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Morphostructural Development of Gunungsewu Karst, Jawa Island

Perkembangan Morfostruktur Kars Gunungsewu di Pulau Jawa

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Abstract

Gunungsewu Karst (also known as Sewu karst in the literature) is synonymous with morphology of a carbonate terrain dominated by hills crowned by accordant-level tops that developed in a humid tropical environment by comparatively more rapid dissolution and denudation. In addition, the hills are sinoid to cone-shaped. Surface drainage is negligible compared to subsurface water flow. Abandoned channel segments and spatial arrangements of karst hills have been found to correspond with fracture patterns that are genetically associated with the regional compression direction of Jawa Island. Images derived from space platforms show many landform patterns that were neither known from ground-based nor from aerial photograph study. Landforms arranged in ring, multi-ring, spiral, polygonal, and long linear to serpentine patterns are common beside the expected depressions of dolines, poljes, and uvalas. The orientations of the long linear ridges appear to change systematically from those near the coast to those located inland. These linear ridges are interpreted as depositional fronts, most likely representing breaker zones. The youngest depositional ridge fronts, located nearest to the present shoreline, are parallel to the geological strike of Jawa Island. Toward the island's interior, linear depositional fronts deviate in orientation by as much as 40^{o}. This is now interpreted to have resulted from counterclockwise rotation of the Gunungsewu microplate since the late Middle Miocene. Similar CCW rotations are indicated by the paleomagnetic orientations of igneous rocks located farther east in the southern range of the island. Active tectonics is expressed in stage-wise net uplift of Gunungsewu whereas regional tilting appears negligible. Stacked and often paired river terraces (thus suggesting land uplift) have been used to relatively date paleoarcheological finds. Very recent uplift on the coast show up in lazy-V limestone notch profiles, and occasionally by stacked notches. At the Klayar coast, slight northward tilt of a few degrees are expressed as counter-regional inclination of a subrecent abrasion platform.

Keywords: Gunungsewu karst, simple to composite landforms, paleo-breaker lines, active tectonics

Abstrak

Kars Gunungsewu adalah sinonim dengan morfologi mandala karbonat yang didominasi oleh bukit-bukit berpuncak samatinggi. Morfologi tersebut berkembang di lingkungan tropis lembab, akibat pelarutan dan denudasi yang cepat. Kebanyakan bukit-bukit tersebut berbentuk sinoid sampai kerucut. Aliran sungai permukaan tidak ada artinya dibandingkan dengan aliran bawah-permukaan. Ruas alur kering dan susunan ruang bukit kars umumnya berkaitan dengan pola retakan yang berasosiasi secara genetis dengan arah tektonika kompresi regional Pulau Jawa. Citra bentangalam Gunungsewu yang diperoleh melalui satelit memperlihatkan sejumlah bentuk permukaan bumi yang sebelumnya tidak dikenal. Morfologi bentuk gelang, multi-gelang, spiral, poligon, serta kelurusan panjang, hingga pola berliku-liku, ternyata merupakan fenomena umum, di samping depresi berupa dolina, polje, dan uvala. Pematang linier panjang yang orientasinya berubah secara sistematis dari area dekat pantai ke arah pedalaman, ditafsirkan sebagai suatu bagian muka-pengendapan, yang lebih mungkin sebagai zona pemecah-ombak. Bagian muka-pematang pengendapan termuda, yang terletak paling dekat ke garis pantai saat ini, berorientasi sejajar dengan arah jurus geologi Pulau Jawa, namun semakin jauh ke pedalaman, jurusnya menyimpang hingga sekitar 40^{o}. Fenomena ini agaknya berkaitan dengan rotasi

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berlawanan arah jarum jam yang dialami benua mikro Gunungsewu sejak akhir Miosen Tengah, yang juga ditunjukkan oleh orientasi paleomagnetis batuan beku jauh di sebelah timur Pegunungan Selatan. Tektonika aktif terekspresikan pada hasil pengangkatan stage-wise net Gunungsewu, sementara tilting regional bisa diabaikan. Undak sungai yang tersusun dan sering berpasangan telah digunakan untuk bahan pentarikhan relatif paleoarkeologi. Pengangkatan terkini pada pantai terdeteksi pada profil ceruk batugamping berbentuk huruf V rebah, dan kadang-kadang pada ceruk tersusun. Inklinasi regional pada permukaan abrasi regional di pantai Klayar, mengekspresikan adanya pengangkatan landai berarah utara dengan kemiringan beberapa derajat.

Kata kunci: *kars Gunungsewu, bentangalam sederhana hingga majemuk, garisan pemecah ombak purba, tektonik aktif*

Introduction

The Neogene limestone terrain bounded by the Opak River in the west and by the Grindulu river system in the east displays the typical Gunungsewu karst morphology that is dominated by numerous sinoid and conical hills. Administratively, the area is called Gunungkidul of which a large part belongs to the Yogyakarta's Special Region or "Daerah Istimewa Yogyakarta" (Figure 1). A relatively narrow eastern border zone of Gunungkidul is under Central and East Jawa Provinces. The Javanese word "sewu" translates into "thousand". Flathe and Pfeiffer (1965) used "sinoid" to describe the convex hill profiles. The karst hills resemble inverted coconut half- shells, that in the local language is referred to as "batok kelapa" or "tempurung". Within longitudinal belts, the multitude of limestone hills possesses summits of nearly uniform elevation. The hill tops in the southern coastal zone are between 30 to 80 m high, while toward the hinterland summit elevations gradually increase to 350 m and slightly over 400 m above sea level. Local topographic relief is around the 50-meter range. Early investigators already interpreted the gently southward decreasing hill tops as remnants of a raised, deposition-related surface or a reef-limestone platform (among others Grund, 1914; Lehmann, 1936; Escher, 1951). Over time, the Sewu karst morphology became accepted as representing a typical advanced stage of carbonate-landform development under humid tropical conditions where denudation and especially dissolution transpire at

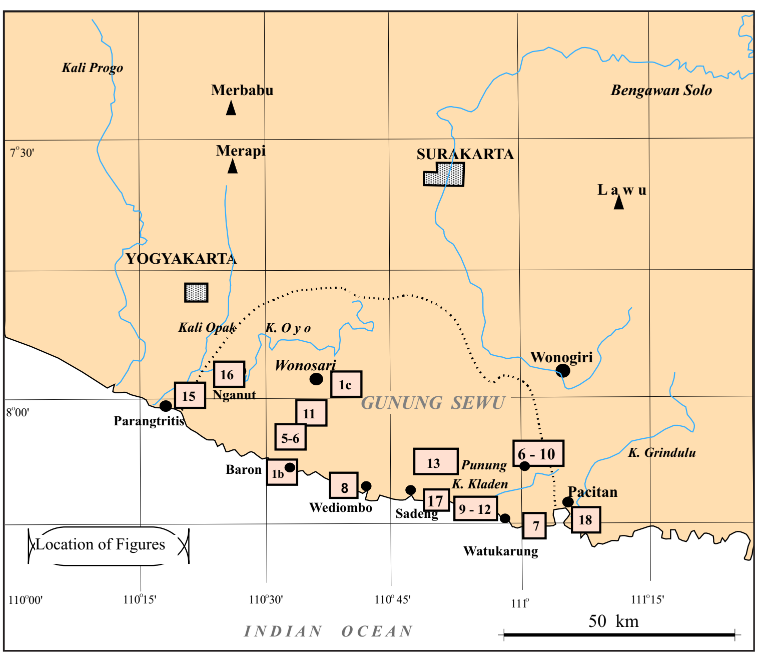

Figure 1. Index map of Sewu karst in the Gunungkidul region. Numerals in squares indicate location of the figures of this communication.

rates more rapid than in other climates. In contrast, limestone karst landforms of non-tropical regions are dominated by planar surfaces that host spatially dispersed individual to composite depressions, such as sinkholes, dolines, poljes, and uvalas. The non-tropical karst most probably represents an early stage of development. On the other hand, in the tropics, carbonate terrains appear to degrade morphologically more rapid resulting in the multitude of hill complexes such as the Chocolate Hills of Bohol, Philippines, the Pepino Hills in Puerto Rico, and the karst hills in the limestone of the Southern Mountains of Jawa Island: Karangbolong-Gunungsewu-Nusa Barung. The term cone karst or Kegelkarst for the Sewu morphology is not fully justified as sinoid profiles of the limestone hills are predominant. Slope profiles of Sewu karst hills are mainly convex (Figures 2 and 3). Such profiles may be explained as result of differential spacing of horizontal fractures in the limestone mass. The fracture spacing decreases upward (Tjia, 1969).

The SRTM (Shuttle Radar Thematic Mapper) map of Figure 4 shows the Sewu karst occupying most of the southern area of the Gunungkidul area. The Wonosari and Baturetno Basins are two large depressions, the latter holding the Gajahmungkur reservoir. The Sewu karst consists of the Wonosari-Punung Formation of Mid Miocene to Pliocene age

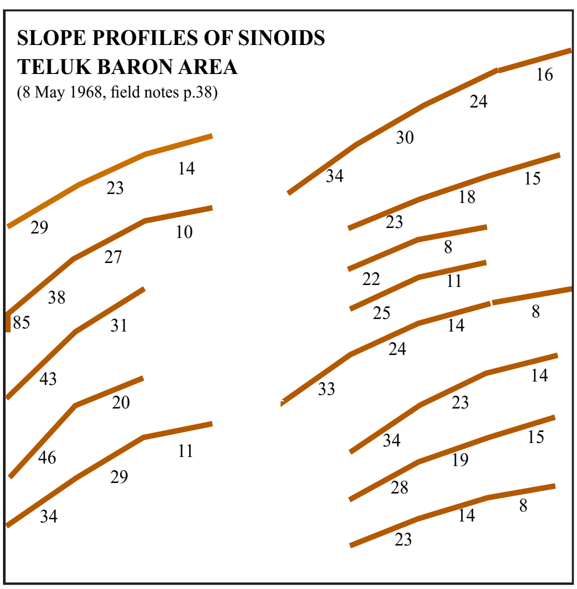

Figure 2. The sinoid karst profiles that were measured along a track from Teluk Baron towards Wonosari. Numerals are in degrees.

Figure 3. Representatives of predominant sinoid karst hills of the Wonosari-Punung limestone at Bedoyo east of Wonosari town.

(Figure 5). The formation is composed of limestone, marly to tuffaceous limestone, conglomeratic limestone, tuffaceous sandstone and siltstone (Surono *et al*., 1992). The other relevant stratigraphic units in close association with Sewu karst are the Oyo and Kepek Formations. These two formations interfinger with the Wonosari-Punung Formation. The Kepek Formation is built of marl and bedded limestone; the Oyo Formation consists of tuffaceous marl, andesitic tuff, and conglomeratic limestone. The Sewu karst terrain is covered by the 1 : 100 000 scale geological maps by Samodra *et al*. (1992), Surono *et al*. (1992), and Rahardjo *et al*. (1995).

The morphological development of karst on Jawa's southern coast is intimately associated with fractures (including faults; Lehmann, 1936 and Escher, 1951 are among several earlier investigators), whose spatial patterns show genetic relation with regional geological stress orientation (Tjia, 1962). More rapid dissolution occurs along the steep to vertical fractures, that ultimately produces remnants of the platform in the form of carbonate hillocks. Surface drainage is usually diverted into subterranean conduits. In the Gunungsewu area the hill tops very often display accordant elevation representing the position of the original platform surface. Haryono and Day (2004) recognized three karst landform groups: labyrinth-cone karst, polygonal karst, and residual cone karst. The labyrinth-cones form rectangular, oval, and straight ridge patterns. The dominant elements among the polygonal forms consists of straight ridges. Residual cone karst is characterised by isolated limestone hills dotting the terrain. This latter landform group is clearly an advanced state of destruction and dissolution of the other more coherently "packed" landforms.

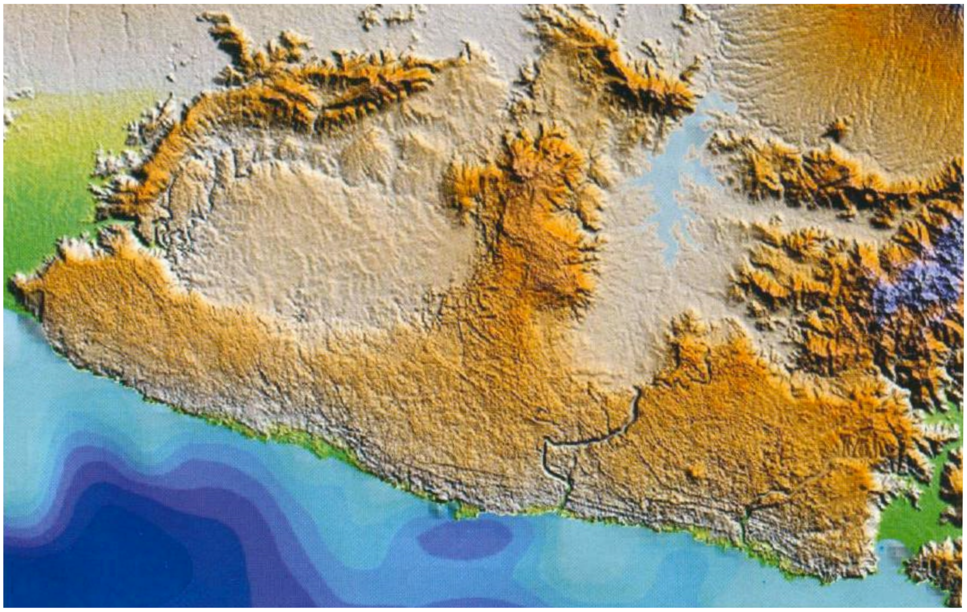

Figure 4. Space Radar Thematic Mapper image of Gunungkidul shows the Gunungsewu karst terrain bordered by the Yogyakarta Plain, the Lawu Volcano in the north, and the Baturetno Basin in the east. Distance between Parangtritis and Pacitan Bay is 90 km. The image was processed by the Geological Agency, Bandung.

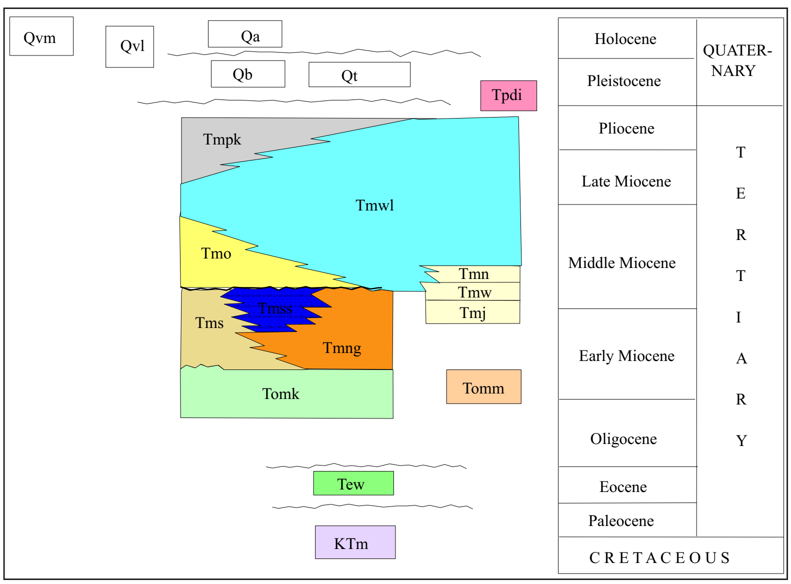

Figure 5. The abbreviated stratigraphy of Gunungkidul after Surono *et al*. (1992). The formations directly relevant to this article are the Mid-Miocene to Pliocene Wonosari/Punung-Kepek-Oyo strata and the preceding Early Miocene formations. The formations are Tmpk - Kepek: marl and layered limestone; Tmwl: Wonosari-Punung: Limestone, marly-tuffaceous limestone, conglomeratic limestone, sandstone and siltstone; Tmo: Oyo: tuffaceous marl, andesitic marl and conglomeratic limestone; Tmn: Nampol Conglomerate, conglomeratic sandstone, agglomerate, siltstone, claystone and tuff; Tmss: Sambipitu sandstone and claystone; Tmng: Nglanggran volcanic breccia, basaltic-andesitic agglomerate and lava and tuff; Tmw: Wuni agglomerate with tuffaceous sandstone and coarse-grained sandstone intercalations; Tmj: Jaten quartz sandstone, tuffaceous sandstone, siltstone, claystone, marlstone, marly limestone; Tms: Semilir tuff, dacitic pumice breccia, tuffaceous sandstone and shale; Tomn: Mandalika dacite-andesitic lava, dacitic tuff intruded by diorite dykes; Tomk: Kebobutak upper part (alternating sandstone, claystone, and thin layers of acid tuff), lower part (sandstone, siltstone, claystone, shale, tuff, and agglomerate).

This differentiation of karst landforms appears to have made use of the widely available Google terrain maps. On the same and annually updated images the author found more details of landform patterns that imply their geological origin and development. Since 2006, the author re-visited the Gunungsewu area on several occasions. These studies combining interpretation of satellite images and field observations form the base of the present article. This communication also highlights the wealth of landform information contained in the satellite terrain maps.

Landforms

Single Landforms and Landforms of Simple Patterns

Lineaments of Ridges and Valleys, Linear and Curving Ridges

Linear features or lineaments are tonal or negative/depressed as well as positive landforms on the satellite images. Segments are traceable over distances of around one to 4 - 5 km. Parallel oriented segments may form zones up to 2 km wide. On Figure 6 are presented lineament zones striking North-South (4 zones), East-northeast (2 zones), East-West (a single zone), and East-southeast (3 zones). The ESE zones are parallel to Pulau Jawa's tectonic axis. These lineament zones are interpreted to represent major fracture belts of possibly tectonic origin. Segments of the dry Sadeng valley correspond with two of the lineament directions. Other smaller lineaments have various orientations and are shown by thin lines on the figure. These shorter linears very probably represent relatively minor fractures in the Gunungsewu karst.

Over a sizable part of the Gunungsewu karst terrain km long linear ridges occur in zones of well-defined orientation (Figure 7). The karst terrain is composed of long linear-ridge zones strike North-northwest from about Teluk Baron westward. A systematic deviation of orientation is readily apparent. The ridge lineaments in the interior are North-northwest. Belts located farther south toward the shoreline are West-northwest, and while still closer to the shoreline the long karst ridges become almost parallel with the current shoreline trend. To the east of Teluk Baron, in the central part of the Gunungkidiul coastal area, linear karst ridges running parallel to the shoreline are prominent (Figure 7). There, the coastal stretch is generally parallel with the axis of Jawa Island, which is N 280^{o} W.

Initially, the author surmised these linear ridges to represent edges of stacked reef terraces in general agreement with other investigators (*e.g.* Hartono and Bronto, 2007; Samodra, 2007). Recent field observations convinced the author that the linear ridges and their crowning carbonate hillocks are mainly built of stratified limestone. Sartono (1964, reproducing a sketch by T.A. Link, 1947) clearly indicated that the Gunungsewu consisted mainly of layered carbonates, while reef bioherms are "occasional" occurrences in the terrain. In this respect, it is also incorrect to identify the numerous karst hills as residual cores of bioherms. That the majority of sinoid and conical karst hills is built of stratified carbonates has been verified in the field.

The author now proposes that the long linear ridges of Gunungsewu are relics of paleo-breaker zones. Inspection of today's world geography indicates that linearity of the frontal/seaward side of reef complexes is not uncommon. The linear plans of the Great Barrier Reef segment in the Mackay/Capricorn Management Area extend over 50 km and also over 130 km are documented on Map No. SDC041206, September 2004. The map can be accessed through the Internet. The landward side of the Queensland Trough, also of the Great Barrier Reef, is lined by stacked carbonate fronts (American Geophysical Union, EOS v. 89, No. 24, 2008). Laboratory water-tank experiments by P.D. Timmermans distinctly show the position of offshore bars to correspond with breaker zones (shown on p. 221, Escher ,1951). On an extensive gently shelving shallow sea floor, breakers can be expected to develop long linear offshore bars. The systematic changes in orientation of such long linear ridges at Gunungsewu are interpreted to correspond with counterclockwise rotation while experiencing spasmodic uplift of the Sewu karst terrain through time. This idea will be elaborated upon in a later part of the article.

Serpentine and Spiral Ridge

Simple curving ridges generally occur in parallel pairs. A curving ridge-pair sandwiches stream valleys, which are usually dry or host underfit rivers (Figure 8). The pairs of serpentine ridges extend over distances that may exceed 10 km. Such pairs

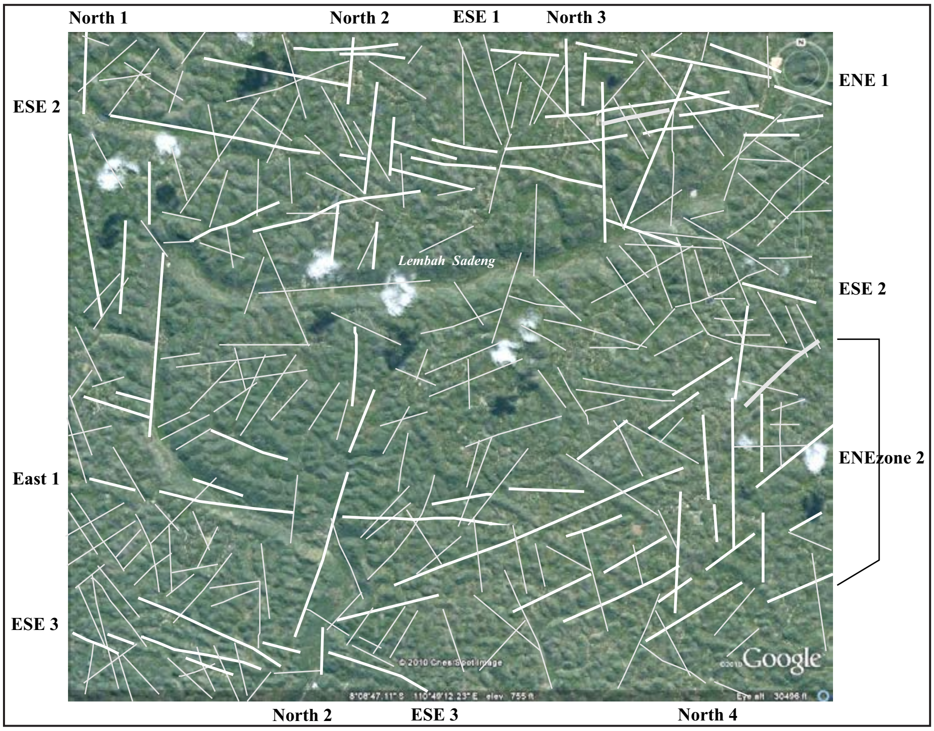

Figure 6. Negative lineaments in Sadeng region of Gunung Sewu, each measuring up to several km in length, represent fractures. The longer lineaments are probably faults and define zones of distinct orientations. Interpreted fault zones strike in four directions: North, East, East-northeast, and East-southeast. Segments of the dry Sadeng valley mimic two of the zonal orientations of faults. Major fracture zones in bold and indicated by North 1 - 3, East 1 and 3, ENE 1 - 2, ESE 1 - 3; the co-ordinates in small font refer to the position of the center of the Google image.

Figure 7. Gunungsewu karst landforms. Dotted lines are ridges, thin full lines are negative topographic lineaments; moderate sized, multiple nested oval and polygonal ridge patterns probably reflect control by the pre-limestone topographic surface. Coordinates of the center of the image is indicated. Base of the Google image is 12 km long.

occur along stretches of the Sadeng Valley and Kali Sambi and along its middle course named Kali Barong. The parallel association of serpentine ridges flanking a valley is puzzling. It is inconceivable that the ridges represent natural levees, as in the Sewu karst these positive landforms are remnants of the original carbonate rock mass, while the valley only began developing after the rock became subaerially exposed. A plausible explanation for the situation of the dry Sadeng Valley is as follows. A moderately large surface river initially carved out the valley. The planimetry of remnants of landforms along the valley became dominated by that of the latter. The "Sadeng" River eventually disappeared to become subsurface drainage. Subsequently, the subterranean channel collapsed leaving a morphology of dry valley aligned by serpentine ridges. Three major terraces within the Sadeng Valley reported by Samodra (2007) suggest that subsidence may have occurred more than once.

Figure 8 also shows a spiral ridge enclosing a relatively wide valley of similar plan. This spiral pattern possibly resulted through fortuitous merging of partially denuded landforms such as circles, ovals or polygons.

Circles, Ovals and Polygons

A remarkable number of curving ridges form distinct arcs to complete rings, circles, ovals or polygons (Figure 9). Several part-circular ridges (their centers indicated by the letter C on the figure) stand out in the drowned karst landforms of the Srau coast (coordinates of the center of the Google image is shown). Base of the image is circa 3.5 km). The ring diameters detectable on the Google images range from about a hundred meters to 4 km. Examples are also on Figures 7 and 10. Single circular ridges are among the smaller category. The positive circular topography includes the insular karst hills. Gunung Batur, a volcanic remnant at the coast of Wediombo is marked by a circular feature (Figure 10). Hartono and Bronto (2007) already noticed this feature. In the Gunungsewu karst terrain, other features associated with the smaller sized circular ridges are dolines/ sinkholes and denudational depressions (Figure 8). The latter category is clearly seen in the drowned karst topography at the Srau coast. Many circular and ring-like drowned karst islets occur in the Raja Ampat Regency (encompassing the islands Salawati, Batanta, Kofiau and Misool in the West Papua region), and the Tukangbesi Islands southeastern Sulawesi. Drowned karst landforms of similar plans are also known from the Palau Islands in the western Pacific. The abundance of circular landforms in the Sewu terrain is remarkable. To author's knowledge, none of the other investigators had attempted an explanation of their existence. Among the most plausible explanation is that the circular landforms in

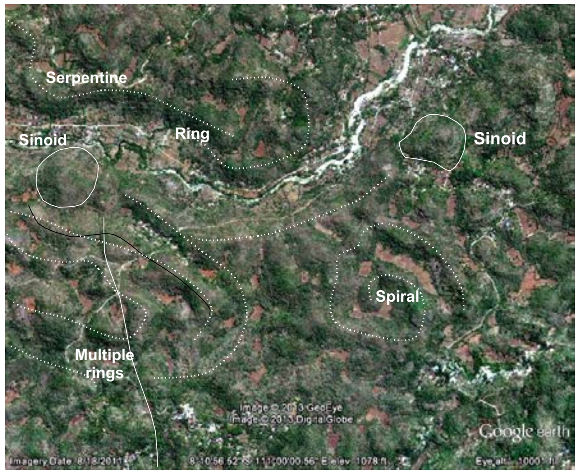

Figure 8. Serpentine ridge segments line the Kali Barong valley. Individual sinoid hills and a doline are present. The origin of the spiral ridge landform is problematic. Discussion in the text. The base of the figure is approx. 4 km long. Location shown on Figure 1.

Figure 9. Circular karst landforms, whose centers are marked in the figure, are accentuated by drowning. The largest, South-central circular landform is almost 500 m across Srau coast, Gunungsewu. Location is on Figure 1.

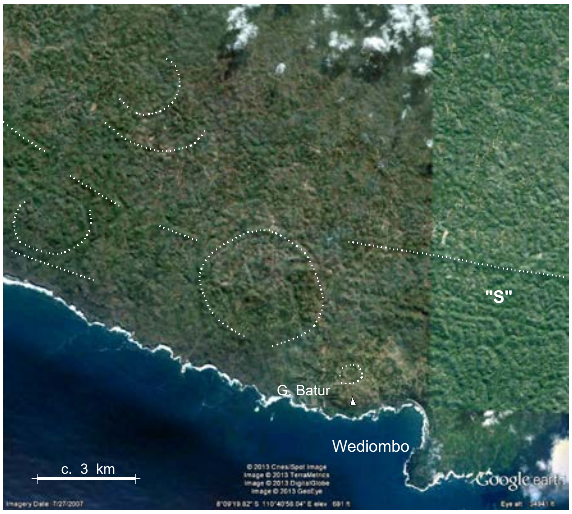

Figure 10. Dotted lines are ridges in the Gunungsewu karst. One long ridge ends in a “hook” (marked “S”). Gunung Batur is a relic volcano, the only volcanic outcrop known from the region. Circular landforms mark G. Batur and occur as well as in the karst terrain.

Figure 11. Multiple circular and oval ridges are abundant in the Wonosari-Punung karst terrain. One straight-sided polygonal landform occurs in the top center of the figure. Agricultural terraces mimic the topography of Oyo beds at the Buyutan coast. Several of the circular features are highlighted. Long lineaments are interpreted as major fractures.

Gunungkidul were atolls that developed atop sinking seamounts and other drowned hill/mountain relief. In Gunungkidul, the Wonosari-Punung-Oyo strata are separated by angular unconformity from older formations (Figure 5). In other words, this unconformity could well represent land surface composed of hills of rounded plans that served as foundations for the growing reefs.

The relatively small positive landforms associated with circular outline consist of individual sinoid and cone-shaped karst hills, representing residual parts of the raise carbonate platform (Figure 8).

Straight to irregular sided polygons are also relatively small and some may be water-filled (Figure 11). Irregular sided polygons mark small depressions of up to a hundred or so meters across. This depressed landform type has probably developed by a combination of denudation creating the hollow and subsequent infilling of sediments that onlapped onto the base of the surrounding hills.

Pseudo-slide Patterns

A remarkable combination of linear ridges and circular landform is displayed near a bend of the dry Sadeng valley and also occur in less distinct form at a few other locations in Sewu karst. For convenience of reference, this morphological ridge and circular feature composite is named “pseudo-slide marks”. The circular feature appearing as a morphological unit with the two ridges resembles trailing tracks. The circular ridge (located at East of center in Figure 12) is prominent and is at the southeast end of two parallel ridges. As explained earlier, the ridges are interpreted as depositional

Figure 12. Long limestone ridges in two orientations and ‘pseudo-slide marks” in the area of the dry Sadeng Valley of Gunungkidul. The “pseudo-slide marks” consist of a circular ridge attached to two long parallel ridges. The paired ridges “trail” in NW and in SE direction, respectively.

fronts marking paleo-breaker zones, while the circular landforms were probably once atolls. In this particular instance, it is envisaged that an atoll (the circular landform) combined with a long strip of shallow submerged ridge that was flanked by breaker zones. At the NW end of the parallel ridges are three other, recognizable ring-like ridges. Diameters measured about 1 km. To the SE of the Sadeng valley occurs an other "pseudo-slide mark" association. The linear parts of the marks trend West-northwest. Center of the Google image is at 8^o 06' 14.05" S, 110^o 45' 51.50"E, elevation is 1179 feet or 354 m.

Composite Landforms

The singular, simple landforms of Sewu karst may combine into definitive patterns. Such composite landforms fall into two categories.

Concentric Multiple Ring or Oval Patterns

On the satellite images multi-ring patterns have diameters of several km (Figures 7 and 11). Double rings are most common among this landform category. More than two concentric rings of ridges are shown on Figures 7 and 11. Figure 13 shows a very large landform pattern consisting of numerous concentric oval ridges near Kuwangan Village to the South of Wonosari. More than ten concentric oval ridges can be counted. Part of the more than 6-km wide oval landform is cut by a WNW - ESE fault (straight lineament).

Figure 13. A large landform in Gunungsewu karst consisting of a large multi-oval ridge complex, almost 6 km across, near Desa Kuwangan, South of Wonosari town (location on Figure 1). A fault striking WNW - ESE forms the southern termination of the landform. Base of the figure is 6 km long.

The pattern of multiple concentric ridges strongly suggests outward growth of calcareous depositional fronts around a central edifice.

Nested Polygons

Straight-edged polygonal ridge patterns are rare as Sewu karst landform. An example of nested polygons is on Figure 14.

Plans of such types of polygons presumably mark control by fractures during topographic degradation.

Figure 14. A nested polygonal landform of limestone ridges in the vicinity of Kali Kladen outlet. The southeastern side of the polygon consists of several parallel arcuate ridges. The figure is 4.5 km high.

Discussion

Morpho-Structural Development

Orientation and distribution of long linear ridges were pointed out in Figure 6 that linear ridges may bunch together and form belts of definitive orientation. These belts of linear ridges most probably define tectonic fault zones. Long, slightly curving ridges to the west of Giritontro trend northwest (Figure 15). Two of such ridges belong to the "pseudo-slide" feature discussed earlier and that have been classified as paleo-breaker zones. A 1.5 km wide belt consisting of landforms of diffused pattern that is contained between two lineaments striking a few degrees West of North transect some of the Northwest ridges. This belt is interpreted as part of

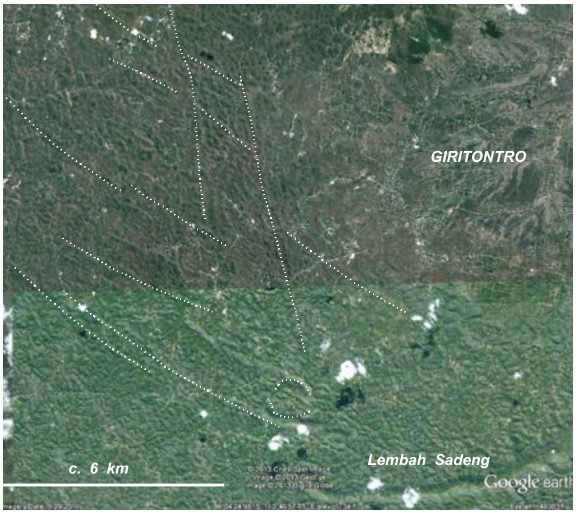

Figure 15. The dotted lines are long limestone ridges. The NNW-trending belt bordered by ridges is interpreted as a major fault zone. The highlighted circular landform is one of the "pseudo-slide marks" discussed with.

a regional fault zone, which is also detectable on the smaller scale SRTM image.

From the current shoreline into the hinterland, systematic changes in orientation of long linear ridges are clearly observable in many parts of Gunungsewu (Figures 8, 10, 11, 12). Arguments for their "breaker-zone" origin were presented earlier in this article. Three changes of long-ridge orientation are shown on Figure 12. Closest to the Indian Ocean, the present shoreline and ridge lineament 1 are parallel, both trending 95°. Farther inland, ridge lineament 2 strikes 100°. Farthest inland on Figure 12, ridge lineament 3 strikes 125°.

This systematic change in ridge-lineament orientation is interpreted to correspond with counterclockwise rotation of the Southern Mountains belt during progradational deposition of the Wonosari-Punung Formation in late Middle Miocene into Early Pliocene. Ngkoimani (2005) measured paleomagnetic orientations of andesites of Central and East Jawa and found among other information that since the period between 11 Ma and 6.7 Ma (Middle to Late Miocene), those terrains of the island had rotated counterclockwise by 8° to 10° while progressing in northerly direction. The change in orientation of interpreted breaker-lines of Gunungsewu have been integrated with dated paleomagnetic CCW-rotation (Figure 16). Ngkoimani *et al*. (2006) also provided

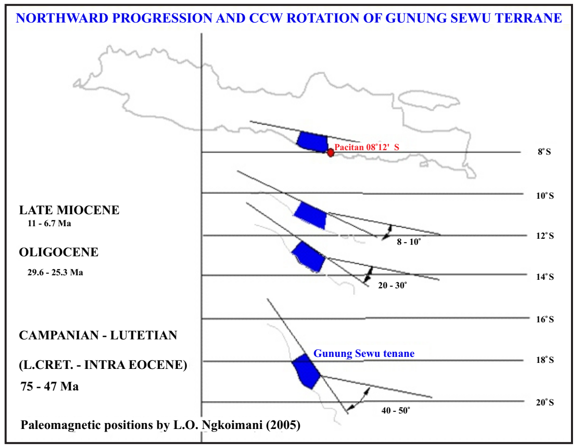

Figure 16. Dated paleomagnetic data derived from andesitic material in the Southern Mountains of Central and East Jawa (Ngkoimani, 2005) combined with systematically divergent orientations of paleo-breaker lines in the Gunungsewu limestone suggest the Gunungsewu terrane (a mircoplate) to have rotated 8° to 10° CCW while progressing in northward direction. During the preceding geological times, the microplate experienced similar rotation and northward lateral progression.

data of the paleomagnetic positions of the Southern Mountains (including Gunungsewu) of Jawa Island from the Campanian - Lutetian (75 to 47 Ma). According to the data, the Gunungsewu terrane was located about 11° farther to the South with an orientation trending Northwest, or 40° to 50° off the current one which is West-northwest. Since then, the terrane had moved northward while rotating CCW.

Parangtritis Fault Zone

The 400 - 500 m high scarp forming the western edge of Gunungsewu exposes Oligo-Miocene volcaniclastic and volcanic rocks of the Semilir-Nglanggran-Sambipitu Formations below the Wonosari-Punung limestone (Rahardjo *et al*., 1995). It is the fault-line scarp of the Opak Fault zone oriented northeast. A probable splay of the fault at the Parangtritis end trends only a few degrees east from the meridian (Figure 17). For reference purpose, this probable splay is named Parangtritis Fault zone (PFZ). The Google image shows en echelon arrays of smaller scarps oriented northwesterly within the PFZ. Individual scarps are associated with topographic drops that increase from 30 m in the vicinity of Parangtritis to 95 m near Desa Cangkring, about 10 km to its North. The en echelon arrangement of

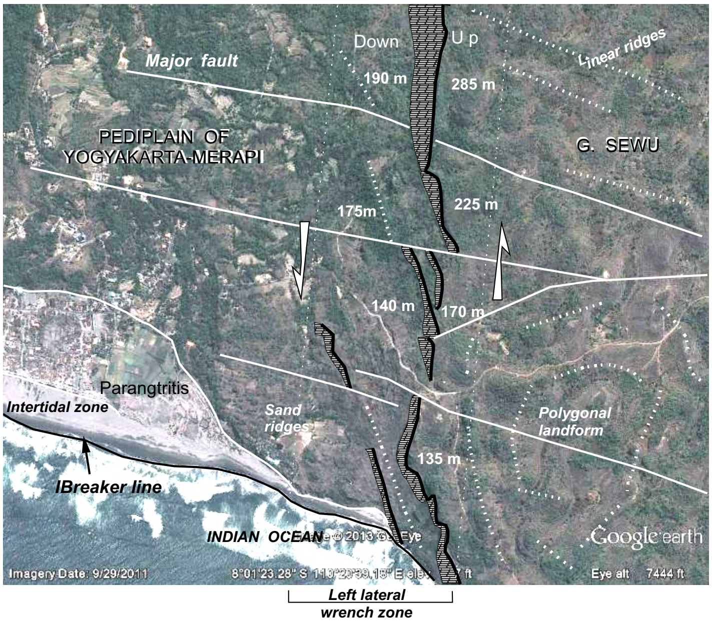

Figure 17. A northerly oriented zone of en echelon smaller scarps accompany the major fault-line scarp that forms the western boundary of Gunungkidul. The smaller scarps are step faults down-throwing to the west with a left-lateral component of displacement. This fault zone, named Parangtritis Fault Zone, is probably a splay of the Opak Fault Zone that strikes northeasterly and separates Gunungsewu from the Yogyakarta lowland.

fault scarps of PFZ indicate left-lateral wrenching in addition to downthrows westward. A series of major faults show up on the figure as lineaments striking parallel to Jawa's Island axis.

Active Tectonics

Stream Terraces

The well-documented stream terraces of Kali Baksoka and those along the Bengawan Solo have been essential in estimating ages of paleo-anthropological findings in the area, among many others by Sartono (1964). The stacked terraces have been considered indicators for geologically recent vertical ground movements. Figure 18 shows the river morphology along the middle course of the Oyo River within Gunungsewu. Three quarters of the figure consist of the Wonosari limestone; clastics of the Sambipitu Formation are in the northwest and in the top-central part of the figure. Vertical crustal movement is immediately apparent from the incised character of meanders. The well-developed meander pattern, including those of the tributaries, points to origin on a level land surface. Three sets of river terraces exist. T1, T2, and T3 comprise terrace surfaces 45 - 60 m, about 105 m, and 120 - 130 m above present datum.

Along the dry Sadeng Valley, Samodra (2007) grouped three sets of terraces at 20 - 80 m, 60 - 100 m, and 100 - 140 m. The lower group of terraces may be covered by alluvium whose thickness can exceed 10 m. The other group of the Sadeng terraces are mantled by terra rossa.

Coastal Terraces

On the limited number of Gunungsewu coasts, the author observed that coastal equivalents of the lower set of the Sadeng Valley terrace-levels can be further subdivided. There appears to be coastal terraces at around 2 m, 6 m, 15 - 20 m, around 40 m, and finally at about 80 m. The still higher-level Sadeng terrace equivalents have yet to be determined on the Gunungsewu coast.

At Pantai Klayar, the vegetation-free abrasion platform of 1.5 to 2 m above current high tide is tilted landward at less than 5^{o}. While the stratified Wonosari beds across which the abrasion platform was cut, dips seaward at 6^{o} to 8^{o} (Figure 19). The landward tilt of the platform implies a very recent counter-regional tilt of at least 4^{o} had taken place.

On the east side of Pacitan Bay are found five major terraces (Figure 20). The top level of the hilly

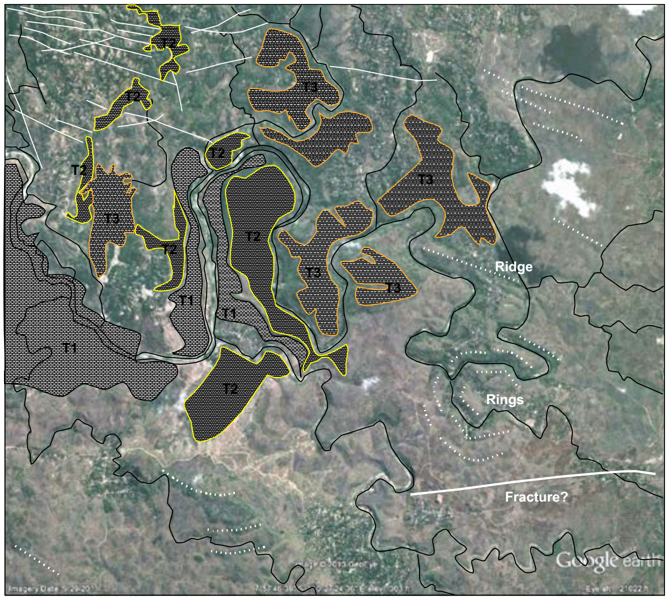

Figure 18. Three groups of river terraces along the Oyo River near Dusun Nganut 2. Terrace 1 is a few meters above the present river surface and is 45 - 60 m above sea level. The other terraces are T2 = around 105 m and T3 = 120-130 m above present datum. The Oyo River and its tributaries developed as free meanders on an essentially flat plain near the western edge of the Sewu limestone platform. Tectonic uplift of the land has caused the rivers to become incised meanders. Four quarters of the figure consist of Wonosari-Punung limestone, the remaining quarter area in the Northwest are of Sambipitu and of Nglanggran Formations on Rahardjo *et al*. Geological map (1995). West-northwest trending ridges and lineaments are parallel to Jawa Island tectonic axis. A multiple ring landform developed in Sewu karst. North-South length of the figure is almost 7 km long.

Figure 19. The young abrasion platform cutting across Oyo beds is tilted in counter-regional sense, that is, landward. Horizontal surface is indicated by the pool of water on the platform. The Oyo beds in the cliff show dips ocean ward a few degrees less that the 10^{o} regional dip of Gunungsewu.

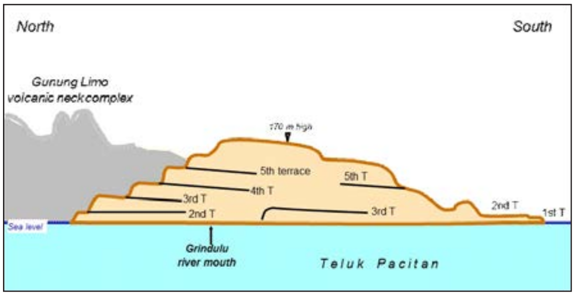

Figure 20. Panorama of major coastal terraces on the East side of Teluk Pacitan. The lower terraces T1 and T2 are level, the higher terraces are tilted oceanward 4º to 5º. The south end of the panorama is Tanjung Ngamber. Length of the sketch is 2.5 km.

area summits at 170 m according to a topographic map and may be a relic of a sixth terrace. Terrace 1, the bottom representative, is a recently uplifted abrasion surface barren of vegetation. This terrace and the second higher terrace are of level surfaces. The third and higher terraces are tilted 4º to 5º towards south. The coastal panorama indicates that the third and higher terraces resulted from a spasmodic vertical uplift and then experienced southward tilting prior to the development of the younger second and first terraces which were subjected to only vertical ground movements.

Sea-level Notches

From more than half of a century of coastal studies, the author has become convinced that sea-level notch- profiles are direct indicators of tectonic condition. First, the deepest part of a notch corresponds with mean sea level. Second, the notch opening/height is indicative of prevailing wave height and tidal range as Verstappen (1960) has stressed. Third, the two basic notch profiles are the “Lazy V” (resembling recumbent letter V) and “Fish-hook” (Figure 19), that correlate with actively rising coast and tectonically stable coast, respectively. On author’s part, this realization has been rather recent. Comparison of notches on many coasts of the core of tectonically stable Sundaland (Bangka, Belitung, Peninsular Malaysia) with those on coasts of known tectonic activity (eastern Sulawesi, Tukangbesi Islands, Banda Sea Islands, Nusa Tenggara, Sabah-East Malaysia, and Gunungsewu) has borne this out.

The limestone coastal cliffs of central and eastern Gunungsewu have Lazy-V notches (Figure 21).

Figure 21. The Lazy-V notch in the limestone cliff at Pantai Baron are characteristic for the entire Gunungsewu coast. In addition, uplift of the land in historical time is implied by the fact that the mean sea-level mark (deepest cut of the notch) remains 1 to 1.5 m above present high tide level while a current mean sea-level notch has yet to develop. Figure 1 shows location of Pantai Baron.

However, the deepest cut of the notches remains a meter to 1.5 m above current high tide. At Teluk Baron and Sadeng, level abrasion benches at the foot of notches are also above the current wave base. The present mean sea level notch has yet to develop. The elevated position of the deepest cut of notches and absence of a notch corresponding to current tidal conditions imply that vertical uplift, estimated at more than 2 m had occurred recently, even in terms of our historical time frame.

Conclusions

In addition to the usual karst morphology of sinoid hills, dry valleys, subsurface drainage channels, caves, and sinkholes, the Gunungsewu karst also form simple patterns of long linear ridges, paired serpentine ridges, circles, ovals, and straight-edged polygons, that may combine into multiple rings and nested polygons. Circular and multi-ring landforms are common, but not all can be related to atolls. It is a fact that reefs represent only a small portion of the Gunungsewu karst, that predominantly consists of stratified calcareous sedimentary rock. Pre-carbonate topography of hill tops was presumably influential in shaping depositional patterns of the carbonates, reefs, and calcareous clastics alike. Km’ long linear ridges are interpreted as elevated paleo-breaker zones. Linear ridges closest to the ocean and the present shoreline run essentially parallel. Toward the hinterland, their orientations increasingly diverge from the shoreline to attain angles of up to 40°. The diverging orientations possibly correspond to progressive CCW rotation of the Gunungsewu terrane when it shifted Northward from a Mid-Miocene position at 10° to 11° S as suggested by paleomagnetic data.

Vertical ground movement of the Gunungsewu terrane has occurred periodically and has produced three major groups of river terraces. Representatives of these terraces are distributed along the dry Sadeng Valley, Kali Baksoka, and Kali Oyo. Incised stream valleys of the "free-meander" category along the Oyo River are also consistent with uplift of the land. Coastal terraces lining the east side of Teluk Pacitan demonstrate older periods of ground uplift combined with slight tilt ocean-ward. The lower, and thus younger, coastal terraces are level and attest to only vertical uplift. Locally, such as on the Klayar coast, an abrasion terrace, 1 to 1.5 m above current high-tide level is tilted up to 4° landward. The counter-regional tilt resulted from very recent tectonics. While Lazy-V notch profiles in the limestone cliffs of Gunungsewu are expected in view of its location in the tectonically active Jawa Island arc, the deepest cut of the notches remains 1 to 1.5 m above high tide level, which imply land uplift in historical time of 2° to 2.5°.

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