Feature

Traversing nature's danger zone: getting up close with Sumatra's volcanoes

The Indonesian island of Sumatra, located in one of the most active zones of the Pacific Ring of Fire, is characterized by a chain of subduction-zone volcanoes which extend the entire length of the island. As a group of volcanic geochemists, we embarked upon a five-week sampling expedition to these exotic, remote, and in part explosive volcanoes (SAGE 2010; Sumatran Arc Geochemical Expedition). We set out to collect rock and gas samples from 17 volcanic centres from the Sumatran segment of the Sunda arc system, with the aim of obtaining a regionally significant sample set that will allow quantification of the respective roles of mantle versus crustal sources to magma genesis along the strike of the arc. Here we document our geological journey through Sumatra's unpredictable terrain, including the many challenges faced when working on active volcanoes in pristine tropical climes.

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Our research aims to address the problem of magma–crust interaction and resulting remobilization and recycling processes along the Sumatran volcanic arc, i.e. to distinguish between source and crustal contamination of arc magmas and constrain the timescales over which these processes occur. With this goal in mind, we set out on our almost 2000 km journey from Jakarta in west Java to Medan in north Sumatra (Fig. 1), sampling and admiring geological marvels, experiencing natural and human wonders and disasters and encountering inquisitive wildlife otherwise only known to Europeans from adventure movies or *National Geographic* magazine.

Sumatra, bordering the Indian Ocean at the westernmost extreme of the Indonesian archipelago, is one of the largest islands of this vast country that stretches over 5000 km as far as West Papua and the Pacific Ocean in the east. Sumatra is formed by oblique subduction of the Indo-Australian plate beneath the relatively thick (ca. 40 km), continental crust of the Eurasian plate. The continental crust underneath Sumatra is variable in composition, but consists mainly of Mesozoic granitoids with siliciclastic and minor carbonate sedimentary rocks. This makes Sumatra an ideal place to test whether continental crust makes a significant contribution to arc volcanism. The SAGE 2010 expedition was led by Profs Valentin Troll (Uppsala University, Sweden) and David Hilton (Scripps Institution of Oceanography, USA), accompanied by Dr Lilli Freda (Istituto Nazionale di Geofisica e Vulcanologia, Italy) and three PhD students: David Budd (Uppsala University, Sweden), Ester Jolis (Uppsala University, Sweden) and Saemundur Halldorsson (Scripps Institution of Oceanography, USA) (Fig. 2). Once in Indonesia, we were joined by our translator and fixer, Mas Mahjum, and four drivers who were able to expertly navigate us through the seldom signposted, and often perilous, roads that wind their way through Sumatra's forested mountains.

SAGE 2010 set out to sample systematically the major volcanoes along a south–north transect that extends the majority of Sumatra's length. We sampled Rajabasa, Ratai, Sikincau, Sekincau, Seminung, Dempo, Kaba, Berang, Kerinci, Talang, Marapi, Sorik Marapi, Bual Buali, Helatoba-Tarutung and Sibayak (Fig. 1), which are mainly basaltic to andesitic in composition, but could not resist including the supervolcano Toba, as well as the recently erupted (August 2010) andesitic Sinabung volcano—that was still marked by strong fumarole activity in October 2010 (Fig. 3). Major and trace element chemistry, along with isotope geochemistry will be performed on these recent volcanics to obtain quantitative controls on the petrogenetic processes that give rise to Sumatran

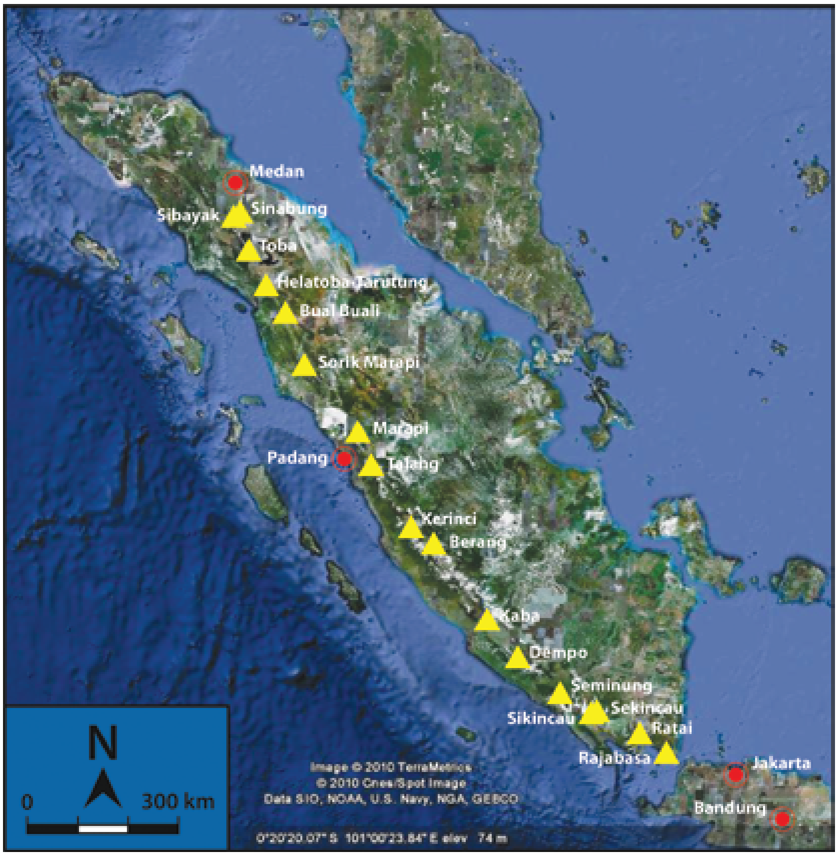

Fig. 1. Google Earth image of Sumatra Island and the volcanoes sampled during the SAGE 2010 expedition. Rock and gas was obtained from 17 volcanic centres during an almost 2000 km south–north transect of Sumatra.

volcanoes. Complementary analysis of the volcanic gases and geothermal fluids captured and subsequent modelling of these data will help assess the natural budget of various volatile species going into and out of the subduction system.

A travel journal

One of the first things we realized when arriving on Sumatra was how remote it was compared to Java. Java, where we started our expedition, is the most densely populated island in the world, at approximately 1000 people/km^2. This figure compares to 250 people/km^2 in the UK and only 96 people/km^2 in Sumatra. As we left the coast, we were surrounded rapidly by jungle, with only the odd village appearing every now and then in the shadows of dormant volcanoes. The feeling of isolation that set in during the first days was quite profound, and it became obvious very quickly that southern Sumatra is not at all developed for tourism yet. Bendy and potholed gravel tracks are often the designated major roads that come with a morning to night cuisine of rice and chilli-infused sambal sauce. Little did we realize at the start that the motorways and the Pizza Huts we would come across on the last days of the expedition near Medan would be such a sight for our sore eyes.

The wildlife on Sumatra also took some getting used to; we almost drove over a colossal monitor lizard sunning itself on the road before it scurried off into the undergrowth, and it was commonplace to have mosquitos, cockroaches and rats around for dinner (even in the nicer establishments), accompanied by an assortment of invisible bugs that would bite us during the nights (Fig. 4). Naturally, we all became ill to varying extents at some stage during the trip, however, we soon realised that it was all part and parcel of the full experience. Despite our best humour about the conditions and a jolly and adventurous spirit throughout the scientific team, when a local guide on one occasion would not take us to a remote sample location due to an infestation of venomous snakes, we did not argue too strongly.

Our sampling intention was to obtain Holocene volcanic rocks (basaltic-andesites) with co-located gas samples from 17 major volcanoes along the Sumatran volcanic range, i.e. ca. 1/100 km. The gas samples were emitted either directly from high-temperature fumaroles (preferred), or from hot springs (≤ 100 °C). Sampling often caused much interest from locals (Figs 5, 6), who are not used to seeing a group of foreigners taking such an interest in the rocks they are quarrying, or the hot springs behind their back gardens (Fig. 7), where the 'geothermal way' of boiling food is still frequently practised. When we were able to find areas where volcanic rock was exposed (e.g. quarried) or with prolific fumarole activity, sam-

Fig. 2. The SAGE 2010 team prepares for the ascent of Mount Marapi volcano. From left to right: David Hilton, Guide 1, 2 and 3, Val Troll, Ester Jolis, Saemundur Halldorsson, David Budd, Guide 4, Lilli Freda.

Fig. 3. Mount Sinabung, October 2010, still showing signs of active fumarole degassing after the recent August 2010 eruption.

Fig. 4. On a typical day in the field we would encounter a selection of weird and wonderful wildlife. This millipede was about 40 cm long and could have given us a nasty bite if we had gone too close.

Fig. 5. Gas sampling at a hot spring at Helatoba-Tarutung, with a little local help.

pling was pretty straightforward (Fig. 8). However, locating a reported outcrop or fumarole in the middle of a dense jungle on the flanks of an irregular volcanic edifice was often a little more challenging. For example, our trek into the jungle surrounding Sekincau volcano provided us with a real taste.

Once we had found a local guide willing to take us into the jungle, we set out on what was to become a >10-hour trip through dense forest and waterlogged tracks (Figs 9, 10). Rumours by villagers about a 'harimau' in these woods were a little discomforting, but then we were told that 'tigers' don't attack large groups. Relieved, we set off and our guide led the way, increasingly scything a path through dense undergrowth to locate the alleged fumarole field. After hours of uphill hiking, we descended into a densely forested crater with rather steep, muddy inner walls. Once in the crater, we were balanced on severely unstable ground, crumbling under prolonged exposure to superheated volcanic gas. Just then, the volcano gods sent us a torrential downpour, complicating any attempt to secure a pristine sample, but eventually we managed. The route back was made more difficult due to the slipperiness of the inner crater walls and a sudden infestation of very lively leeches that were awoken by the rain, something we were quite unaware of as we set off. Suddenly, these small black creatures were everywhere, on the ground, on leaves, and at every opportunity latched onto our skin to suck

Fig. 6. Andesite quarry in the volcanic crater at Lake Toba. Here we were able to sample the 1.2 Ma Harrangoal Tuff.

Fig. 7. Hot springs in the Kerinci Valley of central Sumatra. Villages are built around such features to make use of the low-level steam and hot water activity.

our blood. When we finally made it back to base, it took quite some time to remove all the critters with a sharp knife, by then swollen many times in size from feeding on us. Only after removing all the leeches and using up the first-aid disinfection fluids did we realize that we had secured some important and hard to reach gas and rock samples—mission accomplished. Or so we thought. Waiting for us at our minibus were two officials from Sekincau National Park. Despite obtaining the correct documentation from the Indonesian Geological Survey in Bandung at the start of our expedition, we had apparently failed to notify the authorities of this particular province of our sampling intention. As a result we had to be escorted bandaged, blood-stained and covered in mud, to their headquarters in order to negotiate an appropriate donation to be able to leave with our samples. Interestingly, after returning home, we found out that Chevron had just bought the exploration rights to the geothermal resources at Sekincau. They'd better be ready for what lies inside this particular bit of jungle!

The geothermal energy potential of Sumatra arises from the combined effects of heated ground waters that mix with magmatic gases circulating around molten rock in the Earth's crust. These fluids then rise to the surface to find their expression as fumaroles, hot springs, mud pools and geysers (Fig. 11). However, this 'cleaner' form of energy is currently seldom taken advantage of for commercial means in Sumatra. In fact, only on one occasion did we come across geothermal fluids that were being actively harvested: Ratai volcano. Here, a relatively large geothermal plant had been developed by Pertamina—Indonesia's own energy conglomerate—siphoning off the hot sulphurous gas and steam to heat water and generate electricity (Fig. 12). At all other hot spring and fumarole locations we sampled, the geothermal potential was left largely untapped. The notable exception being where the hot springs had been adapted for tourism, most memorably around Helatoba-Tarutung volcano, whereby calcium carbonate deposition at the hot springs had enabled enterprising locals to sculpt hot pools out of the brilliant white precipitate (Fig. 13). In other areas, on the lower flanks of many of the volcanoes, the hot waters are used as bathing and washing areas for villagers (Fig. 14). A signal of change, however, came in the form of two Australian exploration geologists we met during a stopover in Jambi province. They were from a multinational energy company and had come to Sumatra to scout out potential sites for geothermal energy exploitation, a sure signal that Sumatra's energy usage could change very rapidly. It also became abundantly clear to us that living next to volcanoes is very attractive for Sumatrans for another reason. The fertile ash deposits covering the volcano's flanks are ideal for agriculture. These areas have been exploited and converted into lowland rice paddies and highland tea and coffee plantations to provide sufficient food and a regular source of income. Near volcanoes, up to three rice harvests are possible in a single year! Cinnamon trees are also common in some highland parts of Sumatra,

Fig. 8. Volcanic outcrop perfectly located at the side of the road in the Sumatran highlands. Note the tea plantation above the outcrop. Cool enough to hammer away!

Fig. 9. Final preparations before a big jungle challenge. A school waves us off and wishes us luck for our exciting hike into the wilderness surrounding Sekincau volcano.

Fig. 10. On the way to a vital and hard to reach fumarole. A bamboo bridge over a gully forced us to refocus and find some balance.

Fig. 11. Violent and noisy fumaroles at the peak of Sibayak volcano. Bright yellow stains indicate native sulphur deposition around the fumaroles.

where they are farmed for their bark to provide spice for the flavoursome Sumatran cuisine (Fig. 15). We would often drive past considerable expanses of peeled bark on the sides of the road, drying in the sun, and at times we picked some up to make our two vans and gear smell a little more pleasant.

Having spent some time in such remote countryside, it began to dawn on us that country life is considerably more appealing than that in multi-million population centres like Jakarta, Padang or Medan due to the simple closeness to resources and the beauty and simplicity of the villages and village life. But this quiet lifestyle comes at a price: limited comfort, hard work, and a potentially active volcano nearby that can awake anytime to destroy all one's possessions in the course of a week or less.

Being located above a subduction zone, earthquakes are also not uncommon in Sumatra. The Sumatrans, though, have adapted well outside the cities, living in raised wooden houses that absorb the vibrations during a quake (Fig. 16). This provides safe and stable shelter for man and beast alike, and plenty of storage space to dry timber and hoard other necessities. However, in the big cities, all is different. Padang, the largest city in central Sumatra, has been beset with violent earthquakes, the most recent being a devastating 7.9 M event in 2009. Evidence of earthquakes is readily apparent in the city, with many of the brick and concrete buildings in a state of crumbling disrepair. During our first night in Padang, a 7.7 M earthquake hit the subducting slab 200 km offshore. The quake occurred at 21:42 local time, whilst we happened to be sitting in a restaurant, recovering after a head-on traffic accident on one of Sumatra's windy hilltop passes the night before. Lizards (geckos), normally found happily stuck to walls and ceilings, all of a sudden began to fall onto our laps and table, and the Earth started vibrating. It felt like a biblical occurrence of raining beasts. Incredibly, within hours, Mt Merapi on Java began to erupt explosively and there was sudden renewed activity at Anak Krakatau. Fortunately, the earthquake's epicentre was far enough away and caused no major damage in Padang and the associated tsunami did not make landfall on the mainland on that occasion.

After our brief stay in Padang, the approximate mid-point of the expedition, our epic journey continued towards the north-west. Throughout Sumatra, the temperature would be at a semi-constant 30 °C or above, and when combined with the oppressive humidity, it would not take long to become hot and sweaty. This situation was compounded by the intense hammering required on occasion to obtain sufficiently large rock samples, often from disagreeably hard volcanic outcrops. Every now and then we also made it to the peak of a volcano, such as the 2500 m a.s.l. Sibayak volcano in northern Sumatra. Once at cloud

Fig. 12. Geothermal power harnessed. Ratai volcano provides a lonely source of renewable energy for Sumatra; however, signs of change are on their way.

Fig. 13. Calcium carbonate deposition (travertine) at Helatoba-Tarutung is sculpted into hot pools to provide a bathing area for locals and tourists alike.

Fig. 14. Villagers near Sorik Marapi volcano have made hot springs into a washing and bathing area, providing a central meeting point for villagers and an opportunity for a warm soak.

Fig. 15. Cinnamon bark drying by the roadside. The friendly locals were happy for us to take some on-board to improve the odour of our boots and transport.

level, temperatures would drop rapidly to bring some temporary relief. At the peak, in limited visibility, we had to find an accessible fumarole to obtain a gas sample. This can create the paradoxical experience of standing next to a fumarole and sensing the >100 °C superheated acid steam, with a few steps away being chilled by the dense and moist cloud cover, at times a tough balance to maintain (Fig. 17). Also, it was important not to leave bags on the ground for too long, or they would begin to cook from the heated ground. Largely invisible acid soil degassing will cause even the best gear to eventually dissolve.

The culmination of the expedition was the visit to Lake Toba in north Sumatra, the famous supervolcano that had experienced four caldera-forming eruptions over the last 1.2 Ma (Fig. 18). It is often cited as the site of the largest volcanic eruption of the Quaternary, as Toba erupted approximately 2800 km^3 of rhyolite some 74 ka ago (YTT eruption—see below), depositing a tuff and ash layer found as far afield as India (Fig. 19). The caldera that was created is now an enormous inland lake, measuring some 100 × 30 km, in fact, the largest volcanic lake on Earth. The exposed caldera walls descend for at least 1 km before they reach water, and therefore provide excellent exposure of the older eruptive sequences at Toba. The latest and largest tuff, known as the Young Toba Tuff (YTT), is spread over 20 000 km^2 on Sumatra, and has some stunning exposures at the lake. The highly explosive YTT eruption has been linked to a bottleneck in human population some 70 ka ago, possibly the result of a prolonged volcanic winter when ice-clouds and enormous quantities of aerosols in the atmosphere reduced the incoming amount of sunlight, with severe effects on weather, climate and environments.

Once our travels were completed and we arrived in the bustling city of Medan in north Sumatra, we finally set eyes upon Pizza Hut again. We feasted on all the delicacies they had to offer over the next two days; a rare treat for our chilli-numbed taste buds. During the SAGE 2010 expedition we managed to obtain over 120 samples, with half a ton of rock to be shipped back to our research department in Sweden and several large boxes with glass flasks and copper tubes for gases to go to the USA. In Medan, it was not difficult to find a shipping company to box and send the collection back to Sweden and arrange air transport of the gas samples. We are now beginning to exploit this extensive catalogue of rocks and gases from the full transect of Sumatra for their geochemical treasures. We hope to use these data in conjunction with previous and on-going work from the Java and Bali segments of the Sunda arc in order to establish a link between element cycling, volatile production and eruptive style in arcs on a globally meaningful scale (≥ 3000 km). Our long-term plans

Fig. 16. A typical Sumatran house found in Jambi province. Pointed roofs are very much the fashion in this region, probably reminding us that the early settlers on Sumatra came by boat. Wooden design and hundreds of years of experience help mitigate disaster when an earthquake strikes as these buildings are entirely earthquake-proof.

Fig. 17. Gas sampling from a fumarole atop Sibayak volcano. The superheated acidic steam made for a challenging sample!

Fig.18. View of monumental Lake Toba. The island on the horizon to the right (Samosir Island) was formed by resurgent doming after the climactic 74 ka eruption.

Fig. 19. Hard at work on the Young Toba Tuff. This rhyolitic ignimbrite outcrop boasted an impressive mineralogy, with individual quartz crystals up to 2 cm across.

are to extend our traverse yet further, i.e. eastwards to the island of Flores and beyond, but this will take us a little while to prepare.

Although it was quite a shock to return to our respective bases in Sweden, USA and Italy, especially considering the temperature change from plus 30 degrees to minus 20 °C in Sweden at least, we were certainly happy to be back on geologically familiar and seemingly stable soil. However, it was well worth the effort as we now have a superb sample set for Sumatran volcanics, and although we may have been through some testing experiences, once back, the memories began to blur into what one afterwards can only call 'an unforgettable adventure'.

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