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THE APPLICATION OF A VOLCANIC FACIES MODEL TO AN ANDESITIC STRATOVOLCANO HOSTED GEOTHERMAL ,SYSTEM AT WAYANG WINDU, JAVA, INDONESIA

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SUMMARY - Volcanic facies models for andesitic stratovolcanoes have been utilised in volcanological studies and in exploration for mineral deposits. A four facies model has now been successfully applied to establish a stratigraphic sequence at Wayang Windu geothermal project where overlapping andesitic volcanic piles of similar lithological character are present in the wells. Formational boundaries can be defined where there are rapid non-systematic changes in facies, and the proximity to eruptive centres defined by lateral gradational changes in facies. Structural data and primary mineralogical indicators of different stratigraphic units are in agreement with the facies as are K-Ar dating and geochemical analysis of fresh surficial rocks.

1 INTRODUCTION

The facies concept is widely used in the study of sedimentary rocks and can also provide a useful tool for the study of volcanic products (Walker, 1987), since fossils are rare in volcanic piles, and extensive use of radiometric dating and rock geochemistry is generally impractical, only lithostratigraphy is left by which volcanic piles can be stratigraphically mapped. However, volcanic piles contain lithological units of very similar appearance with extremely complex distributions. Standard stratigraphic methods break down because one lithological unit can suddenly disappear or cannot be readily distinguished from others. Facies on the other hand are more continuous and have more complex and hence more distinctive identifying characteristics. Although it should be noted that the facies dealt with here are strictly facies associations.

A facies is a contiguous body of rock with clearly identifiable unifying characteristics. A facies model is a group of related facies. A single facies can range in scale from outcrop to regional levels, but is most usefully defined on an intermediate scale. The concept is very similar to that of a formation in that one of the aims is to establish a mappable body. However, volcanic facies are also inter-related to each other as parts of a volcanic centre, and the identification of a facies has predictive value, whereas this need not be the case for different formations. Different facies may be part of one formation and be made up of numerous lithological units. Therefore there are two different sets of unifying characteristics for a facies, one compositional and one spatial. The set of compositional characteristics are: what particular lithological types are present, and in what proportion? The spatial characteristics are: what is the relationship with bordering facies, and what is their distribution with respect to the eruptive centre?

2 VOLCANIC FACIES

The major lithological divisions in volcanic facies are between lavas, pyroclastics and epiclastics. The key features of lavas are their thickness and the degree of autobrecciation. The main features of pyroclastics are the thickness of beds and the size and nature of clasts. With regard to epiclastics it is most important to distinguish mass flow deposits from fluviatile deposits. Mineralogical characteristics may be unique to individual lithological units, rather than characterising the facies as a whole, and should be used with caution. However, this is not to say that major mineralogical differences should be ignored. Volcanic facies vary widely between different types of mineralogically different eruptive centres, and it is always possible for these to overlap, particularly where there is a significant time gap between them. On the other hand, the same eruptive centre can produce mineralogically different products at different times.

To determine spatial characteristics requires combining geological data from a number of different points to identify the facies and progressive changes within it. The type of bordering facies and what direction it lies can then be predicted. The nature of the border is very important. In an undisturbed individual volcanic sequence, borders are usually gradational. Sharp borders indicate that either there are overlapping volcanic centres, there has been an erosional break, or there is a structural break.

3. FACIES MODELS FOR ANDESITIC STRATOVOLCANOES

A number of facies models, of increasing complexity, for andesite volcanoes have been put forward. The original model of Williams and McBirney (1979) defines three separate facies, although a multiplicity are possible, for example the models of Vessell and Davies (1981), Smith (1987) and Cas and Wright (1988). However the more facies that are used, the closer they become to being individual lithological units, with their inherent problems, as discussed above. In making three dimensional interpretations, for example of a drilled geothermal field, four facies are adequate; such a model is presented in Figure 1. It is a composite based on those given by the authors above, and the observations of the current authors on stratovolcanoes and their fossil equivalents in the Philippines, Indonesia and New Zealand.

There is some variety in the facies names between the models from different authors. The four facies used here are: the **Central, Proximal**, **Medial,** and **Distal Facies,** as outlined below.

Central Facies- These are volcanic rocks emplaced closest to volcanic vents and are distinguished by some combination of the following features: consanguineous dykes; consanguineous sills that are concordant with breccia pipes and stocks; coarse agglomerates; thick, steeply banded siliceous lavas; and coarsely stratified but poorly sorted tephra with steep initial dips. This facies is found within 0.5 to 2 km from central vents.

Proximal Facies - The rocks laid down at increasing distances on the slopes and outer flanks of a large volcanic complex have many of the following features: dominated by broad, thick partially autobrecciated lavas and intercalated coarse grained pyroclastics, with poorly sorted pyroclastic breccias, they may be cut by consanguineous dykes and they have moderate to steep initial dips. Siliceous domes may also occur on the flanks of stratovolcanoes as part of a proximal facies. This facies surrounds the central facies, and extends up to 5 to 10 km from central source vents.

Medial Facies - These rocks are laid down on the outer flanks of the volcano: pyroclastics dominate over lavas, which can be strongly autobrecciated. Lahars have angular or subangular blocks up to 10 m or so in diameter are intercalated with pyroclastic layers with good sorting and grain sizes mainly in the lapilli to coarse ash range. Clastic debris is reworked by water; and moderate to shallow initial dips are found. This facies is located up to 10 to 15 km from central vents.

Distal Facies - Volcanic rocks laid down well beyond the base of a large volcano tend to have a greater lateral continuity than those of inner zones and they conform more closely to conventional stratigraphic criteria, as epiclastics predominate.

Proximal and medial facies are deposited on the slopes of volcanoes and will form sequences dipping away from the centre, at the angle of their repose, whereas distal facies will be relatively flat lying, occurring on the ring plain around the volcanic centre. These facies will all relate to one individual eruptive vent, however typically andesite stratovolcanoes are more complex. The central vent may move with time, or there may be overlapping eruptive centres and parasitic cones. Therefore some care is required to separate out separate eruptive vents.

The same concepts can be applied to silicic and basaltic volcanic centres with appropriate modifications.

4. APPLICATION TO THE WAYANG WINDU GEOTHERMAL PROJECT

The Wayang Windu geothermal project is located 40 km south of Bandung, Indonesia on the southern slopes of G. Malabar, a large andesitic stratovolcano, and on a string of smaller volcanoes trending towards the south, which includes G. Wayang and G. Windu (Figure 2).

Geological data has been gathered from examination of cores and cuttings from 22 production and reinjection wells and four continuously logged slimholes. Representative surficial rocks have been geochemically analysed for major and trace elements and K-Ar dated (Tables 1 and 2).

In addition there is geological data from downhole formation imaging utilising Schlumberger FMI and FMS tools. In the past formation imaging when used in geothermal wells, has been used mainly for obtaining fracture orientations, for example Komarudin *et al.* (1992) although Nagai *et al.* (1997) also identify lithologies. Coarser gained pyroclastics are readily identifiable by contrasts in resistivity between clasts and matrix, and lava flows are identifiable by their distinctive joint patterns. This allows bed and flow thicknesses, and clast size distribution in coarser grained

Table 1: Major and Trace Element Analysis of Fresh Lavas from Wayang Windu
(Major element oxides in wt%: trace elements in ppm)

Volcanic Centre	Method	DL	Puncak Besar	Malabar	Gambung	Bedil	Wayang	Windu
SiO_2	DIOES	0.2	54.5	57.8	63.1	59.9	61.0	
TiO_2	DIOES	0.01	0.80	0.75	0.68	0.72	0.72	
Al_2O_3	DIOES	0.02	16.25	15.50	15.50	17.39	18.52	
FeO	DIOES	0.01	7.72	6.95	6.18	6.04	6.43	
MnO	DIOES	0.002	0.16	0.13	0.13	0.13	0.13	
MgO	DIOES	0.02	7.64	4.90	2.66	2.74	3.57	
CaO	DIOES	0.001	7.83	7.27	6.01	3.71	5.88	
Na_2O	NOES	0.003	2.62	2.97	3.37	2.59	2.97	
K_2O	DIOES	0.01	11 1	1.28	1.82	1.88	1.28	
P_2O_5	NOES	0.004	0.13	0.14	0.15	01 1	0.13	
LOI	GRAV	0.01	1.20	0.90	0.72	3.20	2.35	1.65
Total			99.96	98.59	100.32	98.41	101.54	99.80
Li	AIMS	0.1	18.5	14.5	17.0	22.5	13.0	20.5
B	DIOES	50	50	LTDL	LTDL	LTDL	50	LTDL
Sc	NOES	2	26	26	18	18	18	20
V	NOES	3	200	190	160	140	155	135
Cr	NOES	2	255	130	26	28	64	28
Co	AIMS	1	36	28	18	17	27	21
Ni	NOES	1	125	54	15	16	41	19
Cu	NOES	1	56	40	38	20	16	37
Zn	NOES	1	84	82	92	86	86	72
As	A/MS	2	4	4	4	2	2	8
Rb	A/MS	0.2	40.0	49.0	70.0	64.0	47.0	49.0
Sr	A/MS	0.1	250.0	240.0	255.0	200.0	300.0	245.0
Y	A/MS	0.1	19.0	20.0	18.5	15.5	25.5	15.5
Zr	AIMS	1	76	90	80	54	80	60
Nb	AIMS	0.5	3.5	4	4.5	5	4.5	3
Ba	A/MS	1	190	180	265	270	195	210
La	NMS	0.1	13.5	13	14.5	12	20.5	13
Ce	A/MS	0.1	29.0	27.5	31.0	28.0	40.0	28.0
Pr	A/MS	0.1	3.5	3.5	3.7	3.2	5.6	3.1
Nd	AIMS	0.1	15.0	14.5	15.0	13.0	22.5	13.0
Sm	AIMS	0.1	3.9	4.1	4.2	4.0	5.6	3.5
Gd	A/MS	0.1	4.5	4.5	4.3	3.7	6.4	3.4
Eu	AIMS	0.1	1.2	1.2	1.2	1.2	1.6	1.1
Tb	AIMS	0.1	0.7	0.8	0.7	0.6	1.0	0.6
Dy	A/MS	0.1	4.0	4.3	3.8	3.5	5.2	3.1
Ho	AIMS	0.1	0.8	0.8	0.7	0.7	1.0	0.6
Er	A/MS	0.1	2.2	2.5	2.3	1.9	2.9	1.8
Tm	AIMS	0.1	0.4	0.4	0.4	0.3	0.4	0.3
Yb	AIMS	0.1	1.9	2.3	2.1	1.9	2.6	1.8
Lu	A/MS	0.1	0.4	0.4	0.4	0.3	0.4	0.3
Pb	AIMS	2	8	8	10	14	10	10
Th	NMS	0.1	6.0	6.0	8.4	8.6	6.4	7.0
U	A/MS	0.1	1.2	1.4	2	1.6	1.4	1.5

Abbreviations

A/MS	Acid Digestion; analysed by ICP Mass Spectrometry.
NOES	Acid Digestion; analysed by ICP Optical (Atomic) Emission Spectrometry.
DL	Detection Limit.
D/OES	Alkali Fusion; analysed by ICP Optical (Atomic) Emission Spectrometry.
GRAV	Gravimetric.
LOI	Loss on ignition.
LTDL	Less than detection limit.

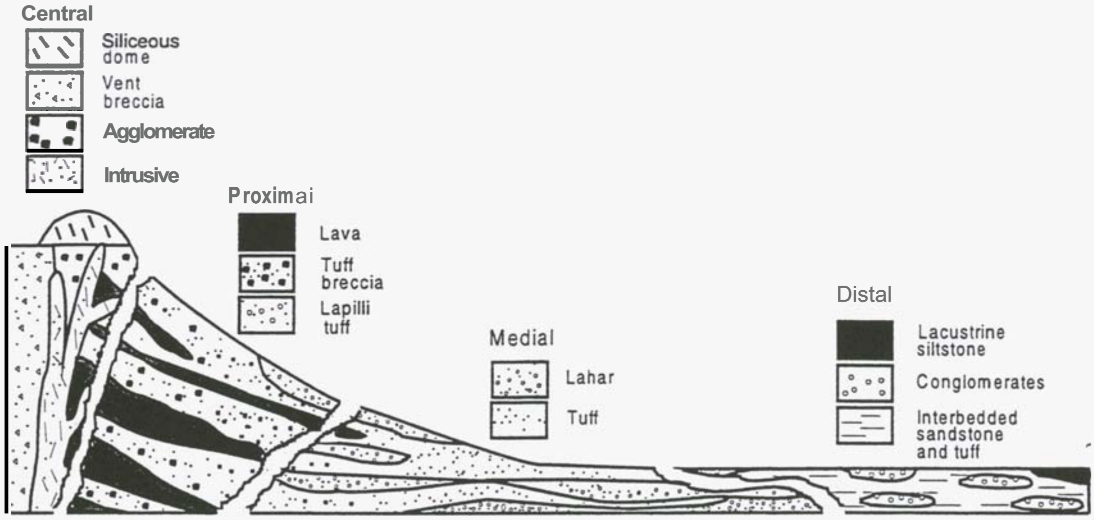

Figure 1 - Four facies model of a structurally undisturbed andesitic stratovolcano.

Figure 2 - Topographic map of Wayang Windu area.

pyroclastics to be established. Dips of beds are also determined aiding identification of facies by determining initial dips and identifying angularunconformities between formations. Five formations have been defined with formational boundaries represented by sharp changes in volcanic facies and/or where an angular unconformity is found.

A north-south cross section along the main axis of the Wayang Windu geothermal field is presented in Figure **3.** The formation containing the youngest lavas, the Wayang Windu Formation, is easily distinguishable because it contains quartz xenocrysts. The oldest formation, the Loka Formation, is also distinguishable where its dip can be determined, but the other formations contain very similar rocks and it is only if they are grouped into facies that formation boundaries can be defined.

The Wayang Windu Formation is exposed at the surface as an approximately north-south trending ridge of small volcanic centres. They consist of quartz andesite overlying quartz andesite crystal tuff. They contain a dis-equilibrium phenocryst and crystal clast assemblage of plagioclase, augite, hypersthene, olivine, hornblende and magnetite with xenocrysts of quartz and hence have a mixed origin. The main eruptive centres of G. Bedil, G. Wayang and G. Windu have K-Ar dates of 0.18, 0.49 and 0.10 Ma. respectively (Table 2) and are all geochemically distinct, although the REE pattern of G. Windu is similar to the rocks from Malabar and it is possible that one of the mixing end-members is derived from the same source as the Malabar rocks. In terms of volcanic facies, because they are small volcanoes, they do not strictly fit into the facies model of large stratovolcanoes, but are too far removed from the Malabar vent to be considered to be parasitic features. Therefore they are better described as a series of coalesced satellite vents to Malabar and hence constitute their own central facies. They are included in one formation by the utility of the readily identifiable quartz xenocrysts and preserved morphology.

Location	Age (Ma)
G. Puncak Besar	**0.23 ± 0.03**
G. Malabar	**0.23 ± 0.03**
G. Gambung	**0.23 ± 0.01**
G. Bedil	0.19 ± 0.01
G. **Wayang**	0.49 ± 0.01
G. **Windu**	0.10 ± **0.02**

Table **2:** K-Ar Dates

The Malabar Formation is also exposed at the surface, as the large stratovolcano G. Malabar with a prominent peak G. Puncak Besar (Figure **2)** and is partially overlain by the northern portions of the Wayang Windu Formation. It consists of interbedded lavas, breccias and lahars of basaltic andesite to dacite in composition. All the lavas contain phenocrysts of plagioclase, augite, hypersthene and magnetite, with the basaltic andesites containing olivine and the dacite hornblende and quartz. The rocks have K-Ar dates of **0.23** Ma **± 0.03** (Table **3)** and geochemically form a differentiated series and have similar REE patterns, (Table 1 and **2)** and are largely distinct from the Wayang Windu Formation. Given their wide distribution they are likely to be derived from a large magma chamber and since the dacite contains hornblende, the magma chamber is likely to be comparatively shallow (Gill, 1981). In the drilled area, there is a gradation between a proximal facies on the southern slopes of G. Malabar, where lava flows predominate and the parasitic dacite dome of G. Gambung is found, to a medial facies where intercalated lahars and medium grained pyroclastics predominate further south of G. Malabar. This is consistent with the occurrence of the eruptive centre in the north, (Figure **2).**

The Pangalengan Formation, possibly of Mid-Pleistocene age, is poorly exposed at the surface and underlies part of the Malabar Formation and all of the Wayang Windu Formation. It has a basal conglomerate overlain by interbedded sandstones, siltstones and minor lignite beds, which are in turn are overlain by intercalated lahars and fine grained tuffs. **Apart from** the lignite the rocks are andesitic in composition. Initial dips are predominantly to the northeast and average 12°. Such rocks define a distal facies which grades towards a medial facies upwards, suggestive of the lateral growth of a volcanic pile. The pile thickens towards the south and lavas are found in the southernmost wells, indicating transition to a medial facies nearing an eruptive centre in the south.

The Waringin Formation, possibly of Mid-Pleistocene age, consists of andesitic pyroclastics and lavas but is too altered to accurately determine phenocryst mineralogy. In the north and near its base it consists of intercalated fine and medium grained pyroclastics. In the south in the bottom half **of** the formation there are low initial depositional dips averaging 14". There are progressively a higher proportion of lavas higher in the formation and initial dips increase, averaging **22"** in the top half **of** the formation. Hence there is a transition fiom a near-medial proximal facies to a near central proximal facies going up the volcanic pile, reflecting progressive lateral growth of the volcanic pile **from** a volcanic centre in the south.

The Loka Formation, possibly of Pliocene age, consists of crystal tuffs, lapilli tuffs and subordinate lavas and hence is a medial facies. Dips of 40° to the southwest are too steep to be initial, and an angular unconformity exists between the Loka Formation and the Waringin Formation. Insufficient data is available from the Loka Formation to establish any gradation in facies to be able to define an eruptive centre, and as this formation is regional, it will have multiple eruptive centres.

5. CONCLUSIONS

A four facies model for large andesitic stratovolcanoes can be used to define stratigraphic units within complex andesitic volcanic piles.

Such a model has been applied to the Wayang Windu geothermal field, allowing the definition of formations in sequences of similar rocks, where there are sudden non-systematic changes in facies.

Lateral gradational changes in facies are consistent with known eruptive centres in surficial units and indicate the direction of eruptive centres in subsurface units. Vertical gradations in facies can also be found, consistent with expanding volcanic pile with time.

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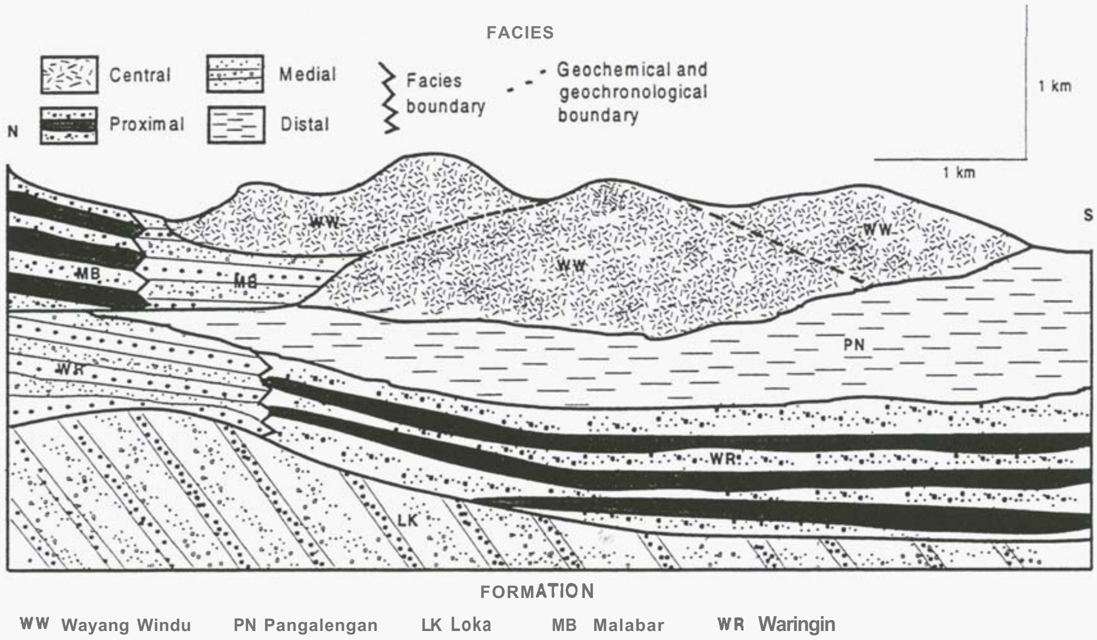

Figure 3 - North-south cross section of the drilled portion of the Wayang Windu geothermal system showing the relationship between volcanic facies and formations.