Volcanic Landforms that Mark the Successfully Developed Geothermal Systems of Java, Indonesia Identified from ASTER Satellite Imagery

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ABSTRACT

The ASTER Volcano Archive (AVA) provides very near-infrared 15 m pixel satellite images of volcanic centres worldwide. The images' utility in this instance is their availability and widespread coverage rather than their spectra. The archive includes the volcanic centres hosting the successfully developed geothermal systems of Awibengkok, Wayang Windu, Darajat, Kamojang, and Dieng on the island of Java, Indonesia.

Volcanic landforms associated with the successfully developed geothermal fields on Java can be identified from the ASTER images as large andesitic stratovolcanos, calderas, resurgent volcanism, sector collapses and maars. Of these features; stratovolcanos, calderas, sector collapses and resurgent volcanism can be interpreted to be found at all of these fields. Maars are found only at Dieng.

The calderas predate sector collapses and maars. There is a closer correspondence between the respective locations of the known productive resources to major sector collapses than to calderas. Sector collapse locations at Darajat and Kamojang are interpreted to be at least partially controlled by the caldera margin location, where one side of the caldera collapsed. Since weakening of the volcanic pile by widespread hydrothermal alteration with ongoing geothermal activity is a strong mechanisms for major late stage sector collapses, these are possibly the most indicative landform of the presence of an exploitable geothermal field.

The volcanic landforms common to these fields can be identified and looked for in volcanic centres elsewhere on Java, Bali and possibly island arcs worldwide in order to evaluate potential geothermal prospects. Not only does this obviate the potentially limited public availability of other high quality exploration data, but it may identify blind prospects.

1. INTRODUCTION

The ASTER Volcano Archive (AVA) provides very near-infrared 15 m pixel satellite images of volcanic centres worldwide. These are freely available on the internet at, http://ava.jpl.nasa.gov by virtue of NASA/GSFC/METI/ERSDAC/JAROS, and the U.S./Japan ASTER Science Team, who are to be thanked for their kind permission to utilize these images in this paper.

The images' utility in this instance is their availability and widespread coverage rather than their spectra. The archive includes the volcanic centres hosting the successfully developed geothermal systems of (going from west to east) Awibengkok, Wayang Windu, Darajat, Kamojang, and Dieng on the island of Java, Indonesia. All these fields have been successfully generating electricity for more than five years and in the cases of Awibengkok, Darajat and Kamojang; much longer. All the fields also have published data from which the ASTER image interpretations can be confirmed in relation to the known resource areas. The field's locations are indicated in Figure 1.

Two other geothermal fields on Java; Karaha-Telagabodas (Moore *et al*., 2002) and Patuha (Layman and Soemarinda, 2003); see Figure 1, have been extensively drilled and have significant amounts of steam at the well head, but since they have yet to see protracted periods of electricity generation, they can not be considered to be successfully developed and have not been included in this study.

The objective of this study is to establish if there are volcanic landforms and relationships between the landforms common to these successfully developed fields that can be identified and looked for in volcanic centres elsewhere on Java, and since it shares a similar tectonic setting (Whitaker *et al*., 2005): Bali. It is possible at least some of these landforms may be common to geothermal fields in island arcs worldwide, e.g.: Bogie and Lawless (1986); in which case potential geothermal prospects in island arcs elsewhere can be similarly evaluated. Not only does this obviate the potentially limited public availability of other high quality exploration data, but it may identify blind prospects.

2. DEFINITION OF TERMS

In making this study, which not only involved examining the successfully developed geothermal fields, but many other andesitic stratovolcanos on Java and Bali, common patterns and sizes of volcanic landforms can be identified. Not all of these have a clearly defined, universally accepted nomenclature, so a definition of terms (in **bold**) used in this paper is offered in the interests of clarity.

Andesitic stratovolcanos consist of a pile of mainly andesitic lavas and pyroclastics, but can also contain basaltic rocks, particularly early in their formation, plus dacites, and more rarely rhyolites, most particularly late in their formation. Shallow intrusives are common in these volcanic piles. While these volcanoes can form near-perfect cones, they tend to be an early phase and multi-eruptive centres with more complex geometries are more common as the centres mature. The eruptive centres are typically originally **summit craters** less than one km across. Following large subsequent eruptions, in which there is significant inflation of the volcano prior to eruption, there can be collapse with the volcanic pile being largely preserved to form **summit calderas** that are typically 2-3 km wide. The caldera margin can be considered to be the innermost ring of a series of ring fractures that are produced by the deflation of the pile following a major eruption. With larger catastrophic eruptions much of the original volcanic pile can be destroyed leaving a **major caldera** of the order of 10-20 km wide. This variation in size allows summit craters, summit calderas and major calderas to be distinguished.

Andesitic stratovolcanos can undergo **sector collapse** (Reid, 2004), which is a large scale gravitationally driven failure of the volcanic pile, which in many instances may be driven by hydrothermal processes. Similar to, and in part, related to craters and calderas, three size variations can be recognised, most particularly in the size of the **cirques** (the arcuate head of the valley formed by the sector collapse; a term borrowed from glaciology). Sector collapses with small (1-2 km wide) cirques are typically breaches of summit craters, with the crater margin making up the cirque. These are **summit crater breach sector collapses**. Sector collapses with wider cirques (2 km wide) are usually breaches of summit calderas with the margin of the cirque being part of the summit caldera margin. These are **summit caldera breach sector collapses.** The lateral margins of the collapse zone may be controlled by radiating fractures produced by the inflation of the volcano prior to the major eruption which ended with the summit caldera formation.

Larger (depending upon the relative size of the volcano, but usually > 2 km wide) cirques possibly form on outer radial fractures produced during summit caldera collapse down slope of the main eruptive centre, on the opposite side of the pile to the direction of collapse. These are **major sector collapses**. They destroy the summit caldera, along with much of the volcanic pile, to produce large debris flows. Care must be taken not to confuse such a large collapse with a caldera even though it is likely that a summit caldera initially existed prior to collapse. The highest point of the remnants of the original volcanic pile should also not be confused with an eruptive centre. In some volcanic centres sector collapses can occur with an intact slab sliding off the side of the mountain rather than forming a debris flow. The top of the detached slab should also not be confused with an eruptive centre.

Craters, other than those on parasitic cones, can be found away from eruptive pile summits, most particularly surrounding or on the lower slopes of andesitic stratovolcanos and on the floors of major calderas. These are typically 1-2 km wide and are often filled with lakes. Usually, these are **maars** (Ulrike *et al*., 2007) produced by phreatomagmatic eruptions. Where such craters occur on a major caldera floor, where there is an associated geothermal system below them and they are comparatively small (<1 km) it is possible that such craters are **hydrothermal eruption centres**, which are of course are not limited to such a setting. These are produced entirely by hydrothermal processes and usually require boiling point with depth pressure-temperature conditions from or near the surface (Browne and Lawless, 2000).

In the figures the main **bore field** for each field is indicated. In this case this means the main contiguous area of drilling pads. This need not represent the full exploitable size of the geothermal field, as some of the wells are deviated, not all the field may have been drilled or successfully drilled and since the area of the bore field has been estimated from public domain data and the AVA images may not be totally up to date.

The Indonesian bahasa (language) term for mountain "*Gunung*" has been abbreviated as "G." throughout and distinguishes the names of volcanic eruptive centres from geothermal fields named after eruptive centres.

3. INDIVIDUAL FIELD INTERPRETATIONS

3.1 Awibengkok

A 3.3 km wide arcuate feature lies to the west of the Awibengkok bore field; it is an old caldera (Stimac *et al*., 2008); Figure 2. Further surrounding the bore field are sector collapses at G. Endut, G. Gagak and G. Perbakti volcanic centres. The sizes of the cirque of the collapse at G. Perbakti and to a lesser extent at G. Gagak are suggestive of the original presence of summit calderas, whereas at G. Endut the size of the cirque is that of a crater breach. Another much larger arcuate structure can be seen immediately east and northeast of the bore field, with possibly a large debris flow towards the southwest, which in the bore field to the northeast may be covered by the products of resurgent volcanism. A major collapse feature can thus be interpreted. If this is the case, it is possible that there was originally another andesitic stratovolcano originally present in between G. Endut, G. Gagak and G. Perbakti. It has now been largely destroyed, but has been the site of continued volcanism, of a silicic nature. The size of the collapse is suggestive of the original presence of a summit caldera and associated ring fractures.

The sequence of volcanic features at Awibengkok is; stratovolcano formation followed by caldera collapse in the west and formation of a multi-centered volcanic pile to the east. Some of these centres developed summit calderas and underwent sector collapse, with resurgent silicic volcanism in the central pile, which had a major sector collapse. A summit crater sector collapse occurred at G. Endut.

2.2 Wayang Windu

The most obvious volcanic landform of note at Wayang Windu is the multiphase summit caldera of G. Malabar Bogie *et al*. (2008); Figure 3. There are some major slope failures on G. Malabar, but as these lack cirques and appear to be closely related to major structures, should be considered tectonic landforms specific to an eruptive centre, rather than volcanic landforms that may be of use in understanding other eruptive centres. The lack of a major sector collapse of G. Malabar is likely to be due to the abundance of shallow intrusives strengthening the volcanic pile, some of which have been exposed by erosion, with others interpreted from gravity surveys.

Sector collapses are found on the western slopes of the smaller volcanic centres of G. Gambung, G. Wayang and G. Windu. Those at G. Gambung and G. Windu are summit crater breach sector collapses. At G. Windu there has been a major sector collapse, but it is not very large, because the original Windu volcano was not very large, although a prominent ridge of G. Bedil to the north does appear to be a large lava flow from the original G. Windu volcano.

The volcanic landforms at Wayang Windu formed in the sequence: formation of a large stratovolcano, repeated summit caldera collapse and then resurgent volcanism of which that at G. Gambung is dacitic. Dating of the volcanic centres (Bogie *et al*., 2008) indicates a migration of volcanic activity to the south with time that has displaced the resurgent volcanism from the area of the caldera formation. Sector collapses then occurred at all three of the smaller volcanic centres.

2.3 Darajat

A long (7.5 km) prominent arcuate structure lies to the west of the Darajat bore field; Figure 3. This has been named the Kendang fault. Distinct drainage patterns on the west side of the Kendang fault suggest sector collapse of a pre-existing stratovolcano to the east (Hadi *et al*., 2005). The overall size and shape of the collapse is suggestive that there was an earlier, elongate NNE trending summit caldera present, similar in shape to the breached summit crater of G. Papandayan (Hadisantono, 2006) to the south, although larger because the collapse at Darajat was from a summit caldera . The G. Kiamas rhyolitic eruptive centre at Darajat (Hadi *et al*., 2005) could then lie on the NNE margin of the original caldera and would represent resurgent silicic volcanism associated with the caldera. Small summit caldera breach sector collapses are found immediately to the south and southeast of the main sector collapse.

The following volcanic features are thus noted; formation of an andesitic stratovolcano, caldera formation, sector collapse and resurgent silicic volcanism, plus further sector collapses in the general area.

2.4 Kamojang

Healy and Mahon (1982) interpret the arcuate structure surrounding the Kamojang bore field as a caldera; Figure 3. There appears to be a debris flow from this caldera towards the northwest rather than a simple erosional breach, so it is likely that this is a partial summit caldera sector collapse structure.

A sector collapse from a small summit caldera occurs immediately northwest of the caldera rim. It is likely that this marks a resurgent volcanic centre that is located on the caldera rim.

Volcanic features at Kamojang are thus; formation of a stratovolcano, caldera collapse and then sector collapse of part of one margin of the caldera; with sector collapse of a resurgent adjacent volcanic centre.

2.5 Dieng

The clear boundary of a major caldera formed on a large andesitic stratovolcano lies north and northwest of the Dieng bore field (Layman *et al*., 2002); Figure 4. A later stratovolcano to the south of the bore field may lie on the southern continuation of the caldera margin. The later stratovolcano shows a summit caldera breach sector collapse. Towards the southeast of the summit there is a lake with an outline and size suggestive of it being a maar. Immediately within and outside of the bore field are a number of circular features on strike from the southeastern maar that are also of a size and shape suggestive of them being maars. The setting, of them being immediately above a geothermal field, may mean that they could also be hydrothermal eruption craters. However, since boiling point with depth conditions do not prevail in the Dieng field (Layman *et al*., 2002) this is unlikely to be the case. Perhaps these craters represent an intermediate situation between phreatomagmatic and hydrothermal in which magma is entering a geothermal system at depth to trigger the explosions that formed the craters. They could also be due to nearly cold gas accumulations as Giggenbach *et al*. (1991) postulated.

The sequence at Dieng is: formation of a large stratovolcano, formation of a major caldera, resurgent volcanism and then the formation of maars and a summit caldera sector collapse.

3. COMMON LANDFORMS

The most obvious volcanic landform associated with the successfully developed geothermal fields is of course an original large andesitic stratovolcano (Table 1). At Wayang Windu the andesitic stratovolcano has been preserved as G. Malabar, but there has been migration of resurgent volcanic centres to the south. In comparison, in the other fields the resurgent volcanism is concentrated in or near the original stratovolcano and only remnants of this original volcano remain.

Table 1. Summary of Volcanic Features of the Successfully Developed Geothermal Fields of Java.

	Awibengkok	Wayang Windu	Darajat	Kamojang	Dieng
Early stratovolcano	Yes	Yes	Yes	Yes	Yes
Caldera	Yes	Yes	Yes	Yes	Yes
Resurgent volcanism	Yes	Yes	Yes	Yes	Yes
Major sector collapse	Yes	Yes	Yes	Yes	No
Sector collapse in vicinity	Yes	Yes	Yes	Yes	Yes
Maar	No	No	No	No	Yes

Following the initial formation of the large stratovolcano there has then been the formation of an associated caldera. These are clearly present at Dieng, Wayang Windu and Kamojang, but are inferred at Darajat and to a larger extent at Awibengkok, although there is an earlier caldera at Awibengkok to the west.

There has then been resurgent volcanism, some of which is silicic. This includes that in the early western caldera at Awibengkok, which was drilled and found to be too cold to be productive (Stimac *et al*., 2007). In this case this may be a reflection of the age of the resurgent volcanism. Some of the resurgent volcanism in the other fields is located on or is interpreted to occur on the caldera rim.

Sector collapses, are found to occur as major collapses associated with summit calderas and within the resurgent volcanic centres; other sector collapses are common surrounding the fields. However, it is the major sector collapses that most closely mark the location of the geothermal resource.

4. IMPLICATIONS FOR FIELD GENESIS

The long series of events that are recorded in the various landforms identified at the successfully developed fields indicates that there has been extensive, protracted magmatism in these areas. These are thus very mature volcanic centres, which since they have developed calderas have associated intrusives at depth and since there is continued volcanism with rock chemistries suggestive of magmatic differentiation, there has been a continued history of intrusive activity at depth.

Generally, five stages in the maturation of an andesitic stratovolcano eruptive centre, which hosts hydrothermal activity, are apparent:

1) cone formation with summit crater;

2) breach of the summit crater, possibly due to localized weakening by hydrothermal alteration caused by magmatic volatile condensates;

3) summit caldera formation;

4) breach of the summit caldera, also possibly due to localized weakening by hydrothermal alteration caused by magmatic volatile condensates;

5) formation of a major sector collapse due to widespread hydrothermal alteration from condensates from gas evolution off a meteoric water dominated geothermal field.

Resurgent volcanism is not specific to any one stage, but its exact relationship to Stage 5) requires more dating information (particularly with regard to the age of the hydrothermal activity) than is currently available to clearly establish.

The early directly-magmatic hydrothermal activity is both too localized and of an unsuitable chemistry to provide economic electricity generation. To become both large enough and to have appropriate chemistry a meteoric-dominated system must form, which since it is larger produces more widespread alteration to produce major sector collapses. Thus, the formation of many major sector collapses appears to be a direct consequence of the development of an exploitable geothermal system, because of the required widespread weakening of the volcanic pile by hydrothermal alteration. There are other non-hydrothermal mechanisms (Siebert, 1984) proposed to produce sector collapses, notably; magma intrusion or gross heterogeneity of the volcanic pile. Thus some evidence for hydrothermal activity in addition to the presence of a major sector collapse should be sought in order to fully establish its exploration significance.

Where appropriate conditions apply (Bogie *et al*. 2008), i.e.: permeability strongly decreases with depth and the field is located within a high elevation volcanic pile, a major sector collapse may trigger extensive boiling in the system to initiate the formation of a vapor-dominated system as at Darajat and Kamojang or a transitional liquid-vapor system as at Wayang Windu.

Dieng differs in that rather than a summit caldera, a large caldera formed. This meant that the geothermal system formed beneath a large flat area within the caldera without the driver of gravitational instability to form a major sector collapse. The absence of a much larger volcanic pile above the geothermal field means that it is also easier for phreatomagmatic activity to vent to the surface to form maars. Noting that many maars elsewhere on Java surround or are found on the lower slopes of andesitic stratovolcanos and not where the pile is thicker. These do not occur within major calderas and are thus of less geothermal significance.

The common occurrence of summit crater breach sector collapses and summit caldera breach sector collapses in the vicinity of the successfully developed geothermal fields is a reflection that the very mature volcanic edifices which host exploitable geothermal systems have multiple eruption centres.

A further senescent stage of field genesis may be marked by strong erosional dissection leaving behind only arcuate structures interpreted as caldera margins. Such features can be observed southeast of Awibengkok (Figure 2) and south of Wayang Windu (Figure 3). These may possibly be the source regions respectively for the Cisukarame and Cilayu springs (Hochstein and Sudarman, 2008) found to the southeast of these features.

CONCLUSIONS

The successfully developed geothermal fields of Java are associated with very mature andesitic eruptive centres that have undergone caldera collapse followed by resurgent volcanism, sector collapses and in one case; maars.

Major sector collapses best mark the location of geothermal resources, but both summit crater and summit caldera breach sector collapses are common in the vicinity of the fields.

The importance of major sector collapses is that they require widespread hydrothermal alteration to extensively weaken volcanic piles to form; this usually requires a large meteoric water hydrothermal system to be present, which is the prime target for an exploitable resource.

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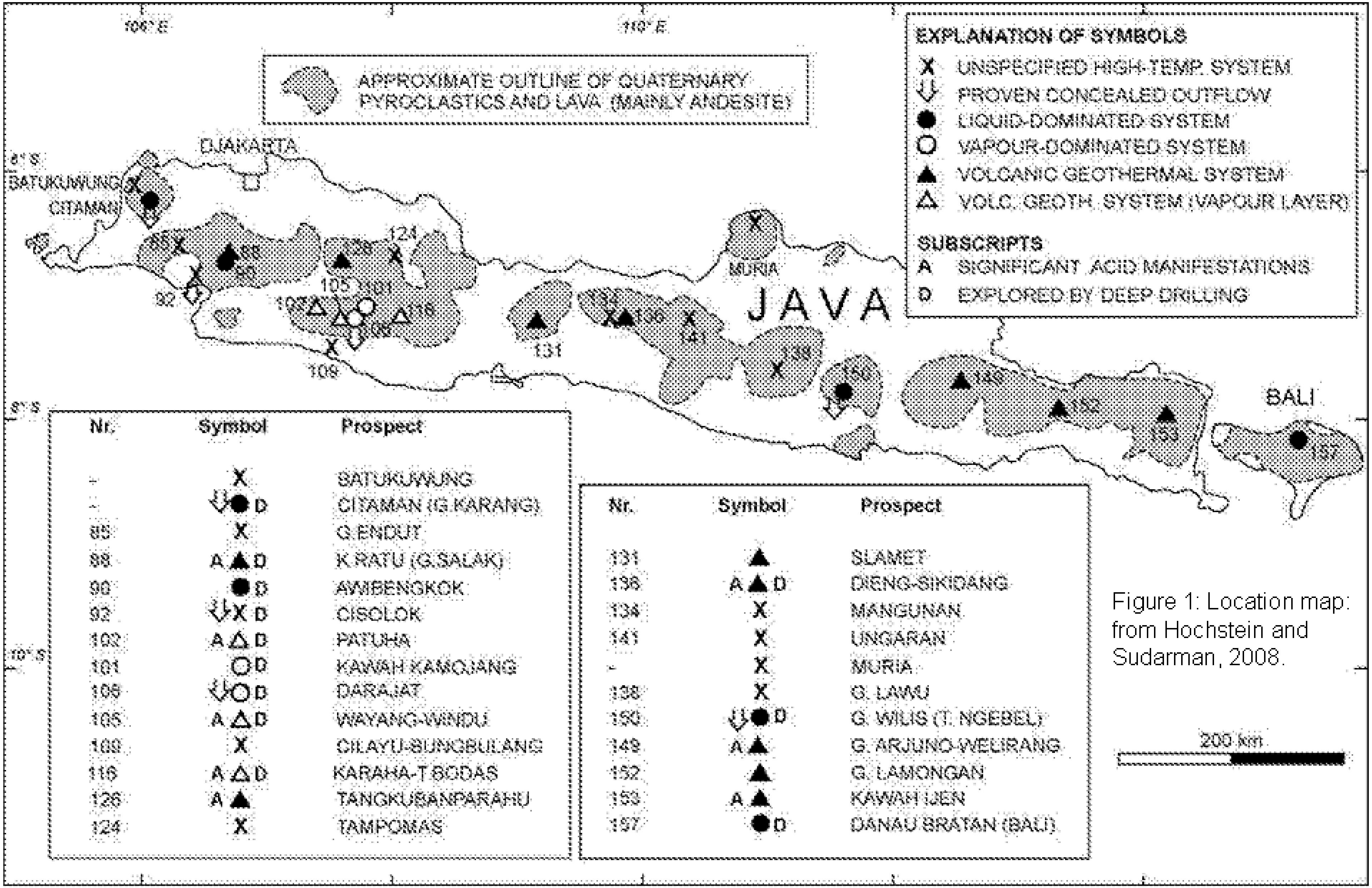

Nr.	Symbol	Prospect
-	X	SATUKUWUNG
-	⇩● D	CITAMAN (G.KARANG)
85	X	G.ENDUT
88	A ▲ D	K.RATU (G.SALAK)
90	● D	AWIBENGKOK
92	⇩X D	CISOLOK
102	A △ D	PATUHA
101	○ D	KAWAH KAMOJANG
106	⇩○ D	DARAJAT
105	A △ D	WAYANG-WINDU
109	X	CILAYU-SUNGBULANG
116	A △ D	KARAHA-T.BODAS
126	A ▲	TANGKUBANPARAHU
124	X	TAMPOMAS

Nr.	Symbol	Prospect
131	▲	SLAMET
136	A ▲ D	DIENG-SIKIDANG
134	X	MANGUNAN
141	X	UNGARAN
-	X	MURIA
138	X	G. LAWU
150	⇩● D	G. WILIS (T. NGEBEL)
149	A ▲	G. ARJUNO-WELIRANG
152	▲	G. LAMONGAN
153	A ▲	KAWAH IJEN
157	● D	DANAU BRATAN (BALI)

Figure 1: Location map: from Hochstein and Sudarman, 2008.

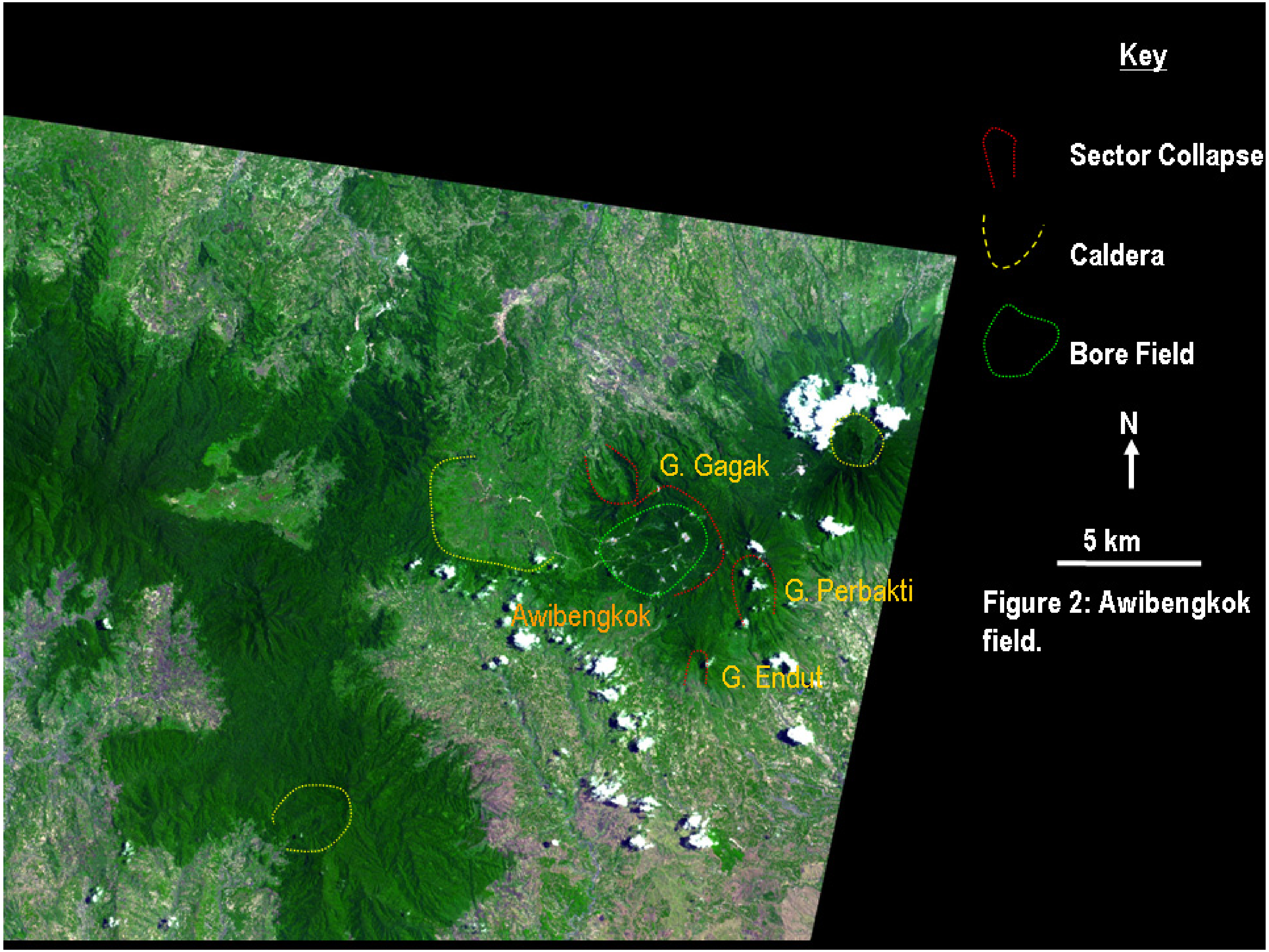

Figure 2: Awibengkok field.

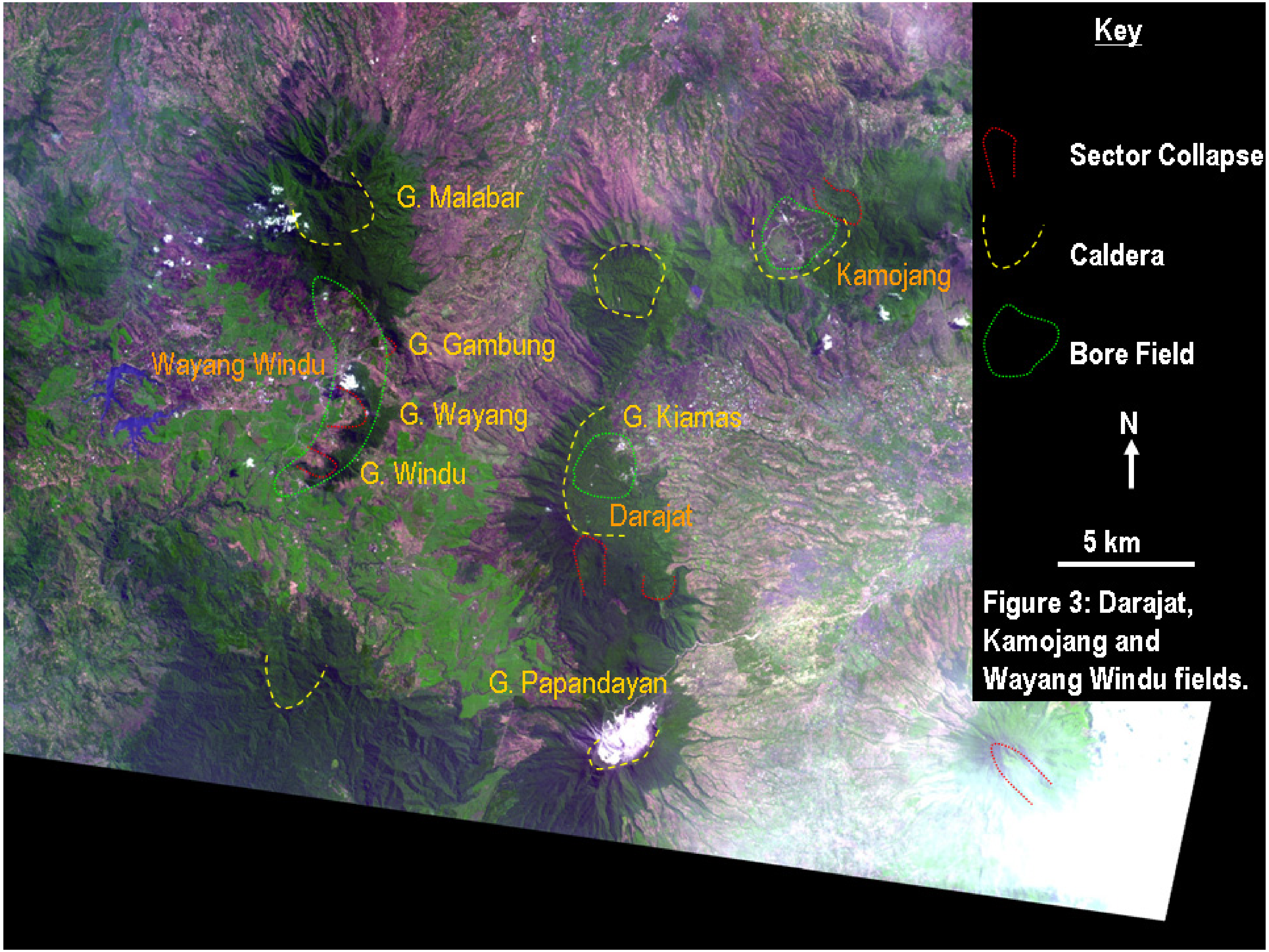

Figure 3: Darajat, Kamojang and Wayang Windu fields.

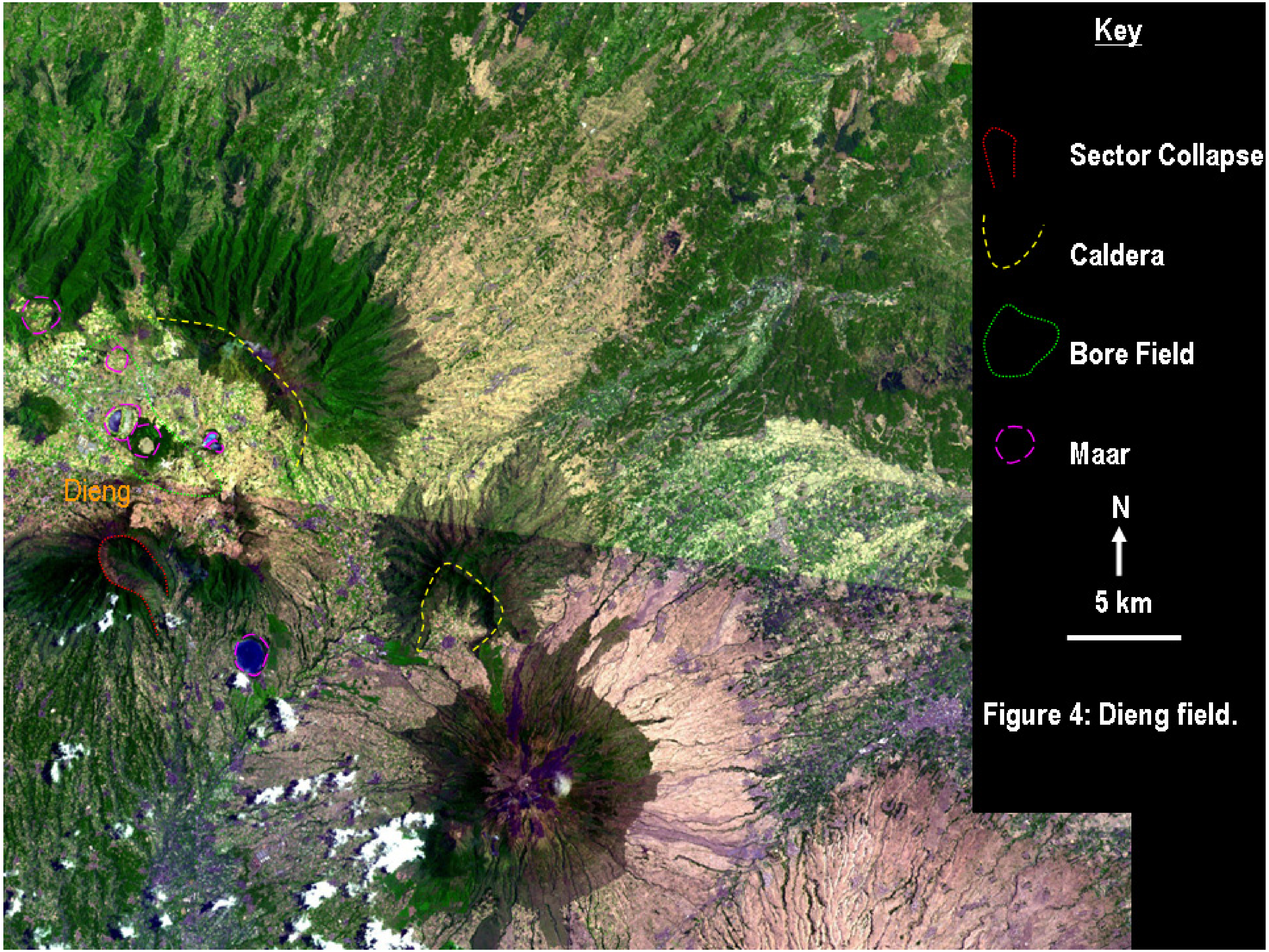

Figure 4: Dieng field.