

#### Jean-Lou Chameau

President, California Institute of Technology (CALTECH)

#### Su Guaning

President, Nanyang Technological University

#### **Kerry Sieh**

Director, Earth Observatory of Singapore (Ex-officio)



## SCIENTIFIC ADVISORY BOARD MEMBERS

#### **Brian Atwater**

United States Geological Survey, Washington, USA

#### **Douglas Burbank**

Institute for Crustal Studies, Department of Earth Science, University of California, Santa Barbara, USA

#### **Kurt Cuffey**

Department of Geography and Department of Earth and Planetary Sciences, University of California, Berkeley, USA

#### **Goran Ekstrom**

Department of Earth & Environmental Sciences, Columbia University, USA

#### **Inez Fung**

Department of Earth and Planetary Science, Department of Environmental Science, Berkeley Institute of the Environment, University of California, Berkeley, USA

#### Michael Gagan

Research School of Earth Sciences, Australian National University, Australia

#### **Richard Kerr**

Science Magazine, USA

#### Philip L.F Liu

School of Civil and Environmental Engineering, Cornell University, USA

#### Liu Shaw-Chen

Research Center for Environmental Changes, Academia Sinica, Taiwan

#### **David Montgomery**

Department of Earth and Space Sciences, University of Washington, USA

#### Setsuva Nakada

Earthquake Research Institute, University of Tokyo, Japan

#### Kenji Satake

Earthquake Research Institute, University of Tokyo, Japan

#### **Stephen Sparks**

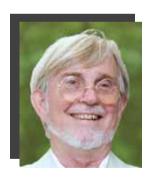
Department of Earth Sciences, University of Bristol, UK

#### **Christophe Vigny**

Department Terre Atmosphère Océan, École Normale Supérieure, France

## PEOPLE

2009 was a year of rapid growth and consolidation at EOS as we continue to hire talented and accomplished scientist and professionals. Our target by the end of 2011 is to hire 8 full-time, out of an anticipated 16 full-time Principal Investigators (PIs) in the Earth Sciences. We will also have several half-time PIs, working in related fields.



#### **Paul Tapponnier**

Professor of Geology & Head, Tectonics Group

Prof Tapponier, who heads tectonics and earthquake research at EOS, arrived in Singapore in September 2009. He brings with him extensive experience in researching the active tectonics of China and its recent great earthquakes. He is extending his work into the Myanmar-Bangladesh region and the Nepalese portion of the Himalayan front. Early in his career, he transformed the scientific understanding of Asia's tectonics with his discovery of the active faults in Tibet that are accommodating the collision of India into Asia. His pioneering use of satellite imagery set the standard for modern methods of tectonic research.



#### **Paramesh Banerjee**

Technical Director

Dr Banerjee, who joined EOS in April 2009, is a geophysicist specializing in the use of GPS and other geodetic techniques for earthquake and tectonic studies. In 17 years as a senior scientist with India's Department of Science and Technology, he implemented GPS networks that have been used to study the crustal dynamics of the Indian subcontinent — work that entailed traversing some of the toughest terrain in the Himalayas.

#### **Adam Switzer**

Principal Investigator, Tectonics Group Singapore NRF Fellow/Nanyang Assistant Professor

Asst Prof Switzer joined EOS in September 2009 to work on coastal hazards in the Tectonics and Climate Groups. A sedimentologist specializing in coastal geomorphology, paleoenvironments and natural hazards, his main research focus is the use of coastal stratigraphy to define the recurrence interval of catastrophic marine inundation in tsunamis or large storms. In January 2010, he was awarded a three-year National Research Foundation Fellowship grant of US\$2.0 million.



#### **Assistant Prof Koh Tieh Yong**

Assistant Professor & Principal Investigator, Climate Group

Koh Tieh Yong came on board in August 2009 as half-time principal investigator in the climate group. He is also an assistant professor in NTU's School of Physical and Mathematical Sciences (SPMS), and a research scientist at NTU's Temasek Laboratories. His research focuses on the dynamics of atmospheric conditions in the topics and the use of mathematical models for weather prediction in Southeast Asia.



#### **Fidel Costa**

Assistant Professor & Principal Investigator, Volcano Group

Fidel COSTA joined EOS in January 2010 as a Principal Investigator in the Volcano group at EOS. He is an igneous petrologist and geochemist specializing in volcanic processes. His main research interests are the conditions (pressure, temperature, volatile contents) and processes that magmas experience below active volcanoes and how these relate to volcanic unrest.



#### Other Research Staff

The following staff came on board between August 2009 and March 2010

#### Senior Research Fellows Volcano Group:

Dr Christina Widiwijayanti Dr Dannie Hidayat Dr Florian Schwandner Dr Alexander Belousov Dr Marina Belousov

#### **Tectonics Group:**

Dr Kenneth Macpherson Dr Meya Yanger Walling Dr Li Lin Lin

#### **Other Program Appointments**

**Isaac Kerlow** Artist-in-Residence

Isaac Kerlow, professor at NTU's School of Art, Design and Media, was appointed EOS' first Artist-in-Residence at beginning August 2009. His first EOS documentary, People-Coral-Mentawi, was launched in October 2009. He will complete a second production, Mayon: The Volcano Princess, by October 2010.

#### **Research Recruitments in Progress**

In the first quarter of 2010, several new recruitments were begun. A candidate for the key post of Climate Group Leader was selected, and we expect the position to be filled in 2011. Also in 2011, we anticipate the arrival of the Head of the Division of Earth Sciences, and a paleoclimatologist. A geodesist, Asst Prof Emma Hill, will join EOS in September 2010.

## EOS TECHNICAL OFFICE

The Technical Office was established with the appointment of Dr Paramesh Banerjee in April 2009. This also includes a field technician and computer systems engineer. Recruitment is underway for a GPS analyst to take care of routine processing activities.

In 2009, the Technical Office completed construction of the EOS Data Centre, a computational and data archiving facility. The EOS Data Centre has now been linked with NTU's high-speed Internet gateway using fibre optic cable. A Data Analysis room was also completed to house a data analysis, operations and instrumentation laboratory. In addition to being equipped with facilities for small-scale briefings, it has four flat screen monitors for real-time display of processed time-series and velocity vectors, and other geodetic and seismic signals. A facility adjacent to the Analysis Centre is being developed into a fully equipped instrumentation lab for making all types of electronics, electrical, telecommunication and mechanical experiments.

#### Sumatran GPS Array (SuGAr):

The first priority of the Technical Group was to bring the SuGAr back to life. The pre-existing telecommunication system, based on the Indonesian GARUDA satellite, was extremely slow and working only intermittently. The communication problem along with the constraint of maximum 90 days data storage limitation in the GPS receivers had caused data outage at most of the stations. We immediately arranged to download the data manually. Just in time, the majority of the GPS stations were made operational again to record displacements associated with the 29th September, 2009 Padang earthquake, for which we were able to compute a useful field of coseismic offsets. As a long-term solution to these technical problems, we decided to replace all the Ashtech GPS receivers with Trimble NetRS receivers, which can store data for more than one year at 15-sec intervals as well as two months of data at 1-sec intervals.

In an effort to densify the GPS network along the unbroken northern half of the Mentawai segment of the Sunda megathrust, we began installation of four new permanent stations, three on the Sumatran mainland, and one on Siberut island. In an effort to overcome telecommunication problems, we began to examine various communication options, primarily radio communication, VSAT and the Inmarsat satellite based system (BGAN). BGAN instruments have been installed at two locations (PSKI and TIKU) on an experimental basis, as described in following reports.

#### Myanmar

In 2009, we began negotiations and preparations for the installation of an experimental array of four permanent GPS stations in Myanmar. A MoU is currently being drafted jointly with our Myanmar partners. We plan to carry out the installations in the course of 2010.

#### Bangladesh

We have reached agreement in principle with the Geological Survey of Bangladesh for a collaborative project comprising both paleoseismology and geodesy. We plan to install at least four permanent GPS stations to determine the rate of deformation across the Shillong plateau, which lies on a sliver block south of the main Himalayan collision boundary, and interacts with the collision of the Indo-Burman ranges at the northern end of the Sunda subduction system.



#### TECTONICS AND EARTHQUAKE GROUP

#### Development of a Standard Procedure for Seismic Hazard and Risk Assessment of Cities in Southeast Asia: Case Study of Surabaya

#### **Principal Investigator**

 Asst Prof Kusnowidjaja Megawati, Earth Observatory of Singapore & School of Civil and Environmental Engineering, NTU

#### Collaborators

- Prof Paul Tapponnier, Earth Observatory of Singapore
- Dr Danny H Natawidjaja, Indonesian Institute of Sciences (LIPI)
- Prof Kazuki Koketsu, Earthquake Research Institute, University of Tokyo
- Prof Hiroaki Yamanaka, Tokyo Institute of Technology
- Assoc Prof I Wayan Sengara, Institut Teknologi Bandung (ITB), Indonesia
- Mr Amien Widodo, Institute Technology Sepuluh Nopember (ITS), Indonesia
- Mr Kwoh Leong Keong, National University of Singapore

#### Researchers

- Dr Meya Yanger Walling, Earth Observatory of Singapore
- Miss Xiao Fang Deng, Earth Observatory of Singapore

The severity of earthquake disasters increases tremendously when major earthquakes hit densely populated urban centres. Re-examining seismic hazard of major cities in Southeast Asia is an important focus at the EOS in mitigating regional earthquake catastrophes. This project will develop a standard procedure to assess seismic hazard and risk levels of urban areas using the Indonesian city of Surabaya as a study case.

The team evaluated the seismic hazard deterministically by: first identifying scenario earthquakes based on geologic and tectonic evidence; then computing the expected ground motions using a 3D discrete model; and establishing building inventory from satellite photos and estimating potential loss. The outcomes are expected to help local governments in Southeast Asia to formulate effective mitigation strategies.

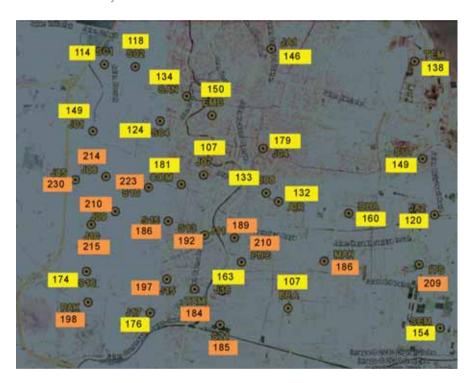
In 2009, we focused on identifying potential local seismic sources that may affect Surabaya based on SRTM data and by constructing a 3D velocity structure underneath the city. We have conducted active fault mapping on SRTM data and put together a geological map as well as historical earthquake data over the past two centuries. This preliminary study enables us to delineate two major fold-thrust belts, known as the Rembang and Kendeng zone, both trending east-west and converging right into Surabaya region.

We found three historical earthquakes in the region, in 1836 (near the Rembang fold zone), in 1902 (around the eastern end of the Kendeng fault zone), and in 1937 which affected the Surabaya region. Hence, it seems plausible that the Rembang and Kendeng fold-thrust zones are still active today, and may be major sources of earthquake hazards for Surabaya – and not the Java megathrust earthquake source far south as previously suspected.



Government and university involvement is essential if the research outcomes are to be useful in hazard mitigation and future city planning. We therefore coordinated with ITS to hold a seminar on campus in December 2009 on the potential seismic threat to Surabaya. The seminar was attended by the deputy mayor of Surabaya and over 100 participants from government agencies, universities and the private sector.

Collaborating with the Institut Teknology Sepuluh Nopember (ITS) in Surabaya, and the Tokyo Institute of Technology, we conducted microtremor measurements in Surabaya in December 2009. Seven vertical geophones were arranged in a triangular array at each site, in an increasing order of sizes ranging from 5 m to 1,000 m. The smaller arrays would reveal the shallow structures, while the larger ones were meant to uncover deeper structures. We completed measurements for medium- and large-size arrays at 14 locations and small-size arrays at 36 locations.



The figure above depicts a map showing the variation of Vs³0 values in Surabaya based on the dispersion curves revealed by the small-array measurements. Vs³0 values are typically used for earthquake microzonation. The deeper structures will be obtained from analysing the dispersion curves obtained from the medium and large arrays of 200 m to 1,000 m. The basin effects (thickness and shape of the deeper structures) will affect the amplitude of ground motions with longer periods of 2-5 seconds, while the characteristics of the upper 30 m of soil will determine the ground-motion amplification factors within 0.8-2 seconds.

#### Plans for 2010

The plan for 2010 is to analyse the microtremor data collected and to construct 3D shear-wave velocity structure underneath Surabaya. Ground motion from scenario earthquakes on the Rembang and Kendeng fault system will be simulated to assess the seismic hazard the city. The site amplification will be computed based on the shear-wave velocity profiles obtained from the microtremor measurements.



#### SUMATRAN GPS ARRAY (SuGAr)

By Kerry Sieh and Paramesh Banerjee

The Sumatran GPS Array (SuGAr) spans 1350 km of the obliquely convergent Sumatran plate boundary. This array is particularly valuable scientifically for three reasons:

- 1) Two-thirds of the stations are on islands that directly overlie the locked sections of a megathrust and, thus, are particularly well situated for recording interseismic, coseismic and postseismic deformation. This situation is unique among the world's subduction zones.
- 2) SuGAr geodetic data complement centennial and millennial paleogeodetic time series and paleoseismic data collected from coral microatolls on the same islands. This enables placement of modern instrumental cGPS data and analyses into the context of several earthquake cycles.
- 3) Three great earthquakes have occurred along the Sumatran margin since establishment of the network and another has been forecast. This provides a unique opportunity to understand post-seismic and pre-seismic behavior of one of Earth's great megathrusts by monitoring tectonic deformation above it.

Notable scientific discoveries already made possible by the SuGAr include these:

- 1) Determination of the spatial extent of a 500-km long locked section of the megathrust between about 0.5° and 5°S and estimation of the spatial variability of its coupling. Using both SuGAr and modern coral data, Chlieh et al showed that this "Mentawai patch" comprises two large, fully locked patches surrounded by large regions of lesser coupling. Multiplication of the coupling factor by the rate of convergence and years since the last historical ruptures yields first-order estimates of the pattern of potential slip in the next great earthquake.
- 2) Exceptionally detailed resolution of the spatial extent, slip patterns and rupture propagation that produced the great Mw8.7 and 8.4 megathrust earthquakes of 2005 and 2007.

Again in combination with uplift measured from coral microatolls, we showed that the 2005 rupture consisted of two separate patches, the lesser one under southern Simeulue island, north of the hypocenter, and the larger one to the south under Nias island. The data allowed us to constrain the coseismic slip to a strip about 100-km wide beneath the islands. In the case of the 2007 rupture, we also showed that slip concentrated in a 100-km wide strip between trench and mainland coast. Moreover, we

were able to resolve the slip pattern well enough to show that slip averaged less than had been accumulated since the previous great earthquakes of 1797 and 1833. One very important result is this: A comparison of the locked Mentawai patch and the 2007 rupture shows clearly that most of the northern half of the locked Mentawai patch remains un-ruptured. The SuGAr data also enabled resolution of slip during large aftershocks. The Mw7.9 aftershock of the 2007 event clearly involved two sources separated by about a minute in time and 100 km in distance.

- 3) Unusually fine resolution of the up-dip region of afterslip following the 2005 and 2007 earthquakes. Because the SuGAr stations sit on islands that overlie the coseismic ruptures, we were able to resolve afterslip with unusual clarity. In the year following both the 2005 and 2007 ruptures, afterslip was largely confined to strips of the megathrust immediately updip and downdip of the coseismic ruptures. These sections did not fail during the mainshocks. Moreover, the moment or potency represented by the afterslip is far greater than that represented by aftershocks. This implies that the afterslip drove the aftershocks and that the aftershocks represent failure of small, coupled patches surrounded by brittle-creeping regions.
- 4) Most recently, and as yet unpublished, is our analysis of the rupture of the downgoing oceanic slab that produced the Mw7.6 Padang earthquake on September 30th 2009. SuGAr stations surrounding the epicentre recorded coseismic motions of up to 6 cm. Initial forward modelling of the coseismic deformations imply that the rupture plane is approximately as suggested by USGS modelling of seismic records. The most likely plane strikes just east of north near the mainland coast. The strike-slip component of motion is about 8 meters left-lateral and the reverse component is about 6 meters. This geometry and sense of slip is consistent with a subducted leftlateral strike-slip fault within the downgoing oceanic slab, perhaps one of the many such faults that form the diffuse boundary between the oceanic Indian and Australian plates in this region.

Looking forward, past analyses of the SuGAr data have opened our eyes to new and particularly interesting questions that we are eager to answer using a combination of geodetic, seismic and paleogeodetic data and modelling tools to explore and interpret these data.

## Data Sensing, Communications and Processing: Sumatran GPS Array

#### **Principal Investigators**

- Assoc Prof Ian McLoughlin, School of Computer Engineering, NTU
- Asst Prof Tan Su Lim Forest, School of Computer Engineering, NTU
- Asst Prof Steven Wong Kai Juan, School of Computer Engineering, NTU

In 2009, the Earth Observatory of Singapore (EOS) assumed responsibility for maintaining and operating the SuGAr from Caltech's Tectonics Observatory. The primary objective was to begin the operation of SuGAr and some innovative engineering to improve the array in terms of operation, maintenance and experimental work. The network was substantially upgraded in collaboration with EOS' Indonesian partners. Upgrades included more reliable telemetry, new station designs to improve reliability and robustness, additional sensors, as well as intelligent and even partially automated operation.

The five planned aspects of SuGAr work in 2009 were: maintain, upgrade, extend, exploit and experiment. Key achievements include:

- 1. **Upgrade** of GPS from Ashtec to Trimble NetRS, and of FR190G to BGAN at several sites. These technologies have been evaluated locally and proven for stability.
- 2. **Exploitation** of SuGAr data is best typified by the 30th Sept. Padang earthquake, which was centred near our recently upgraded PSKI station fitted with both NetRS and BGAN. Within minutes of the earthquake we could connect to the station and retrieve high-rate GPS data online.
- 3. **Experimentation** was conducted primarily in terms of data communications and creation of mesh networks to provide redundancy to existing satellite communications, and also to allow bandwidth reduction. Several data communications experiments were organised and run, particularly in Padang a month prior to the 30 Sept earthquake.

#### **Student Projects**

A PhD student has been working on automated GAMIT processing, particularly to preprocess cGPS data at the remote sites to reduce bandwidth.

A second PhD student is working on a rapid deployable sensing system.

In 2009 we undertook a collaboration with Harvey-Mudd College (California) to develop a rapid deployment sensing system for measuring earth movement (primarily for volcanic areas). During the year, 12 final year project undergraduates, 3 MSc and 3 PhD students have been trained for this, and undertaken field trips in Indonesia. Finally, a prototype hardware was developed and encapsulated ready for on-site testing. Apart from this, an experimental GPS site was set up on the roof of EOS, and high-performance computer equipment were purchased and configured for internal and external access.







#### Earthquake Geology of Myanmar

#### **Principal Investigator**

• Prof Kerry Sieh, Earth Observatory of Singapore

#### Collaborators

- Yu Wang, California Institute of Technology
- Soe Thura Tun, Myanmar Engineering Society
- U Than Myint, Myanmar Engineering Society
- Thura Aung, University of Yangon
- Soe Min, Mohnyin Degree College

In many parts of the world, active faults are too poorly understood to quantify their role in regional neotectonic deformation or to make realistic estimates of seismic hazard. The active faults of Myanmar are a good example of this dearth of information. This project continues ongoing work on the active tectonics of the Myanmar area and the fault behavior of the southern portion of the Sagaing fault, one of the major seismic sources in Southeast Asia. Research focuses on its slip rate and its earthquake history of the past millennium. This project integrate geomorphologic investigations, paleoseismologic and archaeological excavations to obtain the fault's earthquake history and long- and short-term slip rates.

In 2008 and 2009, we and our Myanmar colleagues focused our work in lower Myanmar on the southern section of the Sagaing fault, the principal source of seismic hazard for the country's largest cities and economic centers. Our goal was to initiate paleoseismic work that would illuminate the behavior of the fault over the past millennium or so. Records of destructive earthquakes from the large pagoda at Bago suggested that paleoseismic studies of the southern Sagaing fault might yield more precise timings of earthquake recurrences than those that have been obtained for other, more-thoroughly studied faults, such as the San Andreas Fault in California.

In 2009, we found evidence for an offset ancient fortress near the town of Payagyi, 15 km north of Bago. We conducted detailed field surveys and excavations within the fortress and on its northern wall. Differential sedimentation and erosion adjacent to the wall complicated determination of the offset. However, our stratigraphic and geomorphic data enabled a reliable reconstruction. The Sagaing fault has offset the northern wall of the fortress 6 to 8 meters right-laterally.

One important paleoseismic question is this: What earthquakes resulted in the 6 to 8 meter offset of the fortress wall? To find out, we dug trenches inside the fortress. Unfortunately, the strata in the walls of the excavations were not optimal for paleoseismic work, due both to a rapid rate of soil formation and extensive bioturbation by crabs. Nonetheless, we recovered evidence for at least two fault ruptures prior to 1930.

Our research results were presented in the following international conferences:

Wang, Y, K Sieh, T Aung, S.N. Khaing, S. Min, S.T.Tun, K.K. Lin (2009), Offset ancient city wall yields plausible slip rate for the Sagaing fault, Myanmar (Burma), AOGS abstract, SE-55.

Wang, Y., Sieh, K. E., Min, S., Khaing, S., Tun, S.(2009) Smoking gun of the May 1912 Burma earthquake? Neotectonics of the Kyaukkyan fault system, Eastern Burma (Myanmar), Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract T33B-1912

We have prepared a manuscript that summarizes our work along the southern Sagaing fault, for submission to the Bulletin of the Seismological Society of America in 2010.



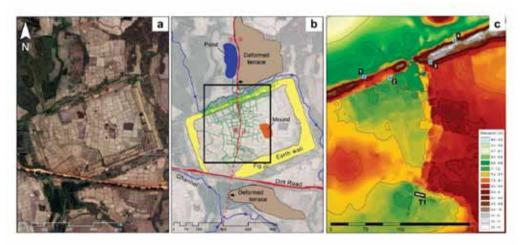


The tentative correlation of cultural debris in the trench walls with construction and occupation of the ancient fortress leads us to believe these two events must post-date construction of the fortress. This suggests a recurrence of major ruptures at least every one and a half to three and a half centuries.

#### Plans for 2010

We propose to continue neotectonic and paleoseismic studies in Myanmar. Our field focus will be paleoseismic studies of the uplifted young terraces along the west coast of the country, which likely reflect deformation during large subduction-related earthquakes. An initial east-west transect of four cGPS stations will enable an early assessment of the distribution of strain across Myanmar.

We will also complete two manuscripts stemming from our earlier work – one detailing our paleoseismic work along the southern Sagaing fault, and the other describing the overall neotectonic framework of Myanmar.



- (a) Birds-eye view of the Payagyi ancient fortress from Google Earth® imagery. The ancient fortress is at 17.480°N, 96.505°E and appears as a 650 m by 400 m rectangle amid rice paddies.
- (b) Geomorphologic interpretation from aerial photography and satellite imagery. Yellow depicts the fortress wall visible on the images. The red line shows the trace of the Sagaing fault on the fluvial plain as revealed by field mapping and remote sensing. Black arrows indicate tectonic tilting of high terraces. Green dots are points surveyed by total station in Spring 2009. The digital topography generated from the survey appears in (c).
- (c) Digital terrain model (DTM) of part of the Payagyi ancient fortress. Grid cell size is 50 cm. The trace of the Sagaing fault is clear along a topographic scarp cutting across the middle of the map. Blue squares show the locations of pits dug through the base of the earthen fortress wall. T1 is the trench we dug across the fault.



## Paleoseismology and Paleogeodesy of the Sumatran Subduction Zone

#### **Principal Investigator**

• Prof Kerry Sieh, Earth Observatory of Singapore

#### **Collaborators**

- Belle Philibosian, California Institute of Technology
- Aron Meltzner, California Institute of Technology
- Dr Danny Natawidjaja, Indonesian Institute of Sciences (LIPI)
- Chuan-Chou Shen, National Taiwan University
- Hong-Wei Chiang, National Taiwan University

To understand how the Sunda megathrust has behaved over long time periods and to resolve details of past earthquakes, we rely on natural instruments—annually banded coral "microatolls" that are very sensitive to the lowest annual tides. These microatolls preserve precise information about past relative sea levels, from which we can extend the geodetic record of vertical deformation and deduce tectonic histories decades to centuries into the past.

#### Simeulue, Nias, and the Banyak Islands

Work on Simeulue and Nias is in various stages of completion. Results from central Simeulue—primarily showing that none of the northern Simeulue ruptures extended to southern Simeulue and that a large rupture in southern central Simeulue did not have a large effect along northern Simeulue—should be submitted for publication by mid 2010.

The northern Simeulue results have been included in Aron Meltzner's Ph.D. thesis, and are now in press in the Journal of Geophysical Research.

#### The Mentawai Islands

Our newest coral data (collected in mid-2008 and analyzed in 2009) is allowing us to improve our understanding of the distribution of past ruptures. One new site corroborates the previously hypothesized late-1300s earthquake, and another will likely include a 200-year record leading up to the 1300s sequence. The record for the 1600s will be significantly refined, since we now have clearer evidence of 3-4 earthquakes and slow uplift between 1590 and 1690. This is particularly relevant as a potential analog to the ongoing rupture sequence. Analysis of the coral data is ongoing; we are working on refining the U-Th dates of a number of samples in order to accurately separate the different earthquakes within the 1600s sequence. Overall, the new measurements hint at significant differences between the 14th-, 16th-, 18th- and 21st-century rupture sequences. This implies that the impediments to rupture within the Mentawai patch are influenced by properties that change from one rupture sequence to the next. Such properties are more likely to be related to the state of stress than structural complexity.





#### Plans for 2010

#### Simeulue, Nias, and the Banyak Islands

Our work in FY 2010 will have four primary goals:

- 1) to finish drafting figures and writing up the results from central Simeulue, making the case that central Simeulue lies over a poorly coupled section of the megathrust that has acted as a repeated barrier to rupture;
- 2) to complete analysis of the slabs collected from over the 2005 patch, and to date additional samples from these slabs, in order to refine the history of tectonic strain accumulation and relief there;
- 3) to draft figures and write up the results from the 2005 patch, making the case for a comparatively short recurrence interval and impending hazard in the region;
- 4) to model slip on the plate interface in the 1394, 1430, 1450, 1861, and possibly other paleoearthquakes, as well as in the 2002, 2004, 2005, and 2008 modern earthquakes, to test the hypothesis that the boundaries of the regions of uplift in these earthquakes can all be explained by a single barrier on the megathrust of finite and limited width (possibly a region of poor coupling, or a tear in the megathrust).

#### Mentawai Islands

Our goal in the next few years is to investigate in more detail how each rupture sequence has unfolded, and what that implies for future rupture of the Mentawai patch. Observing the similarities and differences between sequences in greater detail will shed light on the mechanisms and conditions that control earthquake rupture propagation, and allow us to estimate better the likely future progression of the 21st-century sequence.

Our next expedition to the region, planned for mid-2010, will begin with the helicopter-assisted survey. Following that, we expect to conduct another monthlong boat expedition to collect samples at the sites identified during the helicopter scouting.

Following the collection and analysis of coral data in early 2010, we will construct kinematic models of fault slip based on coral and cGPS surface observations, including data from the SuGAr cGPS network before and after the 2007 Mentawai earthquakes, in collaboration with Prof. Jean-Philippe Avouac at Caltech as well as EOS faculty and staff.



#### **GeoTouch: Interactive Visualization Tool**

#### **Principal Investigators**

- Assoc Prof Goh Wooi Boon, School of Computer Engineering, NTU
- Assoc Prof Ian McLoughlin, School of Computer Engineering, NTU

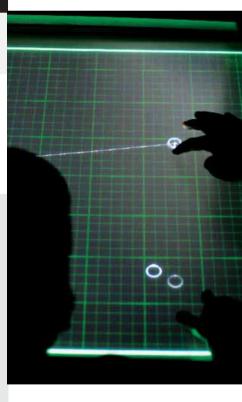
An important component of earth science research is the ability to meaningfully visualize massive amounts of data. The voluminous nature of these data sets requires the effective design of both the visualization techniques and the human-computer interface. This project has developed an interactive multi-touch visualization tool to provide intuitive and seamless gesture-based exploration of geographical information such as high-resolution satellite images, real-time earthquake information amongst others.

A small project operated during FY2009 to build a multi-touch display unit, called GeoTouch, within EOS, and equip this with custom earth-science data visualisation and display tools. One unit has now been built into the entrance foyer of EOS, and is running prototype software of our own design. Although commercial systems exist, these begin at four times the cost of this project, but furthermore come with no EOS-relevant software. This work has involved computer engineers, computer scientists and earth scientists in a multi-disciplinary team to build upon each other's specialisations in creating something that is dedicated to the needs of EOS – both the physical hardware located in the foyer, and the special software for map, satellite image, earthquake and volcano location overview.

Map and image overviews already work perfectly, and the current focus is on collaborative groupware tools: users can send images and documents to the system where they can be displayed and interactively worked upon. The system currently caters for two users simultaneously to control, write upon, annotate and manipulate data objects.

#### Plans for 2010

The system works, and is robust, at displaying mapping and image data of the earth's surface. A real-time earthquake locator is also installed and operational, as are rudimentary groupware mark-up and collaboration interfaces. During 2010 the feature set of the system will be explanded in line with the evolving needs of participating EOS scientists. Most important is an easy-to-use method of sharing and maniplulating data objects for this amazingly intuitive and fascinating interface that is often the first thing that new visitors to the centre will notice.



#### Fundamental Source-to-Siteto-Structure Study of Seismic Impacts and Hazards

#### **Principal Investigator**

Prof Goh Siang Huat, National University of Singapore

#### Collaborators

- Assistant Prof Kusnowidjaja Megawati, Earth Observatory of Singapore & School of Civil and Environmental Engineering, NTU
- Prof Kerry Sieh, Earth Observatory of Singapore
- Prof Jeroen Tromp, Princeton University
- Assoc Prof Lee Fook Hou, National University of Singapore

This project will develop large scale 3-D computational models which can perform `source-to-site-to-structure' simulations. They will start with the rupture on an earthquake fault, followed by the propagation of the resulting seismic waves from the fault to engineered structures of interest, and conclude with an assessment of the structural responses to the imposed ground motion. These models will incorporate the results of ongoing EOS research to characterize the major regional seismic sources. State-of-the-art parallel computing technology will be used to carry out the massive calculations. The results will be useful in assessing the effects and hazards to buildings and infrastructure in Singapore and neighbouring countries.

In 2009, strategies were developed for conducting large scale, long-period, ground motion simulations for large areas including Sumatra and the Malay peninsula, with source zones on the Sumatran megathrust.

#### **Preliminary Simulations**

Two events were simulated and the synthetics compared to USGS Shakemaps in order to evaluate the effectiveness of the finite-difference code and inputs at modeling ground motions. Scenario 1 modeled the 12 September, 2007 Benkulu, Indonesia earthquake, which ruptured a part of the Mentawai segment of the Sumatran megathrust, resulting in a moment release corresponding to Mw = 7.8 (Megawati and Pan, 2009). Scenario 2 modeled the 30 September, 2009 Padang event, which also ruptured the Mentawai segment, with a moment release corresponding to Mw = 7.6.

Synthetic seismograms are captured on a grid of about 1000 "stations" at the free surface. The synthetics were filtered in order to remove spurious signals introduced by grid dispersion, after which any ground motion parameters of interest may be calculated. Comparison of these synthetic ground motions to the Shakemaps indicates that the peak amplitudes are similar after accounting for the amplitude reduction caused by filtering. Differences in the spatial distribution of PHV are not unexpected given the differences in source models, uneven distribution of observations in the Shakemaps, and coarseness of the velocity model used in the simulations.



#### Plans for 2010

We shall focus our attention in 2010 on the use of the spectral finite element method for large scale seismic ground motion analyses of the Southeast Asian region.

We plan to visit Professor Tromp and his group at Princeton University to gain a basic understanding of the computational seismology code SPECFEM-3D, learn first hand how to set up the 3-D model using the crustal and velocity data, and acquaint ourselves with the hardware and software requirements required for running the parallel code on a PC network cluster. Upon returning from Princeton, we will commence porting the computational seismology code onto the NUS high-speed network PC cluster.

Once the SPECFEM code has been successfully ported to the NUS cluster, a 3-D model will be set up to cover an area extending from the Sunda Arc to Singapore, with the boundaries taken sufficiently far away to minimize wave reflection effects. The performance of this model will be carefully examined and calibrated using a recent earthquake.

Once the model has been sufficiently validated, we will develop a suite of source models for a range of plausible scenario earthquakes based on the seismotectonics of the Sunda megathrust.

Besides the computational modeling aspects, part of the work planned for 2010 also includes obtaining more detailed crustal information for the Sumatran and Singapore region, in order to characterize the pathways between the various potential sources and regional sites of interest.

## Tsunami Hazard Mitigation for Southern Bali and West Sumatra

#### **Principal Investigator**

Asst Prof Huang Zhenhua, School of Civil and Environmental Engineering, NTU

#### Collaborators

- Asst Prof Kusnowidjaja Megawati, Earth Observatory of Singapore & CEE, NTU
- Assoc Professor Tan Soon Keat, School of Civil and Environmental Engineering, NTU
- Asst Prof Edmond, Yat Man Lo, School of Civil and Environmental Engineering, NTU
- Dr Danny H Natawidjaja, Indonesian Institute of Sciences (LIPI)
- Prof Philip L-F Liu, Cornell University
- Dr Hamzah Latief, Institut Teknologi, Bandung, (ITB), Indonesia
- Ole Larsen, DHI Singapore

Catastrophic tsunamis are caused by tectonic events, large-scale landslides or volcanic eruptions. This project seeks to combine our understanding of tsunami science with effective engineering measures so as to minimize the risk that future tsunamis will cause loss of life and damage to structures along vulnerable coasts. Proposed activities include: evaluating the tsunami risk from local underwater earthquakes close to southern Bali and west Sumatra, modelling tsunami-induced debris flows and the associated hydrodynamic loads on coastal structures, investigating tsunami hazard mitigation by means of mangrove forests or coral reefs, and developing numerical models of the human evacuation process.

In the second half of 2009, the effects of mangrove trees and city buildings on inundation have been incorporated into the COrnell Multi-grid COupled Tsunami model (COMCOT) using several existing models. Based on a proposed submarine earthquake of Mw=8.92, we have carried out a numerical study of the effects of coastal trees and city buildings on the tsunami inundation in Painan, Indonesia. The study indicated that the flow resistance from the coastal trees or city buildings could significantly reduce the inundation amount, both in the forest areas and inside the city.

We have started experiments on solitary-wave (leading tsunami wave) interactions with mangrove models to calibrate the hydrodynamic coefficients in numerical models. We have also studied the effects of a sudden change in bathymetry on leading tsunami (solitary wave) propagation.

Research Fellow Linlin Li has modified the XBeach code to study sediment movement and geomorphic changes including dune erosion, breaching and overwash during a tsunami event. We have carried out a scenario study of sediment erosion and deposition for the city of Painan, Indonesia, based on a potential tsunami event in West Sumatra. The study examined the factors that influence tsunami erosion and deposition, which provided useful information for designing detailed site survey programs and coastal sediment management for tsunami events in this area.

In the past half year, we also developed a set of codes, using several existing theories, to simulate the initial surface displacements associated with the various types of sea-bottom uplift, especially initial tsunamis due to slow submarine earthquakes.





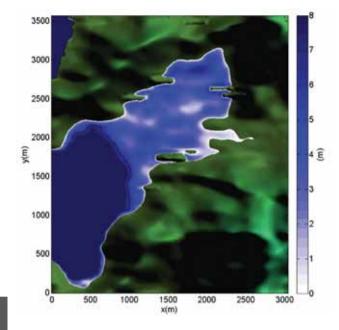


Figure. Inundation map of Painan, Indonesia. According to a rupture model proposed for the West Sumatran megathrust beneath the Mentawai islands, a potential tsunami may hit the coast of Painan about 37 minutes after the rupture. Most of the city will be inundated with the maximum depth about 6.8 m.

#### Plans for 2010

In the fiscal year of 2010, we will focus on:

- (a) Quantifying the hydrodynamic coefficients for various coastal forests and 3D city buildings through physical experiments, and incorporate them in COMCOT which is based on the nonlinear shallow water equations
- (b) Evaluating the effects of wave breaking on inundations and estimating the shoreline change for a given tsunami event
- (c) Pilot physical experiments on interactions between debris flows with idealized coastal structures, and
- (d) Establishing a first—cut model for the human evacuation process. The case study site for 2010 is Pariaman, Indonesia, for which the derived results will be applied.

#### **Publications**

- [1] Zhenhua Huang and Zhida Yuan, 2010. Transmission of solitary waves through slotted barriers: A laboratory study with analysis by a long wave approximation. Journal of Hydro-environment Research, Vol. 179-185
- [2] Zhenhua Huang, Qiang Qiu, and Xiaoming Wang, 2009. Numerical simulations of tsunami inundation for the city of Painan, Indonesia-Effects of coastal vegetations and man-made structures. In the Proceedings of the 3rd South China Sea Tsunami Workshop, Penang, Malaysia.
- [3] Zhenhua Huang, Tso-Ren Wu, and Chunrong Liu, 2009. A Numerical and Experimental Study of Solitary Wave Passing Over a Vertical Thin Wall with a discussion on tsunami seawalls. In the Proceedings of the 3rd South China Sea Tsunami Workshop, Penang, Malaysia.
- [4] Zhenhua Huang, Linlin Li, and Qiang Qiu, 2010. Tsunami-induced coast erosion: a scenario study for Painan, Indonesia. In the abstract book of the 3rd International Tsunami Field Symposium, Sendai, Japan.
- [5] Zhenhua Huang, Yao Yao, Shawn Yisheng Sim, Anqi Deng, Yu Yao, And Qiang Qiu, 2010 Interactions of leading tsunami waves with mangrove forests: A laboratory study with numerical simulations. In the abstract book of the 3rd International Tsunami Field Symposium, Sendai, Japan.
- [6] Zhenhua Huang, 2010. A note on tsunami hazard mitigation by mangrove forests. To be presented at the 9th International Conference on Hydroinformatics, Tianjin, China.

#### VOLCANO GROUP

#### Laboratory Volcanoes: Mayon, Luzon, Philippines

#### **Principal Investigator**

Prof Chris Newhall, Earth Observatory of Singapore

#### Collaborators

- Renato Solidum (Director); Ed Laguerta, Hannah Mirabueno and other staff of Philippine Institute of Volcanology and Seismology (PHIVOLCS)
- Fidel Costa, Florian Schwandner, Dannie Hidayat, Mariton Bornas (EOS)

Mayon, in Southeast Luzon, is representative of arc volcanoes that exhibit sustained SO<sub>2</sub> degassing well in excess of what could have come from erupted magma volumes. In the spectrum from openly-degassing to plugged volcanoes, Mayon is near the openly-degassing end, producing mostly small, frequent eruptions. This project hypothesizes that basaltic andesite magma convects in Mayon's conduit, and will study geologic evidence (petrologic, textural) for and against convection. It will also upgrade geophysical, geochemical and hydrologic monitoring of the entire system. New instrumentation will be added in research wells that respond to intrusion-induced volumetric strain, to supplement existing GPS for early detection of fresh magma batches. Instrumentation will also be added high on the cone to track changes immediately before eruptions.

The open character and relatively low precursory pressurisation make forecasting difficult for Mayon. EOS will introduce a new monitoring approach with low-precision sensors close to the crater, high-precision sensors at greater distances, and new sensors not previously used at Mayon (e.g. water wells as indicators of volumetric strain, continuous IR sensing CO<sub>2</sub> concentration and heat flux in soil, and continuous UV sensing of SO<sub>2</sub> concentration in the volcanic plume).

During 2009, EOS' main activities in the Mayon project were to hire key staff (Joey Marcial, Dannie Hidayat, Christina Widiwijayanti (also on WOVOdat project), Florian Schwandner). They undertook the necessary footwork and purchased seismometers, tiltmeters, UV and IR spectrometers, and other miscellaneous equipment for deployment at Mayon. Other essential groundwork prior to installation (e.g. finalizing the station designs and telemetry links) was also undertaken. It was a major frustration to see the 2009 eruption occur before we could upgrade the monitoring at Mayon, but given recent history, our next chance to track an intrusion and eruption will be in a few years' time. One small silver lining of this eruption is that the summit area will be relatively safe during the next few years, which will ease our installation of the new summit instrumentation. Mariton Bornas (EOS-PHIVOLCS) and Christina Widiwijayanti showed with the PFZ model that collapse of the small lava dome would not reach populated areas, and Ms Bornas lent her experience at Mayon during the eruption.

Dannie Hidayat and Christina Widiwijayanti helped model some tilt data and worked with Toto Bacolcol and Paul Alanis of PHIVOLCS to model recently-received GPS data. In the post-eruption period, Fidel Costa collected an initial set of samples for petrologic testing of the magma convection hypothesis.

#### Mayon video documentary

Chris Newhall and Mariton Bornas advised Isaac Kerlow and NTU students who filmed a documentary on how various players including PHIVOLCS, civil defence, and villagers cope with recurring hazards of Mayon.



#### Plans for 2010

The overall strategy is to understand in detail what is happening inside the plumbing system of Mayon, using all applicable geophysical, geochemical, and petrologic methods. This includes estimation of the times and volumes of magma (and gas) influxes, mixing and other effects of those influxes on already-present magma, tests of whether magma is convecting inside Mayon's conduit, and estimation of volatile budgets to judge how much magma is being degassed and during what periods of activity.

Specific activities in 2010 will be installing new seismometers, tiltmeters, and gas sensors, to get fresh data streams flowing both to PHIVOLCS and to EOS, and more petrologic sampling and analyses with the new EOS field emission gun electron microprobe and the Singapore Synchrotron Light Source (at NUS).

### **WOVOdat - World Organization of Volcano Observatories Database**

#### **Principal Investigators**

• Prof Chris Newhall, Earth Observatory of Singapore

#### Collaborators

- Antonius Ratdomopurbo, Christina Widiwijayanti, Earth Observatory of Singapore
- Members of the WOVOdat Steering and Technical Committees

Volcanoes are frequently restless but only a fraction of unrest leads to eruptions. Uncertainties in interpretation of volcanic unrest are unacceptably high. WOVOdat will capture historical volcanic unrest and make it freely web-accessible for reference during volcanic crises and for basic research on pre-eruption processes. Historical, parametric data will be imported — from the current myriad of data formats, database architectures, servers and storage media — into a single, comprehensive relational database with standardized formats. Further details can be found at www.wovo.org/wovodat1.html.

EOS has begun construction of an epidemiological database, WOVOdat, of the world's volcanic unrest. The WOVOdat team and the database schema are in place, and work has commenced to input test data from three observatories — members of the World Organisation of Volcano Observatories (WOVO) — into common, searchable formats.

In February 2009, the project leader (Ratdomopurbo) and programmers (Liu and Baguet) came on board , and a fourth team member (Widiwijayanti) joined in September.

Most programming during 2009 was devoted to building the tables and MySQL core of WOVOdat, writing XML code to translate data from various observatory formats into WOVOdat XML and thence into WOVOdat itself, and writing utilities for contributor login, contribution tracking, etc. Pilot data sets from New Zealand, Japan and from some other volcanoes were used to test and refine the WOVOdat design. Some suggested revisions have already been made, and more are expected by mid 2010. As of January 2010, the team has begun the main task of uploading data from WOVO observatories.

Three members of the WOVOdat team (Ratdomopurbo, Widiwijayanti, Newhall) co-organized a session at the 2009 AGU meeting, titled "Volcano Databases: Preserving the Past and Present for the Future" where discussions were held with many of the key contributors to WOVOdat. To minimize duplication of effort, WOVOdat is collaborating with the Smithsonian's Global Volcanism Program (GVP), the premier, ongoing repository of data about the eruptive history and petrology of Holocene volcanoes, and also with the VOGRIPA project (Sparks et al.) which compiles details of large eruptions, their deposits, and the risks they pose. In December 2009, Ratdomopurbo and Sian Crosweller of the VOGRIPA project spent a week at the Smithsonian for coordination of WOVOdat, VOGRIPA, and the Smithsonian's database. Widiwijayanti spent a week in Japan coordinating with NIED and the Geological Survey of Japan.

#### Plans for 2010

- Complete development of basic data I/O and visualization utilities. Several previous volcano database projects (e.g., GEOWARN, MULTIMO, EXUPERY, DIVO) have developed excellent visualization tools and we will selectively adopt rather than reinvent the wheel.
- Continue the main data population phase, working first with data that are already wellorganized and in digital formats. WOVOdat staff will write scripts for data reformatting
  and importation as needed, first in Singapore and later at field observatories.





## Laboratory Volcanoes: Gede & Salak, West Java

#### **Principal Investigator**

• Prof Chris Newhall, Earth Observatory of Singapore

#### Collaborators

- Surono (Director) and staff of Centre of Volcanology & Geological Hazard Mitigation (CVGHM), Indonesia
- J Pallister and staff, U.S. Geological Survey, Volcano Disaster Assistance Program
- Fidel Costa, Dannie Hidayat, Florian Schwandner, Mariton Bornas, Alexander Belousov, Marina Belousov, Chris Harpel (EOS)

Gede and Salak, high-risk volcanoes in West Java, are representative of many arc volcanoes that show only minor visible degassing yet exhibit seismic swarms (Gede) and thermal features (Salak) that suggest recent magma and gas input from depth. In the spectrum of open to plugged conduits, Gede and Salak are intermediate to plugged. This project will study past magmatic and eruptive processes, and upgrade geophysical, geochemical, and hydrologic monitoring — all to anticipate the next eruption of either volcano. The study will attempt to quantify magmatic gas budgets. One or two research wells will also be drilled in hopes of measuring transient, intrusion-induced increases in pore pressure that may contribute to multiple sector collapses at both volcanoes.

In 2009, three reconnaissance geology visits involving colleagues from EOS, CVGHM and USGS VDAP produced several highlights:

- One prominent debris avalanche deposit extending east from Gede has a high percentage of relatively fresh lava blocks, though a few hummocks contain remobilized pyroclastic flow and tephra deposits (and, reportedly, datable wood). The radiocarbon age of a paleosol that immediately overlies the avalanche deposit was ~5100 <sup>14</sup>C y BP, and two ages on soil from within the debris avalanche were ~5200 <sup>14</sup>C y BP and ~10,900 <sup>14</sup>C y BP.
- Charred and uncharred wood from a stack of lahar and pyroclastic flows deposits of Gede gave ages of the most recent large (VEI=3-4?) explosive eruptions and their recurrence frequency. Six ages are clustered around 1250 <sup>14</sup>C y BP; one from a different location was ~6850 <sup>14</sup>C y BP.
- Gravel quarries in the alluvial fan of Bogor contain thick lahar deposits from Salak and Pangrango. Some buried trees remain in growth position and can be dated with <sup>14</sup>C and tree-ring dating. Contrary to our expectations, these were not from a 1699 Salak event. Instead, three ages ranged from ~4100-4500 <sup>14</sup>C y BP.

Other activities in 2009 consisted of hiring staff, designing the expanded network, and choosing and ordering equipment for monitoring purposes. A Memorandum of Understanding (MoU) between EOS-NTU and CVGHM-Badan Geologi is still under negotiation. Once this is signed, field work will get underway.

#### Plans for 2010

The overall goals are to learn (a) how magma of Gede and Salak is supplied, ascends, degasses and erupts, and (b) why these volcanoes collapse as often as they do. That is, we will study how these examples of moderately plugged arc volcanoes "work," and whether their plugging may contribute to their relatively frequent collapses. Massive sector collapses can occur because volcanoes become oversteepened, because their rock weakens from hydrothermal alteration, or because transient increases in pore-fluids lower friction and thus slope stability. Deposits and monitoring will contain some clues to why Gede and Salak have so many collapses.





#### CLIMATE GROUP



#### Regional Climate Downscale of El Nino and Indian Ocean Dipole

#### **Principal Investigator**

Asst Prof Koh Tieh-Yong, School of Physical and Mathematics Science, NTU

The project aims to elucidate the impact of El Nino-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) on temperature, wind and rainfall in the Western Maritime Continent, including the Malay Peninsula, Sumatra, Borneo and Java. 25-year re-analysis data for Japan was used to obtain present-day ENSO and IOD patterns for this highly convective region. Hypotheses on the factors affecting the regional climate were tested with model simulations. Understanding the current regional climate is a necessary first-step in EOS' objective of addressing climate change in Southeast Asia.

The project began in August 2009 with the following goals: (a) installation of a High Performance Computing (HPC) cluster; (b) set-up of a numerical model; (c) validation of the downscaling method. We assisted the High Performance Computing Centre (HPCC) at NTU to set up and pilot-test a new 2400-core HPC cluster, dubbed "Nanyang Analytics", providing suggestions and solutions to HPCC@NTU. We set up two numerical models of the atmosphere, a Non-Hydrostatic Model (NHM) and a Weather Research and Forecast (WRF) model, in the new HPC cluster. We completed a few trial runs, from the short term (a few hours) to longer term (one year) using both NHM and WRF. We conducted model performance assessments using reanalysis data and satellite derived data and saw vast improvement to rainfall variability introduced by the downscaling method (Fig. 1). All the above were achieved in collaboration with Temasek Laboratories @ NTU.

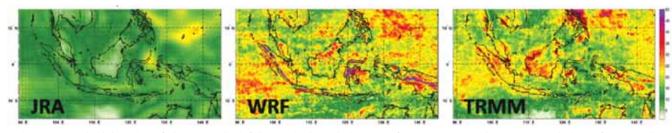


Figure 1: Standard deviation of 6h-averaged rainfall intensity (mm/day) in 2004 from JRA, WRF and TRMM at resolutions of 1.25°, 20km and 25km respectively.

#### Plans for 2010

In the next year, we will continue our efforts to adapt WRF and NHM in the Maritime Continent. We plan to compare the results between preliminary simulations with WRF and NHM.



The Scientific Advisory Board (SAB) of EOS held its 2nd annual meeting in Singapore at the end of January 2010. During the 3-day meeting, the Board reviewed all research project proposals and related scientific posters, including progress reports on ongoing projects as well as new submissions. Additional proposals from the Artist-in-Residence and Education & Outreach Office were also reviewed. The SAB met with the EOS Governing Board and, in follow up to the annual meetings, submitted comprehensive comments on individual proposals to the EOS Director. These were discussed with the management team and the SAB's feedback was then channelled to the individual PIs and project leaders.

New research projects approved for 2010.

#### **TECTONICS GROUP**

**Kinematics of the Bengal-Assam Syntaxis**Principal Investigator: Prof Paul Tapponnier

Discrete Element Modelling of Fault Nucleation and Propagation in Collision Zones

Principal Investigator: Prof Paul Tapponnier

Morphology and Paleoseismology of the Main Frontal Thrust in Nepal

Principal Investigator: Prof Paul Tapponnier

**Earthquake Ruptures in China: Testing Seismic Fault Behavior Models** 

Principal Investigator: Prof Paul Tapponnier

Integrated Seismic and Tsunami Hazard Assessment of West Sumatra, Indonesia

Principal Investigator: Asst Prof Kusnowidjaja Megawati

A Geoarchaeological Investigation of Paleo-tsunami and Paleoseismic Activity in Northern Sumatra, Indonesia

Principal Investigator: Prof Kerry Sieh Co-investigator: Asst Prof Adam Switzer

Modeling Submarine Landslide Tsunamis with a Case Study for Vietnam

Principle investigator: Asst Prof Zhenhua Huang

#### **CLIMATE GROUP**

**High-Resolution Sea-level History on the Sunda Shelf, Near Borneo, over the Past 2000 Years**Principal Investigator: Asst Prof Adam D Switzer

Geological Records of Coastal Hazards from QingAo Bay, Nanao Island, Northern South China Sea Principal Investigator: Asst Prof Adam D Switzer

#### **VOLCANO GROUP**

Reconstructing the Plumbing Systems and Dynamics of Magmatic Processes below Active Volcanoes
Principal Investigator: Asst Prof Fidel Costa

**Exploratory Projects on Volcanoes** Principal Investigator: Chris Newhall

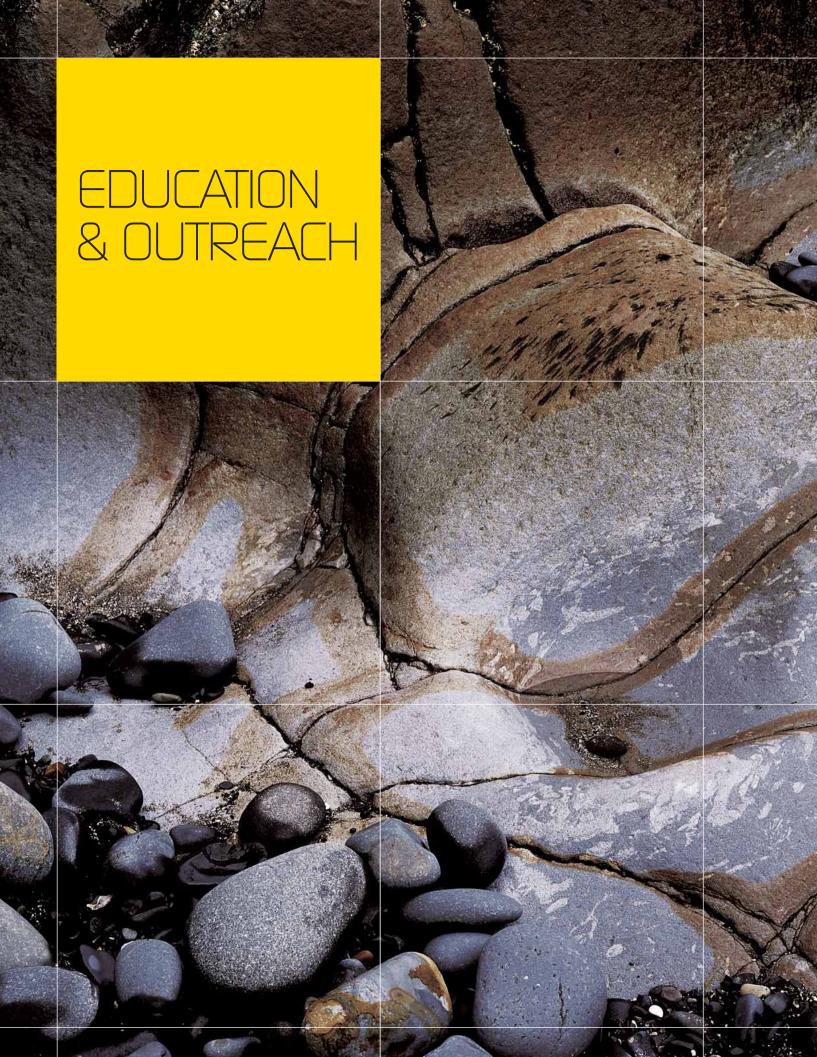
#### **EDUCATION & OUTREACH**

Our Dynamic Earth: An Earth Science Exhibit, Singapore Science Centre

Project Leader: Sharmini Blok

#### **ARTIST-IN-RESIDENCE**

Mayon: The Volcano Princess 'Earth Girl' animated featurette 'Sudden Nature' multimedia project Project Leader: Prof Isaac Kerlow





#### **ARTIST-IN-RESIDENCE**

#### **Prof Isaac Kerlow**

School of Art, Design & Media (ADM)

#### Video documentaries

People-Coral-Mentawai

This video documentary, by Isaac Kerlow and his team of ADM students, follows scientists from the Earth Observatory of Singapore whose research on coral reefs off the west Sumatran coat is helping local communities better prepared for the next natural disaster. By studying coral reefs that were uplifted during earthquakes, researchers have been able to build an earthquake timeline meet the people who live in West Sumatra. The documentary was launched at a special screening at the ADM followed by a discussion between Profs Isaac Kerlow and Kerry Sieh on how art meets science.

#### Mayon: The Volcano Princess

This documentary film, also by Prof Kerlow and ADM students, was shot in the Bicol region of the Philippines in 2009. It focuses on the people who live around Mayon volcano, one of EOS' laboratory volcanoes, and how they cope with living under the threat of periodic, and potentially deadly, eruptions. The documentary contains interviews with local residents and officials, as well as an animated recreation of the tragic legend of Princess Magayon who is believed to be buried under the volcano.

## EDUCATION & OUTREACH OFFICE

The Education & Outreach (E&O) Office of EOS works hand in hand with scientists to respond to the information needs of target audiences, and to enable informed action on natural hazards affecting people in Southeast Asia. The E&O Office delivers tailored programmes and education and communication materials for educators, decision makers and practitioners from a variety of sectors. We also view the media as an important tool for educating the general public as well as decisionmakers in government and business about natural hazards in the region. For example, the 2009 Padang region earthquakes provided EOS the opportunity to communicate high-quality science through extensive coverage by local and international journalists over several weeks.

#### **School Programmes in Singapore**

In 2009, EOS launched a number of initiatives that included organising a series of earth science lectures tailored for students, piloting a teaching module on volcanoes at secondary level, and participating in a nationally televised science competition. EOS is also involved in discussions with representatives from the Ministry of Education and the National Institute of Education about contributing more earth science content to schools. An EOS representative sits on the Curriculum Planning Committee for a new H1 subject in environmental science. The E&O Office also co-developed and mounted a 6-month long exhibit to mark the 5th anniversary of the Aceh earthquake and tsunami with the Science Centre Singapore, beginning January 2010.

## visitors and delegations

Science Council Minister for Taiwan and Taiwanese university presidents visit EOS

July 2009 Delegates from ASEAN Forum on Natural Catastrophe Exposure Risk tour EOS

Prof John Beddington, UK Chief Science Advisor, visits EOS

Visit to EOS by Dr Tony Tan and NRF delegation











Aug 2009 AOGS Booth EOS staff and conference visitors



Mar 2010 Earth Science Education Workshop for school teachers by Prof Scott Graves



**July 2010** National Science Challenge Semi-final Round hosted by EOS with Prof Kerry Sieh



**July 2009** Fieldtrip to Bandung by Assoc Prof Ian McLoughlin and Prof Chris Newhall for Harvey Mudd scholars and NTU students

#### capacity building

## school programs

Kerry Sieh on the Relevance Adam Switzer at NUS High School of Earth Sciences in 21st Century Schools



Talk at National Library by Prof School Lecture with Assistant Prof



May 2009

Indonesian high school students visit EOS



#### **July 2009**

Earth Sciences Talk for BCA-Geography Teachers Association given by Prof Kerry Sieh to 90 students and teachers from secondary schools and junior colleges





July 2009 Oct 2009

EOS with Prof Kerry Sieh at Raffles Institution



National Science Challenge Volcano Module taught by Prof Chris Semi-final Round hosted by Newhall and Dr Antonius Ratdomopurbo



Jan 2010

EOS - Science Centre Singapore Aceh Tsunami 5th Anniversary Commemoration



Mar 2010

University of Tokyo students visit to EOS

## STAFFING AND FINANCE TABLES

#### EOS Manpower Buildup as at March 31, 2010

		General	Volcano	Tectonics	Climate	Total
Management		3.5	1	1	-	5.5
Principal Investigators		-	1	3	0.5	4.5
Researchers	Senior Fellow	-	6	1	-	7
	Fellow	-	-	4	-	4
	Associate	-	1	2	-	3
	Assistant	-	2	2	-	4
	Technical	-	-	-	-	-
Support	Administration	7	1	1	-	9
	Technical	4	-	-	_	4
	Education & Outreach	3	-	-	-	4
Total		17.5	12	15	0.5	45

- Management: Kerry Sieh, Paul Tapponier, Sharmini Blok, Chris Newhall, Paramesh Banerjee
- Artist-in-Residence: Isaac Kerlow\*

#### **Volcano Group**

- Principal Investigator: Fidel Costa
- Senior Research Fellows: A. Ratdomopurbo, Christina Widiwijayanti, Dannie Hidayat, Alexander and Marina Belousova, Florian Schwandner
- Research Associate: Alexandre Baguet
- Research Assistants: Lyou Chin Mei, Sergio Marcial
- Administration: Harpreet Kaur

#### **Tectonics Group**

- Principal Investigators: Adam Switzer, Kusnowidjaja Megawati\*, Ian McLoughlin\*, Huang Zhenhua\*, Goh Siang Huat\*
- Senior Research Fellow: Richard Walker (until 5 May '10)
- Research Fellows: Meya Yanger Walling, Kenneth Macpherson, Li Lin Lin, Aron Meltzner
- Research Associates: Zhang YanMei, Mary Ann McKittrick
- Research Assistants: Linus Ang, Qiu Qiang
- Administration: Clair Elaine Devan

#### **Climate Group**

Principal Investigator: Koh Tieh Yong\*

#### Support

- Administration: Linda Chua, Carol Chan, Loh Li Kiang, Bu Suxian, Oh Hwee Hong, May Pea JingMei, Gordon Ong
- Technical: Jeffrey Encillo, Mariton Bornas, Jonah Yong, Daniel Sin
- Education & Outreach: Liow Hon Sang, Elaine Chong, Pungky Utami (until 31st March)
- \* denotes half-time position

#### **Financial Summary for Fiscal Year 2009**

Categories	Budget	Actual Expenditure	Balance
EOM	\$3.802M	\$3, 628, 275.27	\$173, 724.73
Equipment	\$0	\$2, 158, 339	(\$2,158, 339)
OOE	\$7, 550, 260.50	\$5, 565, 646.23	\$1, 984, 614.27
Total	\$11, 352, 260.50*^	\$11, 352, 260.50^	\$0#

<sup>\*^</sup> Budget revised in Sept 2009

EOM = Expenditure on Manpower OOE = Other Operating Expenditure

<sup>^</sup> Amount includes 20% overheads

<sup>#</sup> In FY09, EOS had a deficit of \$144, 906.29 for overheads. As the budget allocated for FY09 was not sufficient to cover for the over-expense, the deficit was reimbursed in FY10 using the FY10's budget

