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ANCIENT ORAL TRADITION DESCRIBES VOLCANO–EARTHQUAKE INTERACTION AT MERAPI VOLCANO, INDONESIA

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ABSTRACT. Merapi volcano is among the most hazardous volcanoes on the planet. Ancient Javanese folklore describes Merapi's activity as the interaction between the Spirit Kings that inhabit the volcano and the Queen of the South Sea, who resides at Parangtritis beach, 50 km SSE of Merapi. The royal palace in Yogyakarta is located half-way along the hypothetical line between Merapi and Parangtritis (the *Merapi–Kraton–South Sea* axis) to bring balance between these mystical forces.

In 2006 and 2010, Merapi erupted explosively and on both occasions, earthquakes shook the region and the eruptions grew more violent in response. These earthquakes appear to influence the sub-volcanic magma supply of Merapi and a positive feedback loop has recently been postulated between the volcano and local earthquake patterns. The 2006 earthquakes clustered along the Opak River fault to the south of the volcano, which trends NE–SW, and reaches the southern sea at Parangtritis beach, the fabled residence of the Queen of the South Sea.

Our interpretation of the *Merapi–Kraton–South Sea* axis is that local folklore was used by ancient people to describe and rationalize the complex interplay between geological processes. We suggest that Merapi displayed volcano–earthquake interaction many times in the past, and not only during its most recent eruptive cycle. Although now shrouded in mystery, these oral traditions can be thought of as an ancient hazard mitigation tool, which makes them likely useful in helping to foster effective dialogues with a variety of target parties and interest groups around the volcano's slopes.

Key words: geomythology, Merapi volcano, oral traditions, record of volcano–earthquake interaction

Introduction

At Merapi, like at many other active volcanoes, humans have lived with volcanic hazards for generations, which is reflected in rich and plentiful oral traditions. History is usually remembered in folklore, religious practices, and in ceremonies, which often include offerings to avert ongoing or future destruction (Schlehe 1996, 2010; Scarth 2001; Cashman and Cronin 2008; Lavigne *et al*. 2008; Ort *et al*. 2008). Volcanic disasters provide insightful examples of how local people employ culture, religion, and ceremonies to communicate and remember risk and hazard mitigation strategies. These behaviours are collectively referred to as 'volcano' or 'disaster' sub-cultures (Blong 1984; Chester 1998; Lavigne *et al*. 2008; Dove 2008; Donovan and Suharyanto 2011), a phenomenon that is well developed around Merapi and the adjacent region to the south (Schlehe 1996; Dove 2008; Donovan 2010; Donovan and Suharyanto 2011). This diverse religious and cultural world of central Java is in part responsible for conflicts between local communities and the authorities, as scientific hazard mitigation plans and associated evacuations are not always readily accepted by the people living on Merapi's slopes (e.g. Laksono 1988; Lavigne *et al*. 2008; Donovan 2010; Schlehe 2010).

Because certain human responses to hazards are influenced by religious, societal, and cultural factors, any individual society dealing with a hazard will develop its own particular approach. A full impartial assessment of vulnerability and risk must therefore take account of the cultural and societal factors involved (Alexander 1993; Schlehe 1996; Paton and Johnston 2001; Chester 2005; Lavigne *et al*. 2008; Cashman and Cronin 2008; Donovan and Suharyanto 2011; Harris 2012). Societies as well as individuals can hold multiple beliefs simultaneously (e.g. Chester 2005), which inherently influences their decision making, and so a

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population's cultural perception of a hazard will affect preparedness and the ability of appropriate societal responses. In this context, oral traditions may serve to warn about natural hazards and to report on successful mastery of a difficult situation by a previous community (e.g. Ort *et al.* 2008; Schlehe 2008, 2010). Understanding long-lived oral traditions therefore helps to fully grasp the scale of possible processes, mechanisms, and phenomena at play in hazardous environments. It represents another facet of communication that may be drawn upon to help relay information to populations at risk by using linguistic tools rooted in culture rather than focusing on specialized scientific terminology (cf. Cashman and Cronin 2008; Potter *et al.* 2014). In this paper, we explore the cultural environment at Merapi volcano and merge this information with recent scientific advances in volcanology and volcano monitoring. The objectives of our combined historical, cultural, and scientific analysis at Merapi are to further explore the geological context of Merapi folklore and to obtain an improved understanding of Merapi's long-term behaviour. We thus investigate the value of folklore in improving the resilience and responsiveness of local communities that are faced with volcanic threats by helping to open a dialogue that combines cultural and scientific perspectives.

Oral traditions at and around Merapi

Present day cultural landscape at Merapi

Indonesia's population is estimated at ≥240 million, of whom ~60% live on Java, a region that only accounts for ~7% of Indonesia's total land area. While the average population density for the whole country is 124 people per km^2, the population density on Java is >1070 people per km^2, which is enormous compared with ~21 people per km^2 in Sweden and ~256 people per km^2 in the UK. At Merapi itself, it was estimated that approximately 1 million people live on the volcano, and that population density reaches up to 500 people per km^2 in some rural areas on the most fertile slopes (Figs 1–3). Indeed, volcanic ash on Merapi's slopes makes fertile and rich soils that produce three harvests per year, which is highly productive when compared with elsewhere in Indonesia (e.g. Marshall 2008). As a result, many people living in impoverished conditions choose to migrate further up the volcano's flanks to seek out a better living (Lavigne *et al.* 2008). In addition to promoting the development of fertile soil, volcanic eruptions at Merapi also provide rock and gravel from block-and-ash flow deposits, which is mined as building material. Several thousand sand and gravel miners work in the hazardous lahar-filled channels of Merapi despite the high risks involved, because the income from this work is about three times higher than that of a lowland rice farmer (Lavigne *et al.* 2008). Thus, risk acceptance is financially attractive in the region.

In a cultural context, Indonesia hosts some 300 ethnic groups, >700 languages and dialects, and six official religions (Islam, Catholicism, Protestantism, Buddhism, Hinduism, and Confucianism), in addition to various mystic beliefs with animistic roots that influence the practices of the main faiths in the region up to today (Fig. 4; Marshall 2008; Schlehe 2010). Indeed, many people living on and around Merapi have developed a form of spiritual relationship and emotional connection with the volcano, which impacts on their perception of volcanic hazards (e.g. Dove 2008; Lavigne *et al.* 2008; Schlehe 2008, 2010). Additional cultural movements such as revivalist Hinduism, fundamentalist Islam, and rediscovered ancient mysticism all shape Indonesia's culture today and are partly interwoven (Chester *et al.* 2008; Schlehe 2010). The sacred and the secular are usually incorporated into a single conceptual framework on Java and nature is often viewed in terms of opposing poles that depend on some form of exchange to maintain an overall balance (Lavigne *et al.* 2008). Javanese society developed and continues to diversify against a backdrop of volcanic activity and

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Fig. 1. (a) Location map of Merapi and Merbabu volcanoes (red triangles), Yogyakarta city area (hatched orange) and city centre (white square), Parangtritis beach (green triangle) and the Progo and Opak river faults. The 'Merapi–Kraton–South Sea axis' (MKSS axis) links Merapi, Yogyakarta, and Parangtritis beach (dashed line). Modified after Walter *et al.* (2008). (b) Zoom in from (a). The Opak river fault is located to the east of Yogyakarta and extends for ~40 km from Parangtritis beach to the SE slopes of the volcano. A number of fault splays have been demonstrated, likely forming local fault networks. This fault system was the source of the M6.4 earthquake in 2006 and likely some of the smaller tectonic earthquakes that occurred in 2010. Note that the region is covered by young volcanic and lahar deposits, making it prone to earthquake damage (modified after Walter *et al.* 2007). (c) Oblique aerial view of Merapi, the city of Yogyakarta with the Kraton, Borobudur and Prambanan temples, and Parangtritis beach. The locations of the Progo and Opak river faults are schematically shown as lines (see text for details). (d) Close-up image of the Opak River Fault (red dashed line) south of Merapi volcano [location is shown as yellow star in (c)]. Data source: 'Java'. 7° 48′ 58.35″ S and 110° 26′ 05.27″ E. Google Earth. 8 Feb., 2013 and 23 Jan., 2014.

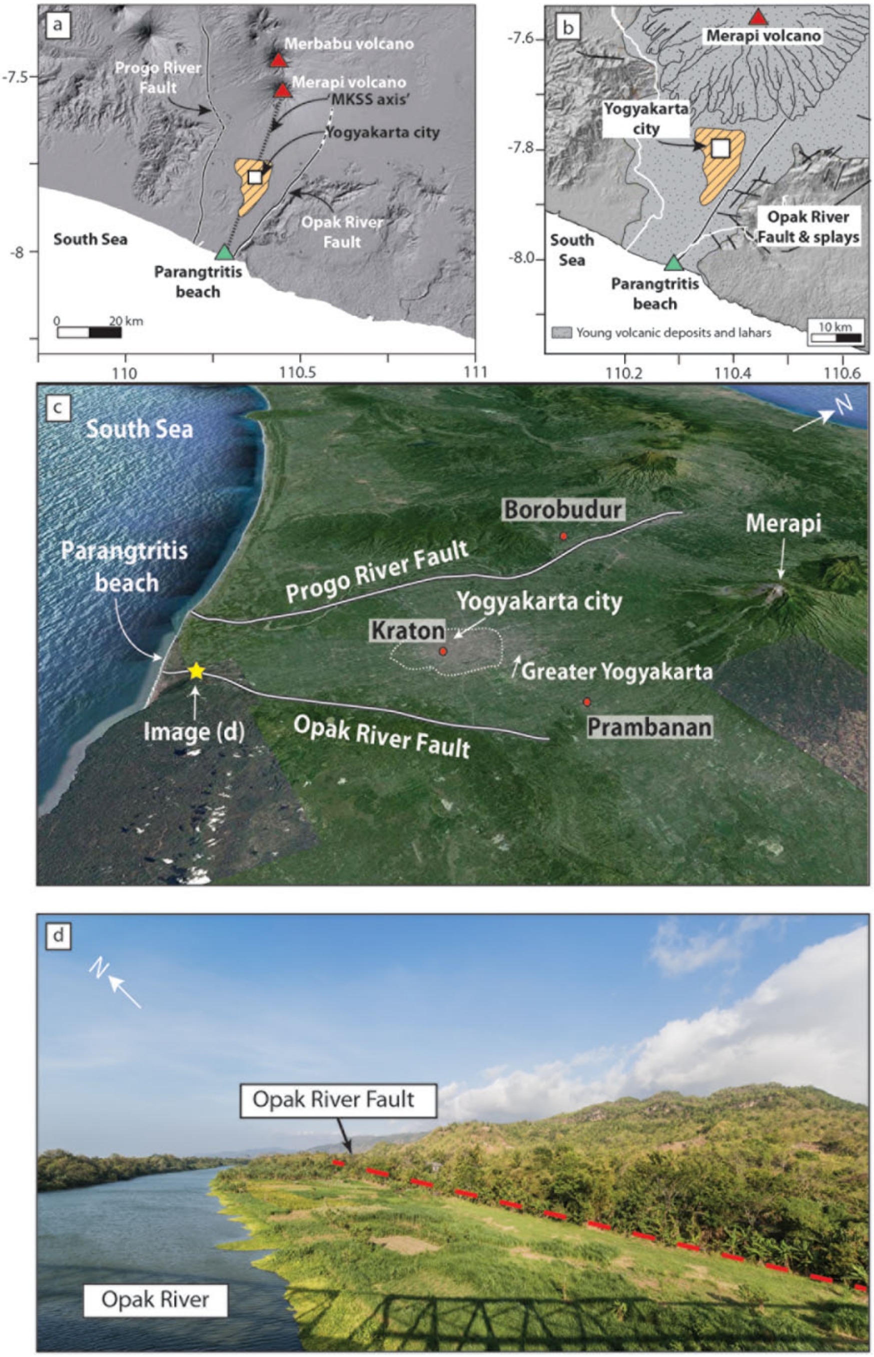
a
Merbabu volcano
Merapi volcano
Progo River Fault
MKSS axis'
Yogyakarta city
Opak River Fault
South Sea
Parangtritis beach
0 20 km
-7.5
-8
110
110.5
111
b
Merapi volcano
Yogyakarta city
Opak River Fault & splays
South Sea
Parangtritis beach
Young volcanic deposits and lahars
10 km
-7.6
-7.8
-8.0
110.2
110.4
110.6
c
South Sea
N
Borobudur
Merapi
Parangtritis beach
Progo River Fault
Yogyakarta city
Kraton
Greater Yogyakarta
Image (d)
Opak River Fault
Prambanan
d
N
Opak River Fault
Opak River

Fig. 2. Merapi volcano, Central Java. (a, b) Merapi viewed from SE, towering over the dominantly agricultural lowlands surrounding Yogyakarta. Note the open crater visible in (b). (c–f) Merapi's summit area with intense fumarole activity. The unstable pre-2010 dome is visible in (d) behind the rock spine with mountaineering group in front, for scale. (g, h) Samples of calc-silicate xenoliths from the 1998 and 2006 eruptions, respectively, provide evidence of magma–limestone interaction inside the volcano. Image in (f) courtesy of L.S. Blythe.

landscapes, and thus Javanese people often share a deeply devout relationship with volcanoes, aspects of which usually come to light during crises (Lavigne *et al*. 2008; Marshall 2008; Donovan 2010). In Java, volcanoes are considered connected to human society to achieve a universal harmony between society, nature, and the cosmos (cf. Schlehe 2010). Although most Javanese people are aware of scientific explanations for natural phenomena, they usually prefer to draw on explanations that relate natural events to their social world (Dove 2008; Lavigne *et al*. 2008; Schlehe 2010; Donovan and Suharyanto 2011). This is exemplified by the manner in which hazard awareness is propagated from one generation to the next, whereby more accessible, non-scientific imagery is used as a mnemonic-type device that is effective at all levels of society, due to the relatable nature of the concepts. Natural disasters in Java are thus usually given spiritual significance and ancient

Fig. 3. (a) View of Merapi volcano and the fertile plains of its surroundings. (b) Traditional batik of Merapi and Merbabu volcanoes, and the surrounding agricultural fields. (c) Modern batik of Merapi and Merbabu. Batiks are by popular local artists and are in the possession of the authors.

traditions are frequently revived and reinterpreted in crisis situations (Schlehe 2010). In turn, these widespread non-scientific explanations often reflect issues that are presently relevant in Javanese society and are commonly interpreted as punishment by higher powers for some form of failure or disrespect towards them (Schlehe 2010; Donovan and Suharyanto 2011). According to Schlehe (2008), many local people at Merapi related the 2006 volcano–earthquake events more or less directly to the myth of the Queen of the South Sea (see also the section 'The Queen of the South Sea, Ratu Kidul'). Legend has it that the South Sea, the Sultan's palace in Yogyakarta (Kraton), and Merapi volcano are connected along a powerful mystical axis that provides protection for Yogyakarta from destructive natural events (Fig. 1; Lavigne *et al.* 2008; Marshall 2008; Schlehe 2010).

In fact, belief in the supernatural permeates all levels of Javanese society and demographic groups (Marshall 2008), from the poorest economic classes to the ruling elites, and from young children to the elderly, all of whom partly engage in ceremonial rituals and sacrifice. For example, prior to his death in 2010, many politicians made it a point to visit Mbah Marijan, the spiritual Gatekeeper of Merapi who lived on the flank of the volcano (Marshall 2008; Schlehe 2010). His role was to protect the slopes of Merapi and the city of Yogyakarta by appeasing the spirits inside the volcano (Marshall 2008; Schlehe 2010; Donovan

Fig. 4. (a) Borobudur Buddhist temple built in the late eighth to early ninth century. (b) The deity Tara depicted at Borobudur. (c) Detail of wall relief at Borobudur. (d) Mendut Buddhist temple, built in the ninth century and located about 3 km east of Borobudur temple. (e) Prambanan Hindu temple, built in the ninth century. (f) Sambisari Hindu temple, built in the ninth century and located about 8 km east of Prambanan Temple. (g, h) Numerous calc-silicate xenolith inclusions are found in the building stones of the temples hinting at Merapi's active eruption record over the past 2000 years.

and Suharyanto 2011). When asked about the dangers of Merapi in 2006, the spiritual gatekeeper replied: 'The creatures will protect us', demonstrating that for him the official hazard alerts were mere guesses by men far removed from the volcano (Marshall 2008). Tragically, in October 2010, together with over 250 others, Mbah Maridjan was killed by a pyroclastic flow (Donovan and Suharyanto 2011; Surono *et al*. 2012). This event underlines an acute need to blend scientific concepts with the more spiritual hazard perception prevalent in many parts of Java in order to reach through to all target groups, particularly those at high risk but who nevertheless resist evacuation.

On the other hand, there are strong tendencies in other parts of Javanese society at present, such as within fundamentalist Muslim circles, to rid Islam of pre-Islamic and outside influences, including 'heretical' references to spirits and volcanoes (Marshall 2008; Schlehe 2008). For example, Islamic relief workers who were brought to Yogyakarta during the 2006 disaster vowed to disrupt the rituals held on the volcano (Marshall 2008). Moreover, the Sultan, a devout Muslim, states that Merapi's eruptions are natural events with a scientific explanation (Marshall 2008; Schlehe 2008), thus causing frustration with those that believe in spirits or a pantheon of controlling deities and higher mystical forces. The latter groups think that Merapi and the South Sea are connected to the rulers of Mataram (see the section 'The Merapi–Kraton–South Sea oral tradition'). Many such people blame the Sultan for volcanic disasters because of his reluctance to engage in balancing the spiritual forces in the region (Schlehe 1996, 2008). People also criticized recent building activity in the Opak River area, as it may have disturbed the river's 'road for the spirits' (Schlehe 1996). Similarly, some argue that the new buildings of Gadjah Mada University in the north of Yogyakarta have broken the spiritual connection between Merapi, the Kraton, and the South Sea (Schlehe 1996. 2008), as apparently 'evidenced' by the notable damage to these buildings during the 2006 earthquake. Many local voices said Ratu Kidul, the 'Queen of the South Sea' (Fig. 5), had sent the 2006 earthquake (Schlehe 2008), while others suggested that it came from Allah to remind people to adhere strictly to Islamic rules, thus reflecting the complex spectrum of beliefs in current Javanese society (Schlehe 2008, 2010). Presently, Islam (literal meaning: submission to the will of God) is the strongest religious influence in this region. For its followers, suffering is viewed as a test of faith and God is thought to use disasters to remind people about the prophet's teachings (e.g. Schlehe 1996; Chester and Duncan 2007). In fact, a large fraction of Javanese people (>90%) consider that losses associated with eruptions are under the control of some form of divine or supernatural force (Schlehe 1996, 2008; Dove 2008; Lavigne *et al*. 2008). On Java, deities are therefore often invoked as the agents of death and destruction, which can result in an attitude of passive acceptance. However, death and destruction are regenerative in Javanese belief systems and death is viewed by many as helping to re-achieve a natural and spiritual balance. This also reflects an element of great humility and a willingness to sacrifice in search of peace and harmony for society as a whole (Lavigne *et al*. 2008).

A major problem in Java, therefore, is ensuring that local people follow the hazard mitigation directives issued from their local authority that are based on scientific understanding of volcanic behaviour (Marshall 2008). Local resistance to official mitigation plans and resettling programmes to move people from endangered areas is strong as, for example, the number of harvests away from Merapi's slopes would decrease and livestock is not usually supported by resettlement programs (Lavigne *et al*. 2008; Donovan and Suharyanto 2011). Moreover, people know intuitively that the risks of living in newly settled areas, for example on Sumatra, are statistically as high or higher than the risks imposed by the volcano (Laksono 1988; Schlehe 1996), thus strengthening resistance to governmental resettling and evacuation policies (Lavigne *et al*. 2008). The rich local myths, legends, and ceremonies further reinforce the attachment of local people to their villages and settlements and give at times a distorted sense of 'immunity' to these local communities (Lavigne *et al*. 2008; Donovan 2010). Despite extensive emergency plans at Merapi, local residents do not always follow official warnings, and sometimes even refuse to evacuate. For example, residents along the Gendol River refused to evacuate in 2006, even though they were exposed to eruptive hazards, choosing instead to trust their traditional beliefs in protector spirits that reside inside the volcano (Donovan 2010). Also, during the 1994 and 2006 eruptions, the poor residents of the Boyong valley were evacuated, but returned to their settlements daily despite a ban by the authorities. The threat of looting and the risk to livestock posed a greater apparent immediate risk to them than the volcano (Lavigne *et al*. 2008). This short-term risk perspective creates reluctance among the local population to abandon property and livestock. At the time of the 2006 eruption, more than 80% of Merapi residents interviewed either refused to evacuate or did so on a part-time basis, leaving their livestock and homes only at night. The complex and intricate behavioural pattern by some communities at risk is counteractive to the volcanologists' and civil protection authority's efforts. As seemingly many local people do not, or only reluctantly, respond to

Fig. 5. (a) Horse-drawn carriage on Parangtritis beach. (b) Parangkusumo shrine near Parangtritis beach. This site is believed to be the location of the first encounter between Ratu Kidul and Senopati. Flowers and incense gifts at the entrance of the temple are offered as a gift to the Queen during the ceremony in her honour (c, d). (e, f) Traditional batik paintings of Ratu Kidul, Queen of the South Sea. (e) Ratu Kidul rides a dragon and holds a trident. (f) Ratu Kidul rides her chariot out of the waves and onto land. Batiks are by popular local artists and are in the possession of the authors.

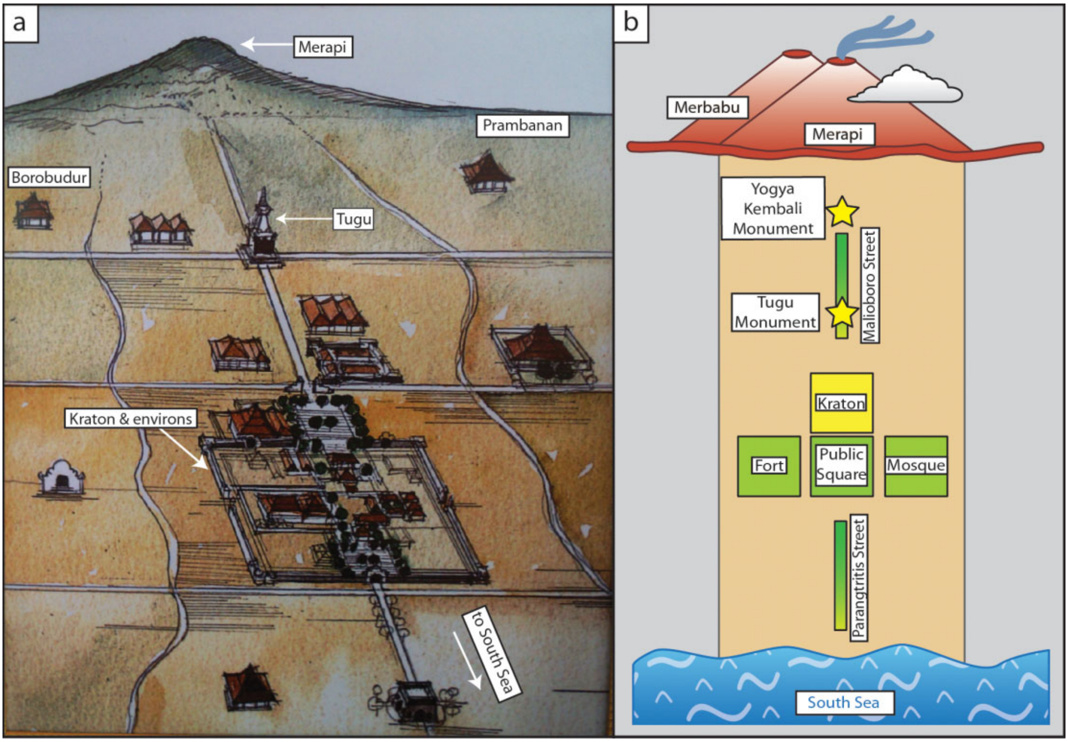

Fig. 6. Impressions of the evolving MKSS axis through time. (a) Photo of a painting of the MKSS axis displayed in the Kraton in Yogyakarta (annotated by the authors). Note the absence of the Yogya Kembali monument from the painting, indicating that the painting pre-dates construction of the monument in 1985. (b) Schematic representation of the MKSS axis (modified after Lavigne *et al*. 2008) with traditional and relatively recent constructions in Yogyakarta marked (e.g. Kembali monument). The MKSS axis continues to be a major control on city planning up to the present day.

scientific and official warnings of potentially serious (even fatal) volcanological threats, a necessity to understand the cultural and social dynamics of these communities becomes mandatory (Donovan 2010).

The Merapi–Kraton–South Sea oral tradition

Natural disasters such as violent volcanic eruptions often become the core of legends (e.g. Duffield 2001). Worldwide, many such myths and legends have been linked with geological studies and are found to be a useful source of information concerning the types of volcanic hazards posed by a region and the responses that have been taken by a specific community in the past (e.g. Blong 1984; Duffield 2001; Cronin and Cashman 2008; Chester and Duncan 2007).

Merapi in Central Java is among the most hazardous volcanoes on the planet, and ancient Javanese folklore describes Merapi's activity as the interaction between the spirits that inhabit the volcano and the Queen of the South Sea, who resides off Parangtritis beach, ~50 km SSE of Merapi. The royal palace in Yogyakarta (Kraton) is located half-way on a hypothetical axis that connects Merapi and Parangtritis (the *Merapi–Kraton–South Sea* axis or *MKSS* axis; Figs 1 and 6) to bring balance between these mystical forces (Schlehe 1996). In Yogyakarta, the axis is also marked by the Tugu and the Yogya Kembali monuments, the former being an obelisk-type spine that commemorates the creation of the Yogyakarta Sultanate, while the latter is a modern pyramid-shaped memorial dedicated to the Indonesian National Revolution (Fig. 7).

In this local legend, which is very popular on all levels of Javanese society, the Queen of the South Sea promised the founder of the Mataram kingdom (effectively the region of Central Java) that she

Fig. 7. Architectural elements of the MKSS axis. (a) Yogya Kembali monument (1985), built to commemorate the recapture of Yogyakarta during the revolution years (1945–49). (b) The Tugu monument (built in 1755) commemorates the establishment of the 'Yogyakarta Special Region' and is a symbol of unification in Yogyakarta. (c) The Royal Palace of Yogyakarta (the Kraton), was built in 1755. (d, e) Taman Sari, known as the Water Palace of the Sultanate (built in 1765) is located within the Kraton district.

would protect him and his offspring against the hazards from nearby Merapi and other outside threats (Schlehe 1996). The present-day (Islamic) court of Yogyakarta still performs annual rituals that have for many centuries helped the people of Yogyakarta to feel protected, such as the Labuhan ceremony (Ras 1987; Schlehe 2010). In this context, the earthly kingdom of Yogyakarta maintains strong ties to the mystical kingdoms of Merapi and that of the South Sea. These three kingdoms are connected by major rivers (Fig. 1), the Opak and Progo rivers, on which the sea spirits are said to travel, using drawn carriages to visit the Kraton or Merapi.

The spirit world of Merapi

At just under 3000 m a.s.l., Merapi towers over the surrounding Central Javanese lowlands and ranks among the most active volcanoes in the world (Figs 2 and 3; Marshall 2008; Surono *et al*. 2012). Javanese society has great respect for the volcano and it plays an important spiritual role for people on its slopes, which is reflected in many local legends and illustrations (Fig. 3). In Hindu traditions, mountains usually symbolize heaven and ancestors (Karsono and Wahid 2008) and the journey from the mountains to the sea reflects the overall cycle of one's life. The owner of one of Bali's top newspaper and television stations states that 'Volcanoes are the thrones of the gods' (Marshall 2008). Indeed, for many in Central Java, Merapi hosts a subterranean spirit world which interacts with the other mystical realms of the region.

The founding legends on Merapi revolve around a common creation theme. When the gods created the Earth (Java), it was not balanced because a large volcano stood in the west of Java, 'Mount

Jamurdipo'. The gods wanted to move the mountain to Central Java, while two brothers, Rama and Permadi, wanted to forge a mystical dagger at that site. When the two brothers insisted to stay, the gods became angry and threw part of Jamurdipo volcano at them. The thrown lump of the volcano became Merapi. Further lumps were thrown, which became Merbabu and Sumbing volcanoes (Fig. 3; Handojo 1985; Jordaan 1987; Schlehe 1996). The two brothers were buried under the first lump and so became the rulers of 'Merapi', which likely means the 'fire of Rama and Permadi' (e.g. Schlehe 1996). Villagers near Merapi believe that a spirit court or kingdom is present inside Merapi, ruled by these two spirits (Rama and Permadi). The Merapi spirit court (or kingdom) is similar to that of the Sultan in Yogyakarta, consisting of soldiers, workers, servants, and an entire population of spirits, some with great popularity in certain villages (e.g. Mbah Petruk to the north of Merapi). The Merapi court is thus envisaged as an elaborate realm, including roads, vehicles, and even pets. The ancestral spirits of those who grew up on Merapi's flanks are said to live inside Merapi where they work as courtiers. Occasionally, ancestral or popular spirits are said to appear and give messages of warning (Schlehe 1996). In turn, if the Merapi court needs a new worker, a person on Merapi's flank or dome will die (Jordaan 1987; Schlehe 1996). It is further rumoured by some that there is a secret tunnel connecting the kingdom of Merapi with the kingdom of the South Sea (Schlehe 1996).

In an Islamic and a socio-political context, the kingdom of Mataram (since ~1600 AD) always felt protected from Merapi, and the court chronicles detail the connection between the Sultan of Yogyakarta, the spirits inside Merapi, and of course with the mystical Queen of the South Sea (e.g. Jordaan 1987).

The Queen of the South Sea, Ratu Kidul

Ratu Kidul, the Queen of the Sea, is the ruler over fresh and salty waters, on Earth, in the oceans, and in the clouds (Resink 1997). She is in control of the violent waves of the Indian Ocean from her residence offshore and she is usually portrayed as a beautiful woman in green, rising from the depths of the ocean (Schlehe 1996; Jordaan 1997). The colour green is her favourite and it is forbidden to wear it along the south coast of Java. The Queen of the South Sea has the power to take lives, such as those of fishermen or visitors to the beach, but she is also a provider who assures safety and prosperity (Fischer and Danandjaja 1994). The devotional paintings to the Queen by local artists and the annual offerings reflect her immense popularity to the present day (Schlehe 1996; Resink 1997). In her honour, the Labuhan ceremony is held and gifts are sent afloat into the sea (e.g. Schlehe 1996). Belief has it that she either gives out fortune or misery, depending on how offerings are made, and that she is dangerous to those who disrespect her or her authority (e.g. Fischer and Danandjaja 1994). Offerings of food, flowers, fabric, and clippings of the Sultan's hair and nails are meant to ensure balance between Merapi, the Kraton, the people of Yogyakarta, and the South Sea, thus guaranteeing the region's safety from natural disasters (e.g. Fig. 5; Schlehe 1996; Resink 1997; Dove 2008; Lavigne *et al.* 2008; Marshall 2008).

Before turning into the powerful Queen of the South Sea, Ratu Kidul was a young princess from West Java named Dewi Kandita, a once privileged girl that was pushed aside by court intrigue (Jordaan 1987). Part of the reason was that Dewi Kandita suffered from a skin disease and her body smelled of fish (Jordaan 1987, 1997). When the disfigured princess arrived at the South Sea and immersed herself into the waves, her beauty was suddenly restored. She discovered that she had become a mermaid with the status of a Queen and the ruler of the South Sea (Fischer and Danandjaja 1994).

Senopati, founder of the Mataram kingdom (ruled from 1584 AD to 1601 AD), is said to have had a vision as a young man to visit the South Sea to meditate (Fischer and Danandjaja 1994; Resink 1997). Parangkusumo, near Parangtritis, is the alleged place of the encounter between Ratu Kidul and Senopati. Ratu Kidul, alerted by his prayers, emerged and took him to her kingdom under the sea (Fischer and Danandjaja 1994; Schlehe 1996). Senopati spent three days and three nights with the Queen and she educated him in strategy, magic, and art. When Senopati departed, the Queen promised that she would help him or his offspring whenever help was required (Jordaan 1987; Fischer and Danandjaja 1994; Schlehe 1996). In 1633, Senopati's grandson Agung (1613–1645) adopted the title 'Sultan' and installed the Islamic calendar. To this day, Ratu Kidul is said to support the Javanese Sultans (Jordaan 1997). In fact, in a mystical context, it is the relationship with Ratu Kidul that 'enables' the Sultans to rule the state (Resink 1997). Therefore, to this day, Ratu Kidul visits the

Sultan of Yogyakarta on occasion, either in his palace to observe the dances, or in the Water Palace, the 'heavenly garden' in the Kraton district in Yogyakarta (Fig. 7; Epton 1974; Resink 1997). In this case, the Queen travels over land, as frequently depicted in batik paintings, where she is illustrated as driving her sea-dragon or horse-drawn chariot out of the waves (Fig. 5; e.g. Schlehe 1996). Local stories report that she then travels on the Opak River to the Kraton or to Merapi (Fischer and Danandjaja 1994). When she travels on the river, 'drums accompany her journey' and local sources furthermore report that the Queen's spirit bodyguard beats percussions when she travels upstream to Yogyakarta or Merapi (Epton 1974; Resink 1997). Her visits ashore are usually accompanied by spring tides or shaking of the ground itself (Epton 1974; Jordaan 1997; Resink 1997). In fact, around the Opak River, coconuts, fruits and palm sugar are offered to the travelling spirits to prevent flooding, earth slides and minor earthquakes (e.g. Jordaan 1987; Schlehe 1996). The traditional reason that is often cited when people drown or disappear in a river in Central Java is that 'the spirits needed a servant' (Schlehe 1996), and that 'a life' claimed by the spirits will help restore the imbalances in the cosmic harmony.

The Kraton

Yogyakarta's city plan follows an elongate but concentric pattern, with the Sultan's palace (Kraton) in the centre (Fig. 6; Karsono and Wahid 2008). Kraton is the official centre of government in Yogyakarta and an impressive representative building that aims to symbolize the greatness of the Javanese rulers (Fig. 7; e.g. Karsono and Wahid 2008). Merapi holds significant symbolism for the Sultans of Yogyakarta as part of the MKSS axis tradition. The axis is expressed in Yogyakarta through Malioboro street (nowadays the main commercial street), the Tugu monument and the squares around the palace (Figs 6 and 7), which connect to Parangtritis street and ultimately the South Sea, thus establishing physical alignment between the spirits of Merapi, the Sultan of Yogyakarta, and the Queen of the South Sea (Jordaan 1987; Schlehe 1996; Lavigne *et al.* 2008; Karsono and Wahid 2008).

The centre of this alignment between Merapi and the South Sea is considered especially rich in spiritual power (Fig. 6; Karsono and Wahid 2008; Lavigne *et al.* 2008). On the other hand, such junctions can be a source of disaster if the balance of forces is not maintained (e.g. Schlehe 1996) and usually it is assumed that only a selected few, such as the Sultan, possess the spiritual power to control the forces within the alignment (Schlehe 1996; Karsono and Wahid 2008). At Yogyakarta court, the Queen's relationship to Senopati, and later Sultan Agung, is honoured in the annual Labuhan celebration. Clippings of the Sultan's hair and fingernails together with elegant fabrics, food and incense are brought in an elaborate ritual procession from Yogyakarta to Parangtritis and simultaneously to Merapi volcano where they are presented as offerings, thus strengthening the MKSS axis through ceremony and tradition up to the present day (Schlehe 1991; Fischer and Danandjaja 1994; Lavigne *et al.* 2008).

Notably, the Kraton was constructed long after the original urban settlement of Yogyakarta had been laid out. The Kraton and associated buildings function as a landmark, which was purposefully placed to shape the city and align the Sultan of Yogyakarta with the 'natural forces' of the region (Schlehe 1996; Karsono and Wahid 2008). Specifically, in 1755 AD the centre of government for the Sultanate of Yogyakarta moved from Gamping to the Kraton and can only be viewed as 'taking seat' in the middle of the Merapi–South Sea axis (Karsono and Wahid 2008). The delicate balance the Sultan needs to maintain is between gaining power from this central position versus the political risk of being responsible for imbalance between these major forces. For example, the Sultan's palace was severely damaged by an earthquake in 1867 AD and although it was already renovated by 1889 AD, the incident was viewed by many as a wake-up call to resist Dutch overlordship as the 'overall harmony' of forces in the realm was 'obviously' no longer in balance (e.g. Schlehe 1996). Probably as a result of such long-lasting beliefs, the Yogya Kembali monument was erected in 1984–1989 on the MKSS axis, which commemorates the struggle for independence, thus bringing back an element of natural balance to the realm (Figs 6 and 7).

Historical background

Yogyakarta, located in the centre of the MKSS axis, reflects fundamental influences from Hinduism, Buddhism, and Islam (Karsono and Wahid 2008). The principal urban arrangement follows the ancient Hindu concept of space and aims to connect human environments with natural landmarks (e.g. Jordaan 1997; Lavigne *et al.* 2008).

Cities in Indonesia are often influenced by concepts established in India and that came to Indonesia around the fourth to fifth century. This is reflected by many Hindu-Javanese names still in use, such as the 'Progo' River (Jordaan 1984, 1997; Karsono and Wahid 2008). Conceivably, the arrival of Hinduism in Java integrated local pre-Hindu concepts and these ancient beliefs appear still influential in the city structure and its planning up to today (Karsono and Wahid 2008). Indeed, the MKSS axis features in the city's layout in the form of the main road system, which follows a NNE–SSW main traffic axis (Karsono and Wahid 2008). The Yogya Kembali monument, the Kraton, the market square, the Tugu monument, Malioboro Street, and the central mosque (Fig. 7), i.e. a whole cluster of civic and sacral buildings, are thus thought to balance the natural forces of Merapi and the South Sea (Schlehe 1996; Karsono and Wahid 2008; Lavigne *et al*. 2008).

Specifically, the Sultan's Palace was founded in 1755 AD and the Tugu monument was built shortly after to commemorate the establishment of the Yogyakarta Sultanate, both of which were built in line with the MKSS axis (Fischer and Danandjaja 1994). The Mataram Sultans were clearly exploiting the pre-existing beliefs, a situation somewhat similar to, for example, Christian churches in Europe which are often erected on former pagan sites. The Sultan's mosque is very close to the Kraton, as is the former fort, thus enabling the Sultan to claim religious and political lordship over land and sea (cf. Karsono and Wahid 2008). In this context, Senopati's mystical relationship with Ratu Kidul (dated ~1600 AD) reflects the Mataram Dynasty's initial approach towards integration of Islamic, Hindu and indigenous Javanese beliefs (e.g. Jordaan 1997), a relationship the Mataram dynasty actively maintains to the present day (Resink 1997).

Indeed, looking through time, a rich Hindu and Buddhist culture pre-dates Islam. Prambanan Hindu temple, located ~17 km east of Yogyakarta, is almost 50 m tall and was built in the ninth century (Fig. 4). The main temple comprises three shrines that are dedicated to Shiva, Vishnu, and Brahma and each of them is opposing a smaller shrine dedicated to the cow Nandi, the eagle Garuda and the swan Angsa. Prambanan was a major religious centre at the time, with panoramic views over its surroundings, including Merapi in the north and the Southern Ocean.

Buddhist shrines are also common in the region with Borobudur being the most famous. Borobudur was erected between the late eighth and the early ninth centuries (Fig. 4) by the Saliendra dynasty (Jordaan 1997) and is located *c*. 30 km NW of Yogyakarta. When Buddhism decreased in Java, Borobudur was abandoned and was only rediscovered in 1814. The decline of Buddhism on Java followed the disappearance of the Saliendra dynasty. The consequent further development of Hinduism likely intensified the Hindu aspects of the MKSS oral tradition (Jordaan 1997).

A number of Buddhist and Hindu mother-goddesses, e.g. the deity Tara, take on a variety of forms and are readily connected with the destructive and beneficial aspects of Ratu Kidul (Jordaan 1997). The cult of Tara of north-east India dates from the third to fifth centuries (Jordaan 1997) and likely influenced the legend of Ratu Kidul. Tara, who is also associated with the colour green, is one of the most celebrated deities in Bengal and is linked to both Hindu and Buddhist traditions (Fig. 4b; Sircar 1967; Jordaan 1997). Notably, green represents 'youthful vigour, freshness, activity, and divine energy' and Ratu Kidul is up to the present day associated with a trident that symbolizes her likely Hindu provenance (standing for Vishnu, Shiva and Brahma) (Fig. 5).

Indeed, the boundaries between Hinduism and Buddhism were never well-defined on Java, reflecting an element of religious cross-fertilization, as exemplified by the Siva-Buddha cult in East Java (e.g. Jordaan 1997). The Siva-Buddha cult originated around the tenth century, but an earlier dating in Central Java is highly likely (Jordaan 1987). On the decline of Buddhism, a blend of Tara and pre-existing beliefs were likely integrated into the local Hindu pantheon (Jordaan 1987, 1997). However, recurrent folkloristic elements, such as a rejuvenating woman and skin disease support the notion of a pre-Hindu and pre-Buddhism origin of Ratu Kidul (Stutley & Stutley 1977; Jordaan 1997). This is conceivable given the fierce waves of the Indian Ocean on the southern coasts, including tsunamis on occasion, which probably resulted in fear and respect for the power of natural forces already in pre-Hindu and pre-Buddhist Javanese societies.

Cultural complexity depends on population size and density and larger groups usually develop higher levels of cultural diversification (Derex *et al*. 2013). Larger populations also have higher probability of observing unusual or sporadic (but significant) events and thus create rich local myths and traditions by adding new layers to existing legends (Derex *et al.* 2013). These ever more complex legends then pass on from generation to generation, and then become themselves the tradition of a society (e.g. Duffield 2001). This is a necessity in many habitats where we are highly vulnerable without specific adaptations. Rich cultural transmitted knowledge is thus a tool large groups of people have developed in the face of threats, to ensure information flow over time (Derex *et al.* 2013; Richerson 2013). The local geographical and geological environment around Merapi must thus have had a fundamental influence on people's perception of their world and the development of legends, lasting over many tens of generations and through varying cultural and religious episodes (e.g. Schlehe 1996; Resink 1997; Karsono and Wahid 2008). Specifically, the 'ancient MKSS axis' concept has not fundamentally changed irrespective of religious influences, such as Hinduism, Buddhism or Islam, and continues up into the twentieth century (Karsono and Wahid 2008). In this paper, we argue that the basis for the MKSS axis, and the reason for frequent cultural overprint, is a set of geological factors that connect Merapi volcano with a continental fault system that reaches the South Sea at Parangtritis. We will now review the geological evidence and then provide a combined discussion of the social, cultural and geological aspects that relate to the MKSS axis phenomenon.

Geological background

Volcano–earthquake interaction

Volcano–earthquake interaction is a topic that has only been fully appreciated by modern geosciences over the last two decades. Volcanoes are long known to show local volcanic-tremor, *volcano-tectonic* (*VT*), *long-frequency* (*LF*) seismicity, and mixed earthquakes due to magma and gas movement (e.g. Hill *et al.* 2002; Tsuji *et al.* 2009; De la Cruz-Reyna *et al.* 2010; Delle Donne *et al.* 2010; Surono *et al.* 2012; Shelly *et al.* 2013). The concept that regional (tectonic) earthquakes can cause distant volcanoes to respond is more controversial, but has recently been documented in a number of cases (e.g. Moran *et al.* 2002; Walter and Amelung 2006, 2007; Harris and Ripepe 2007; Walter 2007; Walter *et al.* 2008; Eggert and Walter 2009; Cannata *et al.* 2010; Troll *et al.* 2012). This realization requires a rethink of volcano–earthquake interaction, accepting that volcanoes can cause earthquakes, but that earthquakes can also influence volcano eruptive behaviour (Hill *et al.* 2002; Walter and Amelung 2006, 2007; Harris and Ripepe 2007; Walter 2007; Walter *et al.* 2008; Eggert and Walter 2009; Tsuji *et al.* 2009; De la Cruz-Reyna *et al.* 2010; Delle Donne *et al.* 2010; Troll *et al.* 2012; Shelly *et al.* 2013). This rarely documented phenomenon is increasingly observed due to improved instrumentation at volcanoes, which now allows us to pinpoint processes which were until recently mere speculation (e.g. White and Power 2001). In the sections that follow, we discuss volcano–earthquake interaction in a Merapi-type context, where this process might be particularly pronounced because of the likelihood of magma–carbonate interaction at depth (Deegan *et al.* 2010, 2011; Troll *et al.* 2012). Magma–carbonate interaction can cause violent degassing of heated and fragmented carbonate rock, a process which is, in turn, likely promoted by earthquake activity due to increased reaction surfaces, possibly generating a 'self-catalysing' feedback loop between these processes (Deegan *et al.* 2011).

Geological setting of Merapi volcano

Java is part of the active volcanic front of the Sunda arc, which results from northward subduction of the Indo-Australian plate beneath Eurasia at a rate of about 6.5–7 cm yr^{-1} (Tregoning *et al.* 1994). Java is home to a population of ~130 million people (Donovan and Suharyanto 2011), and some 25% of the world's active volcanoes, which in the past 500 years have caused more than 140 000 fatalities (Marshall 2008). Merapi is ranked as one of the most active volcanoes on Java (Fig. 2), thereby representing a formidable threat to the city of Yogyakarta, the largest city in Central Java (e.g. Surono *et al.* 2012) (Fig. 1).

The upper parts of the crust underlying Merapi comprise a thick sequence (>10 km) of Cretaceous to Tertiary limestones, marls, and volcanoclastic deposits (van Bemmelen 1949). These sequences outcrop in the immediate surroundings of Merapi and at Parangtritis beach on the south coast. Remnants of sedimentary rock can also be found as abundant metamorphosed calc-silicate xenoliths in Merapi eruptive deposits (Figs 2 and 4; Camus *et al.* 2000; Gertisser and Keller 2003b; Chadwick *et al.* 2007).

Merapi degasses continuously through high-temperature summit fumaroles and is characterized

Table 1. Major Merapi eruptions of the past 330 years and associated fatalities.

Year	Fatalities
1675	~3000
1872	200
1930	1369
1954	64
1976	28
1994	64
2006	2
2010	>350

Data source: Andreastuti *et al*. (2000); Camus *et al*. (2000); Newhall *et al*. (2000); Thouret *et al*. (2000); Gertisser and Keller (2003a, 2003b); Donovan (2010); Donovan and Suharyanto (2011); Surono *et al*. (2012); Innocenti *et al*. (2013); Komorowski *et al*. (2013).

by periods of dome growth and intermittent explosive events (e.g. Gertisser and Keller 2003b; Toutain *et al*. 2009). Its recent eruptive activity has been dominated by basaltic-andesite dome lavas and associated pyroclastic flows [*block and ash flows* (*BAFs*); Schwarzkopf *et al*. 2001, 2005], however, it is noteworthy that Merapi's 2010 eruption was considerably more explosive than the events of the last ~100 years (Surono *et al*. 2012; Borisova *et al*. 2013). In the nineteenth century, Merapi erupted in a similarly explosive fashion (1822 AD and 1872 AD; e.g. Surono *et al*. 2012) and from about 3000 years ago to the present day, at least 93 significant eruptions took place (Table 1) (Andreastuti *et al*. 2000; Camus *et al*. 2000; Newhall *et al*. 2000; Gertisser and Keller 2003a,b; Innocenti *et al*. 2013; Komorowski *et al*. 2013).

In total, there were about 23 eruptions at Merapi in the last 100 years (Voight *et al*. 2000) and ≥1.1 million people live on the flanks of the volcano in settlements that reach up to 1700 m a.s.l. and as close as 5 km from the crater as the crow flies (Schlehe 1996). Effusive eruptions are frequent, while explosive activity occurs every 8–15 years, with particularly violent behaviour occurring every 26–54 years (Thouret *et al*. 2000; Donovan 2010) and Merapi is currently considered to be at the very beginning of a phase of long-term increased activity (Gertisser and Keller 2003a). Furthermore, the 2010 eruption implies that Merapi's activity has migrated southward (Donovan and Suharyanto 2011; Surono *et al*. 2012) and the combined realizations pose serious challenges to hazard mitigation efforts in nearby Yogyakarta, *c*. 25 km to the south of the volcano (Newhall *et al*. 2000; Walter *et al*. 2007; Surono *et al*. 2012).

Millions of cubic meters of brittle rock make up the dome complex of Merapi which may be transported catastrophically to lower altitudes. For instance, debris avalanches and rock falls together with lahars frequently occur at Merapi (Thouret *et al*. 2000). In response to this risk, the Sabo Technical Centre in Yogyakarta was established in 1982 with the purpose of building multifunction Sabo dams, and simple early warning systems (Fig. 8). Today, the efforts of the Sabo Technical Centre also involve dialogue with the residents in disaster prone areas to encourage participation in disaster mitigation programmes. The participation of communities in preparing disaster countermeasures is critical to reduce vulnerability through awareness and increased self-protection (see also 'Practical use of findings').

The 2006 eruption and earthquake events

The 2006 eruption commenced on 25 April and lasted until October of that year (e.g. Wilson *et al*. 2007; Ratdomopurbo *et al*. 2013). On 14 June, the largest pyroclastic event of the eruption occurred, destroying the village of Kaliatem on the southern flank of the volcano (e.g. Donoghue *et al*. 2009; Troll *et al*. 2013a,b); Fig. 9). A magnitude 6.4 earthquake preceded this event on 26 May, along a splay of the Opak River Fault system to the south and east of Yogyakarta (Fig. 1). The 26 May Yogyakarta earthquake accelerated the ongoing eruptive activity at Merapi and dome growth and collapse activity increased by a factor of three to five in the two weeks following the earthquake (Walter *et al*. 2007, 2008). The earthquake caused devastating damage to Yogyakarta and its southern suburbs, killing >6500 inhabitants and destroying 280 000 homes. An estimated ≥1 million people were accommodated in temporary shelters and refugee camps for many months after the disaster (Figs 10–12).

The link between volcano and earthquake activity likely results from stress changes in the upper crust. Earthquakes fracture the bedrock underlying Merapi, which is dominated by limestone rocks, and thus allows release of trapped CO_2 and subsequently encourages magma–carbonate interaction on newly generated fracture surfaces. As experiments demonstrate (e.g. Deegan *et al*. 2010; Jolis *et al*. 2013), this process would rapidly increase the CO_2 pressure in the magma plumbing system, and, in turn, promote increased eruptive activity and a more

Fig. 8. Hazard mitigation. (a) Example of a Sabu dam on the slopes of Merapi. The Sabu channel system aims to confine lahars and pyroclastic flows and creates artificial basins to trap material that is moving downhill. (b, c) Early warning system in steep valleys on Merapi's higher slopes. An electric signal is sent if the steel rope is disturbed. (d) Sand mining creates sediment traps in recent BAF deposits on the medium altitude slopes of Merapi. (e–g) Impression of recent BAF deposits from Merapi. Note the mixture of large blocks and fine ash plus entrained debris like charcoaled tree trunks.

explosive, albeit erratic, eruptive style (Deegan *et al*. 2010; Troll *et al*. 2012; Borisova *et al*. 2013).

The process is also reflected in gas chemical data. Prior to the 2006 eruption, summit fumarole CO_2 gas $\delta^{13}C$ ratios of Merapi were relatively constant at –4.1‰ ± 0.3 (1994–2005). This value is typical of subduction zone volcanoes (e.g. Hilton *et al*. 2002) and small fluctuations have previously been interpreted as the influence of the local limestone basement underneath Merapi (see Troll *et al*. 2012). CO_2 from fumarole gas collected during the 2006 eruption but after the earthquake showed a dramatic increase from this baseline value, reaching up to $\delta^{13}C$ = –2.4‰ ± 0.2 (Troll *et al*. 2012). Notably, the earthquake had a shallow hypocentre depth of 10–15 km, and an increase in eruptive intensity was observed directly after the earthquake (Walter *et al*. 2007). The elevated carbon isotope gas data and the mid-crustal depth of the earthquake source are consistent with crustal volatile components added to the volcanic system during the 2006 eruption. In 2007 and 2008, the

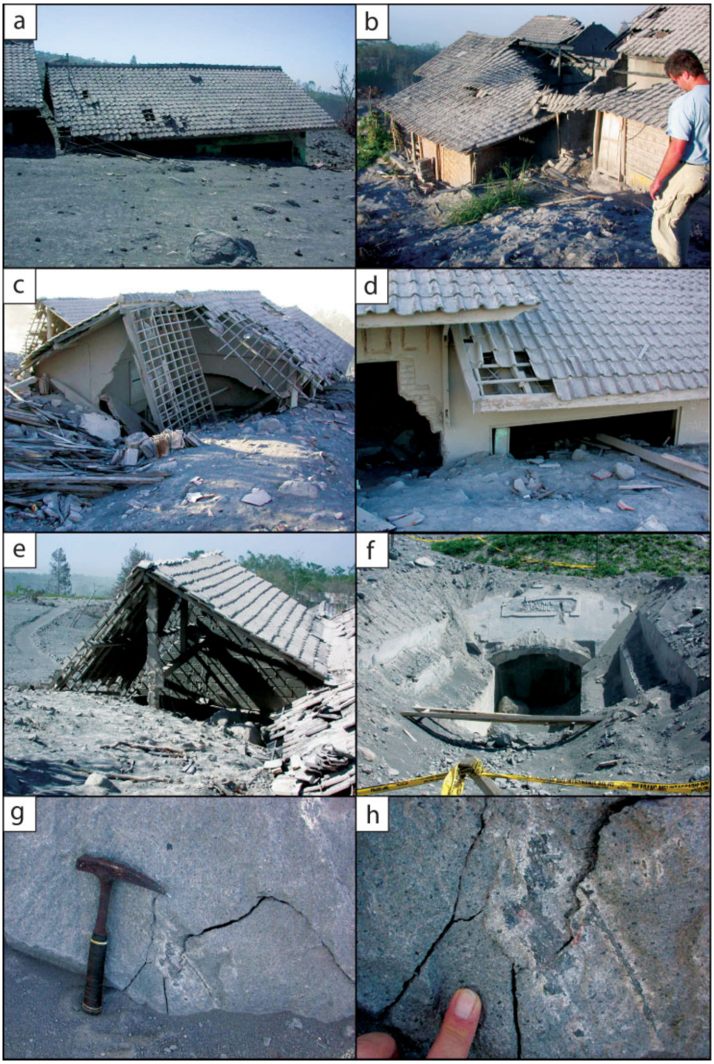

Fig. 9. (a–e) The 2006 eruption of Merapi devastated Kaliatem village, *c*. 6 km to the south of Merapi's summit. Although the village was evacuated in time, two observatory members were killed in the observation bunker (f) as the exit became blocked with hot volcanic deposits. (g, h) Impact site of presumably a large block from the 2006 pyroclastic eruption into a large block in the substrate. Note the fractures that indicate shattering and the striation of pseudotachylite, implying enormous kinetic energy that is transferred into heat on impact, sufficient to melt the impacted rock locally (approximate melting temperature: 1200°C).

$\delta^{13}C$ fumarole values returned to the previous background levels. 'Extra' crustal gas therefore likely played an important role in modifying and intensifying the 2006 and also the 2010 eruptive behaviour at Merapi (see below) (Deegan *et al*. 2010; Borisova *et al*. 2013; Troll *et al*. 2013a,b).

Monitoring of $\delta^{13}C$ gas values over the last ~25 years shows that besides the 2006 earthquake, a deep slab seismic event occurred in 2001 with its hypocentre at ~150 km depth. The 2001 earthquake was therefore located deep in the subducting slab and was only accompanied by a mild increase in fumarole temperature (Zimmer and Erzinger 2003; Walter *et al*. 2007). The 2006 seismic events, in turn, were directly coupled with changes in eruptive activity, consistent with a crustal earthquake as the major cause for the volcano's responses.

Abundant 'degassed' skarn-type xenoliths (metamorphosed limestone fragments) are frequently found in Merapi's 2006 and earlier eruptive deposits

Fig. 10. Damage caused by the 2006 earthquake in Yogyakarta city and surroundings. (a) Collapsed building south of Yogyakarta. Note the roof rests on the ground, i.e. the walls have collapsed entirely. (b, c) Building of the governmental financial and development agency in Parangtritis Street (Jalan Parangtritis). (d, e) Damaged building of the Department of National Education, Institute of Art of Indonesia, Gadjah Mada University.

of the twentieth century (Figs 2 and 4), which suggests that the sedimentary carbonate basement underneath Merapi indeed acts as an extra CO_2 source. The pronounced increase in $\delta^{13}C$ in 2006, its transient duration, the crustal depth of earthquake hypocentres, and the link with eruptive and seismic intensity imply the addition of CO_2 from a mid- to upper-crustal source (Troll *et al*. 2012, 2013a,b) and creates a picture of intense magma–crust interaction in the top few kilometres beneath Merapi during eruptive episodes. Such additions of crustal CO_2 may modify volatile budgets of ascending magmas at Merapi considerably (>50% based upon the shift in $\delta^{13}C$ values in 2006; Troll *et al*. 2012) and CO_2 from the thick limestone basement may sustain or amplify eruptive activity, especially when aided by external seismic events.

It is therefore likely that the 26 May earthquake caused stress changes in the upper crust that resulted in thermal and dynamic fracturing, release of trapped gas pockets, magma injection, xenolith entrainment, and xenolith disintegration, which together acted to increase the area of new reaction surfaces, and thus temporarily accelerated the rate of magma–carbonate interaction (e.g. Deegan *et al*. 2010, 2011). High rates of crustal CO_2 additions would then have increased the volatile budget and thus the explosive character of an eruption and would have contributed to seemingly erratic events with very limited forewarning (e.g. Deegan *et al*. 2011; Troll *et al*. 2012).

It has moreover recently been proposed that CO_2 can lubricate the slip planes of crustal faults, thus

Fig. 11. (a–d) Refugee shelters after the 2006 earthquake created mainly from western donations. Over one million people were living in temporary shelters for months after the disaster. (e, f) Improvised schooling for the youngsters, aiming to bring life back to a familiar rhythm.

aiding fault slip, so it is therefore conceivable that volcanic activity can lead to increased gas pressure in the mid-crust, which may, in turn, represent a potential trigger for increased regional seismicity. As the 2006 eruption was already ongoing for six weeks prior to the 26 May earthquake, it is possible that high crustal CO_2 degassing at Merapi volcano could have released CO_2 into crustal fracture zones, thus changing the stress regime to promote an earthquake elsewhere along the fracture network (cf. Miller *et al.* 2004). This would be consistent with slightly elevated $\delta^{13}C$ values in fumarole gas in 2005, and with estimates of fluid travel speeds in faults and fractures (Zoback and Harjes 1997; Shapiro *et al.* 2006; Troll *et al.* 2012).

We therefore suggest that shallow-level crustal CO_2 degassing due to magma–crust interaction released CO_2 into crustal fractures and fracture zones, thereby modifying the regional stress regime to promote the 2006 Yogyakarta earthquake further along the fault system (cf. Miller *et al.* 2004; Shapiro *et al.* 2006). This chain of events, whereby the volcano and earthquake interacted in a positive feedback loop, underline that crustal earthquakes intensify ongoing eruptions independently of traditional magmatic processes, while in turn, magmatic activity at Merapi may be a factor in promoting regional seismic activity (cf. Surono *et al.* 2012; Troll *et al.* 2012). Volcano and earthquakes therefore appear to 'communicate' with each other at Merapi and likely have done so for some time.

The 2010 eruptive events

Towards the end of October and during November 2010, a large volcanic eruption occurred at Merapi. Although over 350 people lost their lives, more than 410 000 people were successfully evacuated from the 20 km exclusion zone around the volcano (Surono *et al.* 2012). The 2010 eruptions also resulted in major air traffic disruptions, underlining

Fig. 12. (a–f) Reconstruction in full progress. Yogyakarta in September 2006. Return to normality after the 2006 earthquake–volcano disaster. The attempt to 'order' chaos as soon as disaster struck reflects that the society around Merapi is used to coping with this type of disaster.

concerns that much larger eruptions, like the one in 1872, could represent a serious future threat at Merapi (Gertisser and Keller 2003a; Surono *et al*. 2012). Following 4 and 5 November, eruptive activity decreased and no explosions or aftershocks were produced. By the end of November, the activity ceased, but the summit morphology of the volcano had changed considerably due to intense cratering and partial collapse (Surono *et al*. 2012; Pallister *et al*. 2013; Jousset *et al*. 2013).

Seismic swarms began to occur in late 2009 and again in mid-2010. In October 2010, Merapi saw an increase in ground deflation, earthquake intensity, and degassing from summit fumaroles (e.g. CO_2 and H_2S; Surono *et al*. 2012). On 26 October, a phreatomagmatic blast began the eruptive sequence that then culminated in the climactic eruptive phase on the night of 4–5 November (Surono *et al*. 2012; Jousset *et al*. 2013).

The eruption was characterized by rapid dome growth, about 20 times greater than recent events, and 10 times greater than what has been inferred for the more explosive episodes of the nineteenth century (Pallister *et al*. 2013). The 2010 eruption, together with large explosive events in 1931 and 1872 and those between 1822 and 1872, mark a change in Merapi's behaviour, potentially heralding a heightened phase of eruptive activity (Fig. 13; Gertisser and Keller 2003a; Surono *et al*. 2012).

Just before the 2010 eruption, CO_2 levels in fumarole gas increased from ~10 wt% in September 2010 to between 35 and 63 wt% in late October. The increase in CO_2 in fumarole gas coincided with LF earthquakes at the end of October and the start of November, implying a deep degassing source and input of fresh magma into Merapi's plumbing system (Surono *et al*. 2012). In addition, crustal decarbonation of limestone in the magma system likely contributed to CO_2 production, with an estimated 2.1 Mt CO_2 liberated (Borisova *et al*. 2013). The contrast between the

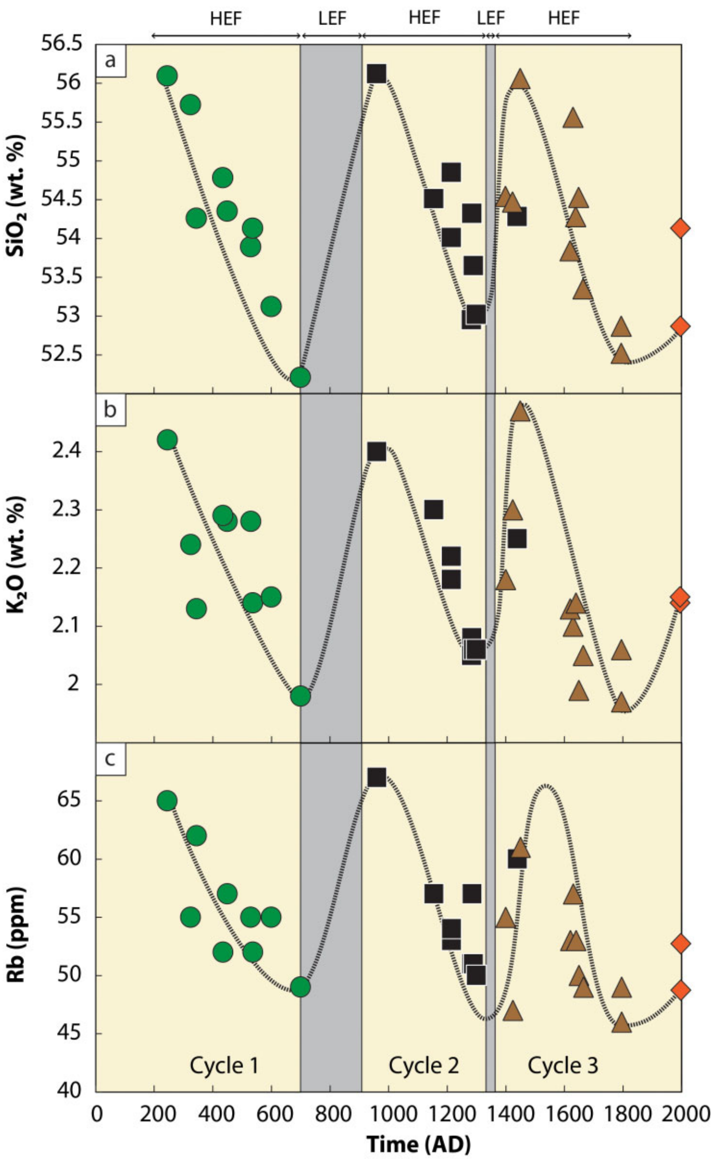

Fig. 13. Temporal variations in SiO_2 (a), K_2O (b) and Rb (c) in eruptive rocks from Merapi volcano. The trends of SiO_2, K_2O (wt%) and Rb (ppm) indicate periods of high eruptive frequency (HEF areas) and periods of low eruptive frequency (LEF areas). The HEF periods divide the activity at Merapi into three main cycles. The diamonds are from the 1996 eruption and are representative of the current Merapi eruptives, likely heralding a new cycle that is about to start. Data source: Gertisser and Keller (2003a, 2003b).

mildly explosive eruptions of the twentieth century (i.e. block-and-ash flows of Merapi type) and the subplinian 2010 event was potentially influenced by the efficiency of carbonate assimilation by ascending mafic Merapi magmas. In this context, incomplete (selective) assimilation promotes less explosive events, while near-complete (bulk) assimilation may have facilitated the more explosive behaviour in 2010 (e.g. Troll *et al*. 2012; Borisova *et al*. 2013).

The climactic event on 4–5 November 2010 generated an ash plume that reached an altitude of 12 km, and produced pyroclastic density currents that extended ~8 km down the southern valleys of the volcano (towards Yogyakarta). The eruption tragically killed the gatekeeper of Merapi, Mbah Marijan, who refused to evacuate his village some 7 km from the summit (Surono *et al.* 2012).

A large number of earthquakes accompanied the eruption, including VT and multi-phase earthquakes, tremors, as well as LF and very long period earthquakes, which indicate transport of large volumes of magma and fluids (e.g. Surono *et al.* 2012; Jousset *et al.* 2013). Regional tectonic earthquakes also coincided with the eruption, such as in 2006, and may have triggered higher levels of eruptive activity at Merapi on 3 and 4 November, similar to the 2006 Merapi events. Specifically, on 3 November, a magnitude 4.2 earthquake occurred south of Yogyakarta at a depth of ~60 km (Surono *et al.* 2012; Jousset *et al.* 2013). A link between eruptive intensity and regional tectonic faulting, probably aided by crustal CO_2 release, is suggested (e.g. Surono *et al.* 2012; Troll *et al.* 2012), and likely affected the loading and slip on nearby faults (cf. Shapiro *et al.* 2006). This type of relationship has recently been observed elsewhere (see section 'Geological background') and can explain distal VT earthquakes preceding eruptions (White and Power 2001; Moran *et al.* 2002; Pozgay *et al.* 2005; Eggert and Walter 2009; Cannata *et al.* 2010; Surono *et al.* 2012). Although volcano–earthquake interaction has now become increasingly recognized, it has so far rarely been carefully documented during an eruption (Surono *et al.* 2012). It appears, therefore, that volcano–earthquake interaction is a well-developed phenomenon at Merapi during periods of heightened eruptive activity (Walter *et al.* 2007, 2008; Surono *et al.* 2012; Troll *et al.* 2012, 2013a,b). With this geological background in mind, we shall now discuss the ancient oral traditions at Merapi.

Discussion

Origin and meaning of the MKSS oral traditions

Examples of oral traditions that describe experiences of natural phenomena are widespread in many places around the world. For instance, during the 2004 Boxing Day tsunami, the almost 80 000 residents of Simeulue Island, near Sumatra were saved by an old local lullaby that advised people to move to high ground (McAdoo *et al.* 2006). Despite volcanic quiescence for >600 years, disaster was averted at the 1991 eruption of Mt Pinatubo as warnings of rare and very large volcanic eruptions had been memorized in local legends and proved extremely helpful in responding to unexpected events (Rodolfo and Umbal 2008; Donovan and Suharyanto 2011). Another example is at El Chichón, where an ancient local legend about a flood of boiling water seemed to lack rational explanation or common natural examples (Duffield 2001). However, a hot flood occurred in the 1980s when lake water that had been dammed against hot pyroclastic deposits became heated above boiling point (Duffield 2001), thus providing a mechanism for the legend. Severe flooding episodes dating back to the time of Spanish conquerors in Santa Fe City, Argentina, have been immortalized through diverse forms, such as myths, novels and film. Here, historical and mythical narratives have become entwined as a method of remembering disastrous past flooding events that have overwhelmed this community (Ullberg 2013). Communities that have previously experienced widespread natural disasters therefore often acquire knowledge that may not be obvious from the geological or sociological record, but which is frequently built into legends, dances, art, or religious ceremonies (Duffield 2001; Chester 2005; Chester *et al.* 2008; Ort *et al.* 2008; Donovan 2010; Harris 2012; Derex *et al.* 2013; Richerson 2013; Ullberg 2013).

Although research concerning culturally overprinted information is challenging (Ikeya and Sokolov 2003; Derex *et al.* 2013), if it is ignored, there is a risk of overlooking potential threats and warnings (e.g. Donovan 2010). For effective disaster mitigation, oral traditions should therefore be considered as potential traditional knowledge (Chester 2005; Donovan 2010; McAdoo *et al.* 2006; Cashman and Cronin 2008; Donovan and Suharyanto 2011; Harris 2012). When working with oral traditions, and especially the ones around Merapi, we must remember that cultural transmission is much less clear than, for example, written transmissions, and the extended backdrop of diverse cultural development must naturally be considered (cf. Richerson 2013). We hypothesize that reasons other than purely cultural are responsible for the origin of the MKSS legend and that these reasons explain why the MKSS concept was retained and strengthened over generations amid variable religious and cultural influences. The geological record of the last 2000 years demonstrates that Merapi passes through cycles of eruptive intensity (Fig. 13), which influenced and affected human societies in its surroundings. Geological research (e.g. Gertisser and Keller 2003a) implies that there

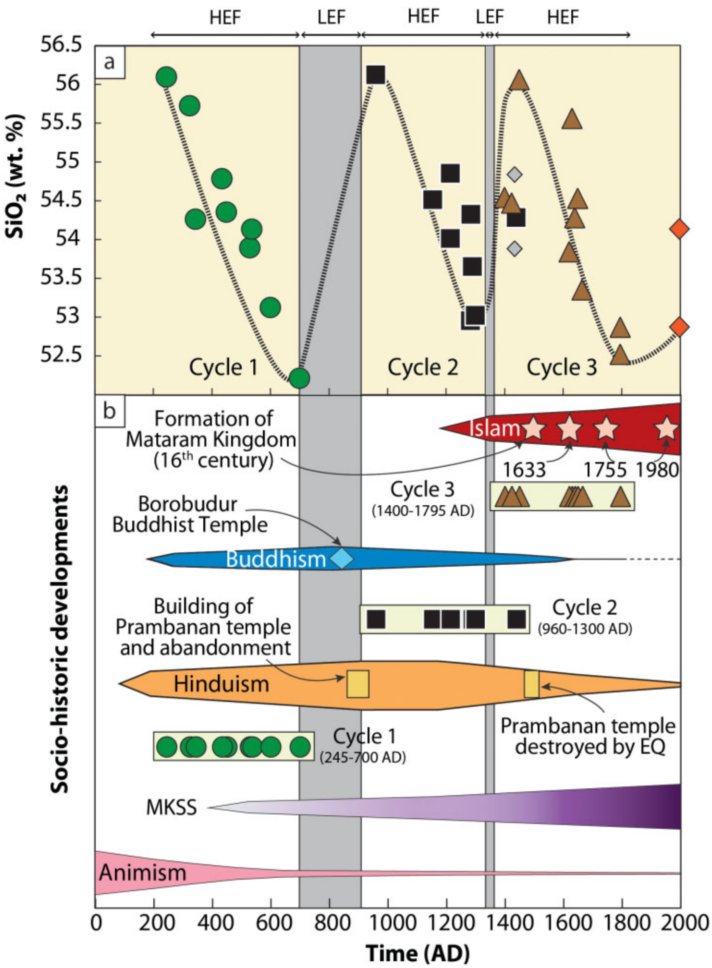

Fig. 14. (a) Temporal variations in SiO_2 in eruptive rocks from Merapi volcano (last 2 ka; see Fig. 13 for details). (b) Correlation of Merapi eruptive cyclicity with the broad socio-historical background of cultural diversification in Central Java. Hinduism started to arrive on Java in the first to third century AD and became the dominant religion on Java by the early eighth century. During this period, the Temple of Prambanan was built (Figs 1, 4), but was abandoned ~930 AD, probably because of a Merapi eruption. The Prambanan temple site was later severely damaged during an earthquake in the sixteenth century which was widely interpreted as the eventual decline of Hinduism on Java. Buddhism arrived in Java around the second century also and was running parallel to Hinduism for a considerable time, a period marked by the construction of the Borobudur Buddhist Temple (~830 AD). Buddhism declined from around the twelfth or thirteenth century, initially at the expense of Hinduism, and further in the sixteenth century when Islam became the dominant religion in Java. Although Islam dates back to as early to the eighth century, it was not until the thirteenth century that it began to spread through Java. Important dates during the Islamic period (orange stars) are the foundation of the Mataram Kingdom in the late sixteenth century; 1633, when Agung of Mataram assumed the title of Sultan and adopted the Islamic lunar calendar; 1755, establishment of the Yogyakarta Sultanate in its current form and construction of the Kraton and the Tugu monument. The last star marks the construction of the Yogya Kembali monument, erected on the MKSS axis in the 1980s to commemorate the struggle for independence in the 1940s. The Merapi–Kraton–South Sea Oral Traditions thus include Hindu, Buddhist as well as older animistic beliefs, plus several layers of Islamic overprint. The tradition must date back to at least the time around the third to fourth century where animist beliefs, Hinduism and Buddhism blended in the backdrop of heightened activity at Merapi. Data sources: Schlehe (1991, 1996, 2008, 2010); Fischer and Danandjaja (1994); Jordaan (1997); Resink (1997); Gertisser and Keller (2003a); Karsono and Wahid (2008); Lavigne *et al*. (2008).

were particularly intense eruptive episodes at Merapi between ~1000 and 1200 AD and ~1400 and 1800 AD, which appear to correlate with cultural development trends in Central Java (Fig. 14).

It is therefore most probable that previous periods of heightened activity at Merapi (Fig. 10) left a lasting impression on the local population, engraving in mind and culture the idea of a supernatural connection between Merapi and the Parangtritis area (in other words Merapi and the Opak River fault; Fig. 1). Volcano–earthquake interaction was likely a common phenomenon in Merapi's previous cycles and represents a recently renewed phenomenon, consistent with an overall notion of increasing intensity of activity at Merapi (e.g. Gertisser and Keller 2003a; Surono *et al*. 2012).

Specifically, Merapi's eruptive cyclicity over the last 2 ka, reflected through major and trace element data of erupted lavas and pyroclastic flows, suggests that Merapi is just now at the beginning of a new cycle of heightened eruptive activity (Figs 13 and 14). This cyclicity seems to occur in intervals of ~800 years and suggests that at the beginning of the Mataram dynasty (sixteenth century), Merapi was 'calming down', i.e. it was reaching the end of a period of intensified eruptive activity. The early Sultans needed to stabilize their realm through the support of the local population (that initially adhered to Hindu and Buddhist beliefs), and by signalling partial acceptance and integration of the old and the new traditions, stronger support by the population was likely ensured. Indeed, it is worth noting that legends and ceremonies commemorating the relationship between Ratu Kidul and Senopati have been likely important in Java in terms of strengthening and legitimizing the current Sultanate in the minds of the Javanese people and are expressed through the ceremonial grounds near Merapi, Cepuri Parangkusumo at the South Sea, and through the annually celebrated and extremely popular Labuhan ceremony (Fig. 5).

In contrast, in the seventh to ninth century, when Hindu and Buddhist traditions incorporated the local phenomena into their traditions, Merapi was at a stage of heightened activity. Intriguingly, a former spiritual advisor to the Kraton explained the eruptions of Merapi with a time cycle and with a rhythmicity of ~700 years for a new era to begin and an old one to end (Schlehe 1996), showing that non-scientific approaches can arrive at surprisingly similar conclusions.

The recent activity of Merapi has repeatedly demonstrated volcano–earthquake interaction phenomena, with the 2006 earthquake said to have come from the south by the local people (Schlehe 2010). This matches the projected location of the epicentre and identifies the Opak River fault system near the south coast as the earthquake's source (e.g. Walter *et al*. 2007). Based on the link between the MKSS axis and major faults in the region (e.g. Lavigne *et al*. 2008), as well as evidence of intense past eruptive episodes, we suggest that volcano–earthquake interaction is a central aspect of the MKSS tradition. Cultural overprint then led to increasingly complex modifications of the MKSS concept, adding multiple layers of information from successive human and cultural generations and epochs.

Traditions often appear unchanging and to preserve the customs of the past. Modification with time is important, however, to ensure transmission over successive generations and to adapt to new or variable hazards (e.g. Shanklin 2007; Cashman and Cronin 2008). Traditions are often purposefully transformed to fit the strategic needs of certain groups (e.g. Kohl 2006; von Benda-Beckmann *et al*. 2007; Schlehe 2010). For example, the Islamic rulers in the sixteenth and seventeenth century (see above) clearly imprinted their preferences onto existing legends by altering the details of what is actually transmitted in ceremonies and rituals to help stabilize and maintain the social order, especially in times of crisis (Schlehe 2010).

A further noteworthy aspect is that the relationship of man to Hindu-Buddhist gods or to nature and ancestral deities and spirits is conceived in Java as a relationship to senior but intimate kin, which contrasts Allah and Muhammad, who are very powerful, but also very distant beings (Jordaan 1987; Schlehe 1996). Ratu Kidul, for example, can be approached without the help of an intermediary, which may be a further reason for her continued popularity (cf. Jordaan 1984, 1987; see section 'Discussion'). The core information recorded in the MKSS tradition is, however, the link between volcano and earthquakes, which science has only began to grasp in the last two decades or so (see section 'Geological background'). The phenomenon is, however, duly recorded in the oral traditions at Merapi, ready for us to consider and apply. In 2006 and 2010, the volcano's behaviour reproduced the worries expressed in the MKSS tradition and consequently past and future scenarios like the ones in 2006 and 2010 appear extremely likely.

Practical use of findings

Traditional agricultural societies are critically dependent on their natural environment and knowledge of natural cyclicity. While some natural phenomena are considered a blessing, others are considered negative, and supernatural forces are often assumed to be the underlying cause. By externalizing blame, a community is often better able to cope psychologically with the outside dangers it faces (e.g. Lavigne *et al*. 2008; Schlehe 2010; Donovan and Suharyanto 2011). Belief has it that many of these supernatural powers can also be influenced by 'good behaviour', such as offerings or sacrifice. In an attempt to secure lasting positive support, such actions lead to repetitive ceremonies in order to maintain a positive relationship with nature and any supernatural forces invoked (Karsono and Wahid 2008; Schlehe 2010; Richerson 2013). Documentation of volcanic hazards is almost a 'side-effect' in this sense, but ceremonies record processes that communities have experienced in the past, thus being of prime importance to volcanologists. A community needs to anticipate and respond to eruptive activity, but also needs to cope with and recover from disasters (Chester 2005; Chester *et al*. 2008; Chester and Duncan 2007). Regarding the first aspect, descriptions in oral traditions can provide information on the types of processes possible at a given volcano, especially where geological background data are incomplete. Oral transmission can then represent a durable, all-inclusive method for traditional communities to record catastrophic events for future generations (Chester and Duncan 2007). The 'worst case scenario' is often captured by a 'mystical reminder' (e.g. Duffield 2001; Chester and Duncan 2007; Richerson 2013), making traditions an ancient form of hazard awareness program. Religious and traditional belief systems should therefore not be detached from risk mitigation, because they may record unfamiliar phenomena and will impact on behaviour patterns and vulnerability of local populations (e.g. Ikeya and Sokolov 2003; Lavigne *et al*. 2008; Chester and Duncan 2007; Gaillard and Texier 2010; Harris 2012).

Oral traditions thus provide a means by which subsequent generations can understand and contextualize volcanic catastrophes and support recovery from them (Cashman and Cronin 2008). For Merapi, this implies that local knowledge of intense past volcano–earthquake activity is likely preserved within the MKSS oral tradition. Once we accept this notion, then the multi-layered oral tradition of the MKSS axis reflects accumulated observations and interpretations on natural processes that can act together to a devastating effect. In this respect, it is noteworthy that a series of researchers have argued that oral traditions can help in building up resilience of local communities, yet it is not always clear on all levels how this is accomplished. Punishment, however, especially for moral shortcomings is an 'adaptive advantage' in maintaining and reinforcing societal structure and behavioural principles, and, in addition, the threat of supernatural punishment reduces tendencies towards selfish behaviour (Johnson 2005; Schlehe 2010), thus likely providing a fertile ground for legends like the MKSS to take root, grow, and diversity in the service of a community.

We consider yet another critical aspect being the personal (emotional) relationship humans develop within communities and with their environment. In this sense, an overpowering natural force, like a tsunami, an earthquake, or a volcanic eruption is beyond the control or influence of an individual or a community and will likely instil a sense of helplessness and lack of hope. In contrast, personifying natural forces helps to (re-)gain access to them and, albeit unlikely, this approach allows the possibility that the supernatural power behind a phenomenon may be persuaded, through intense efforts and sacrifice, to change the course of events. People thus get a sense of subjective security, when confronting natural hazards with such a belief system (Schlehe 2010). The phenomenon is global, as Christian traditions in southern Europe for example show, in principle, a similar approach when processions are held to 'calm the volcano' at e.g. Etna or Vesuvius (see e.g. Chester 1998, 2005; Donovan 2010). Here, an element of influence is seemingly given back to communities, and to the individual, allowing direct contact to the 'mastermind' behind a phenomenon. Psychologically, this is superior to a situation where no influence is possible at all and is therefore a form of creating hope, a vital virtue when faced with disaster, hardship, and uncertainty during crises.

Respect for supernatural powers is so deeply rooted in Central Java that we suggest the MKSS oral tradition can be considered a potential tool to introduce a dialogue with communities that resist evacuation, particularly under situations of urgency and high pressure. This would likely be a more successful approach than risking rejection and disbelief towards foreigners that argue for evacuation on scientific grounds and, furthermore, this 'emergency' strategy would aid fruitful interaction between all parties involved. However, it remains important to increase resilience within the community through measures such as improved access to suitable food and shelter before eruption. In addition, the development of social support networks, which aim to increase preparedness, improve coping capacities, and minimize negative psychological impacts after a crisis, will help to reduce vulnerability (Blaikie *et al.* 2004). Importantly, long-term actions should be taken to diversify income sources for those who are economically reliant on agriculture on Merapi's flanks in order to prevent the need for farmers to return to crops and animals during an eruptive event (Blaikie *et al.* 2004; Lavigne *et al.* 2008).

Traditional beliefs form a considerable part of people's attitudes to danger, with a complex combination of folk beliefs, trust in volcano guardians, assessments based on past hazard frequency and location, concern for loss of property, and all this combined with widespread mistrust towards the government. For example, those living in isolated locations west of Merapi distrust the authorities, because of rumours of land being sold while residents are in evacuation centres, thus creating additional reluctance to respond to official warnings and ordered evacuations. Clearly for Disaster Risk Reduction to succeed, the relevant organizations must take account of people's beliefs, their attitudes to volcano hazards, and their economic concerns, all of which are embedded in their lives. A glimmer of hope here is that after his father was killed in 2010, Asih Lurah Surakso Sihono was appointed as the new spirit guardian of Merapi. When interviewed in 2012, he indicated that he would be willing to liaise with the local volcano observatory to avert future disaster (Hodal, K., http://www.theguardian.com/world/2012/nov/15/merapi-volcano-spirit-guardian-tradition, 15 Dec., 2014), thus helping to remove the differences between traditional beliefs and the concepts used in current disaster management approaches. This is reinforced when considering that most people in Asia and around the world respect some forms of local traditions (e.g. Lavigne *et al.* 2008). Therefore, the average citizen around Merapi, in part aware of scientific reasons for earthquakes and volcanic eruptions, but also aware of traditional concepts, would be more likely to follow advised precautions when approached through a familiar emotional belief system (cf. Ikeya and Sokolov 2003; Cashman and Cronin 2008; Dove 2008; Lavigne *et al.* 2008). In this case, the popular and widely known tradition of the MKSS axis seems highly appropriate (Ikeya and Sokolov 2003; Chester and Duncan 2007; Dove 2008; Lavigne *et al.* 2008), as local traditions and belief systems can be extremely influential in volcanic regions when aiming to motivate local reactions during a crisis (Cashman and Cronin 2008; Donovan 2010). At Merapi, these actions must be used sympathetically within the wider framework of building more resilient communities and creating acceptance of preventive strategies by government initiatives (t'Hart 1997).

Lastly, the processes of reconstruction include more than just economic recovery but also the psychological habitat (Schlehe 2010). Symbolic and religious explanations are important psychological elements in the aftermath of a disaster (Cashman and Cronin 2008; Schlehe 2010) and in many traditional societies, oral traditions may have helped to maintain social order (e.g. Gossen 1974). This approach creates hope and the prospect of improvement, but also threats of divine punishment, hence offering a 'recipe' on how society may cope with disaster through reliance on past experiences (Cashman and Cronin 2008; Chester and Duncan 2007; Cronin and Cashman 2008). Oral traditions thus often provide a record of natural events, but also act as a blueprint for community response that aims to stabilize society by avoiding a post-disaster breakdown.

Employing the MKSS oral traditions may thus offer a way to 'reach through' to the target groups at Merapi that currently show distrust of scientists and civil protection authorities (see Dove 2008; Lavigne *et al.* 2008; Donovan 2010; Schlehe 2010) and who lack full understanding of the uncertainties of scientific predictions (Richerson 2013). Employing a language common to both sides might make for a more fruitful exchange and would add a 'human touch' to volcanic hazard mitigation at Merapi, as the current Indonesian official disaster management framework is strongly focused on hazard- and damage-related themes (Lavigne *et al.* 2008).

In conclusion, we reiterate that Buddhism, Hinduism, and Islam have all built on and employed ancient indigenous beliefs, such as of the MKSS legend, likely because human experience seemed to confirm the legend, thus keeping it alive over some 15–20 centuries. This realization tells us that volcano–earthquake interaction was likely a frequent phenomenon in past episodes of intense volcanic activity at Merapi and that we may expect further events of this type. Various religious systems have successfully integrated this information in central Java, possibly by drawing on the deep emotional connection between humans and their environment in hazard-prone areas. Modern science seems to have not yet fully penetrated this level of affection, especially regarding communities who resist evacuation (except for some historical examples like those listed above in section 'Origin and meaning of the MKSS oral traditions'). Our geological, historical, and social analysis in Java thus leads us to suggest that the relevant authorities may consider tapping into, and improving their understanding of, the well-known MKSS folklore to help improve hazard mitigation and foster dialogues with the communities residing on Merapi's slopes, especially in cases where scientific approaches alone appear insufficient.

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