Geological heritage features of Tawau volcanic sequence, Sabah

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Abstract— Semporna Peninsula area was built up by thick Tertiary sequence of volcanic flows and volcaniclastic rocks. Early Cretaceous tholeiite basalt is the oldest sequence of volcanic rocks interpreted to have formed as part of a wide spread submarine volcano or volcanic complex within an MORB characterized by rapid volcanism. Miocene to Quaternary volcanisms from volcanic arcs contributed sequences of lava flows and pyroclastic rocks of dacitic, andesitic and basaltic rock types forming the major mountain chains of southeast Sabah. This Neogene volcanic sequence is dominated by low to high K-calc alkaline andesitic to dacitic volcanic rocks similar to modern island arc type. The subaerial of the latest lava flows of the region indicates volcanism consistent with tholeiitic basalt type. It has been accepted that during the Cenozoic, Sabah has been subjected to series of major tectonic regimes. A number of deformation phases have been determined include: Middle Eocene, Middle Miocene and Plio-Pleistocene phases of crustal movements of this region. The area appeared, therefore, to have been subjected to compressional tectonic regime throughout much of the late Cenozoic. However, the structural and sedimentological expression of these tectonic regimes varies considerably. It is suggested here that compressional episodes were interspersed with periods of active transtensional basin formation and that Late Miocene extension of the eastern part of Sabah which was related to compressional forces. On the basis of geological data and kinematic reconstructions, two types of island arcs can be differentiated: those related to the progressive closing of the Celebes and Sulu marginal basins during Middle Miocene and those belonging to the south Philippine Sea Plate during Plio-Pleistocene. The combined age and chemistry for these two magmatic belts allow us to decipher the Tertiary evolution of the complex zone of interaction of the Semporna Peninsula and the surrounding areas. This Tertiary sequence is underlain by the Early Cretaceous pillow lava basalt, and culminated by the late Pleistocene volcanisms those contributing to the major topography of the area include Andrassy, Lucia, Maria, Wullersdorf and Magdalena mountains formed the prominent topographic features of the area. This youngest volcanic apron covers an extensive area of the Semporna Peninsula. Semporna volcanic associations form important link with the long chain of Tertiary volcanic activities in this region that extend from the Sulu Archipelago, Philippines to the southeastern part of Sabah.

Keywords: Geological heritage, Tawau hills, Pleistocene volcanic sequence, Semporna Peninsula

INTRODUCTION

The suggested Tawau geological heritage area is located in the eastern part of Semporna Peninsula, Sabah, Malaysia. The area is a mountainous feature, forming the major backbone of Semporna Peninsula called the Tawau Hills. The Tawau Hills were built up by the Miocene to Late Pleistocene andesitic, basaltic and dacitic volcanic rocks. The Middle Miocene andesitic-basaltic compositions are associated with clastic sedimentary rocks and subordinate limestone facies, classified as the Kalumpang Formation (Kirk, 1959). The thick volcanic apron forming Andrassy, Lucia, Maria, Wullersdorf, Pock and the Magdalena mountains, Pleistocene dacite and andesites, featuring the major topography of Tawau area. Mount Magdalena, Mount Lucia and Mount Maria are made up of Pleistocene dacites. The youngest volcanic rock, which is the olivine basaltic types, erupted during the late Pleistocene time. Their outcrops occur in random distribution overlying the older volcanic rocks covering an extensive area of the low-lying areas of Semporna Peninsula. A small portion on the southwestern part of it is located the Tawau Hills Park, established in 1979, primarily as a protection for the water catchment area of Tawau town. Administered by Sabah Parks, this water catchment is meant for an important continuous water supply for the area around Tawau and Semporna. Tawau Hills of Sabah Parks cover 280km square and is situated 25km northwest of Tawau town, the third largest town in the state of Sabah.

On the eastern part of Tawau mountains is situated the Ulu Kalumpang Forest Reserve, which was gazetted as a forest reserve in 1956 and it is meant as a refuge for the endangered iconic animals of Borneo and serves to protect the headwaters and water catchment areas that are a source of water for the inhabitants of the Semporna Peninsula. The block of land about 511 km square was reclaimed and classified as Class One Forest Reserve. Ulu Kalumpang is linked to other forest reserves and in the south, it links with Tawau Hills National Park and Mount Wullersdorf Forest Reserve as well linking to the Ulu Segama Forest Reserve. Now, we are suggesting to include all the current undisturbed area of the mountainous part of the Peninsula to be reclaimed and marked as Tawau Geological Heritage (Figure 1).

GEOLOGIC SETTING

The oldest rock association of Semporna Peninsula is classified as the Chert-Spilite Formation of Early Cretaceous age. It is part of the fragmented oceanic crust of this region. Outcrops of Albian and Cenomanian oceanic crust materials fragmented together with the older Mesozoic materials

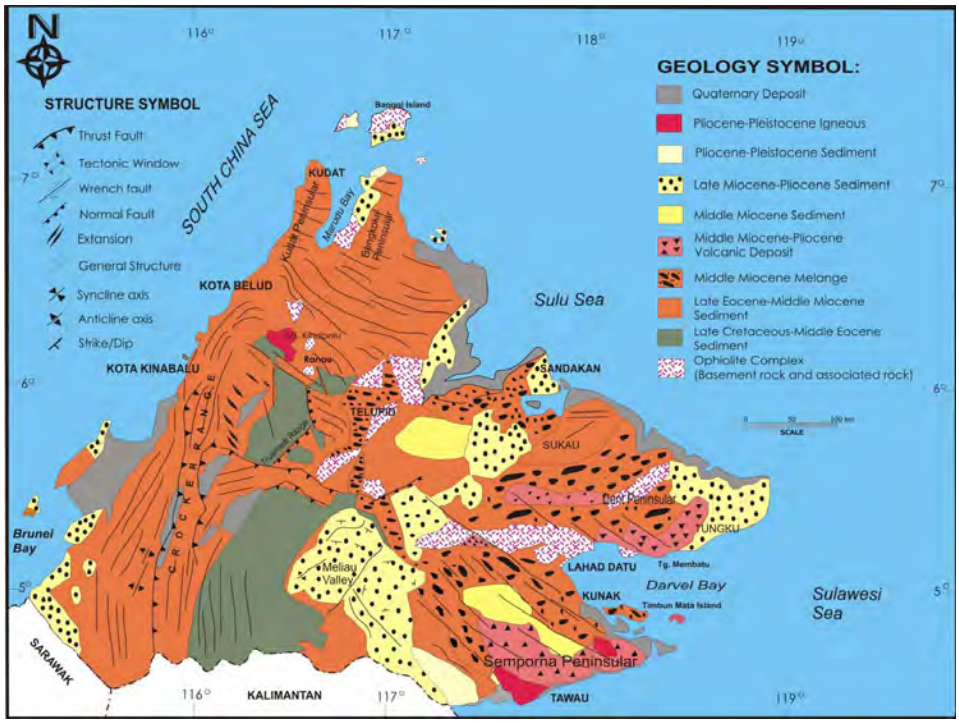

Figure 1: Geological map of Sabah showing the study area in Semporna Peninsula, southeastern part of Sabah (modified from Yin, 1985).

suggest an early Cretaceous age for the emplacement of the basement in the northern part of Borneo. The sequence was tectonically intercalated with the metamorphic lithological units consists of red and dark siliceous shales, sandstones and siltstones, radiolarian cherts, serpentinite, basalt and diorites. The presence of similar age of metamorphic rocks in Meratus Mountains in southeast Kalimantan and Sulawesi suggest that the basement complex in this part of Borneo could be part of a dismembered fragment of a larger Late Mesozoic accretionary complex of the region.

Late Cretaceous sediments found in the eastern and northern parts of Sabah, include the Madai limestone, estimated to be the oldest sedimentary sequence of the area. The oldest clastic formation unconformably overlies the ophiolite sequence and is composed of interbedded meta arenite, slate and phylite with less important pebbly sandstones and conglomeratic breccias classified as the Trusmadi Formation. The sandstones are mostly feldspathic greywacke which are locally composed of quartz, plagioclase, and orthoclase with subordinate biotite, muscovite and angular lithic fragments embedded in a matrix of clay minerals, chlorite and sericite. Graded bedding is occasionally present in most of the sequence. Coarser units of the formation contain sedimentary structures typical of gravity flow deposits, including the chaotic fabric of debris flows, graded bedding and sole marks indicative of turbidites. The lithologies and fauna of the Trusmadi and contemporaneous Crocker Formations to the west are typical of an open marine, deep neritic to bathyal environment. The Temburong Formation is interpreted to be the distal equivalent of the Crocker Formation, based on facies considerations. The tectonic setting of the Trusmadi Formation is interpreted to be an open arc basin on the trench slope. The above sequences are estimated to be the underlying rock associations of the Neogene volcanics and younger sedimentary sequences of the Semporna Peninsula.

Volcanic rocks of Cretaceous age occur in several areas and unconformably overlie the older rocks. The rock association consists of lava with rare intercalations of limestone and shale towards the top of the sequence. The calc-alkaline nature, and enrichment of certain light rare earth elements, suggests that the volcanics were subduction related probably from a northwest dipping subduction zone.

The chert-basaltic association outcrops in Sabah comprises of volcanic breccias and lavas, in the form of pillow lavas or massive flows. Overlying by chert, these materials are interbedded with minor sandstone and shale. The lavas are characterised by spillitic basalts which have been slightly metamorphosed. The Darvel Bay chert-spilite association has been interpreted as part of an ophiolitic sequence based on high gravity anomalies and the marine oceanic island basalt in nature. K/Ar dating on pillow lavas of the rock formation gave early Cretaceous and this may represent an emplacement age of the suggested ophiolitic suite in this region of Borneo. Department of Mineral and Geoscience Malaysia relates these intrusive bodies to calc-alkaline volcanics in the Lower Cretaceous formations and suggested that it was derived from Late Mesozoic subduction. However, this is inconsistent with a Middle Miocene age suggested by K/Ar dating of the volcanic rocks and foraminifera in marine sediments interbedded with the volcaniclastics of the Semporna Peninsula, the Kalumpang Formation. The lower member of the Kalumpang Formation consists of tuffaceous sandstone, interbedded with tuff, sandstone, claystones, volcanic conglomerates and breccia and limestone lenses. The rock sequence shows that the clastic facies of the Kalumpang Formation was probably formed in a shelf environment as suggested

by the numerous sedimentary features and could be part of the Miocene basin of the Dent – Semporna Peninsula area. These rocks were deposited in a shallow to neritic marine environments in early Middle Miocene times. This formation is followed by volcanic activities throughout the late Neogene and the Quaternary. Volcanic activities during the Pliocene time resulted in eruptions of predominantly andesitic lavas followed by dacitic lavas and pyroclastics. Towards the Late Pliocene and early Pleistocene uplifting, faulting and erosion took place causing the volcanics to be deeply dissected. Volcanic activities recurred during the Late Pleistocene with eruptions of andesitic-dacitic composition that formed amalgamated volcanic cones giving the present mountainous features of the area. The sequence of the volcanic eruptions is difficult to determine owing to the absence of traceable stratification.

STRATIGRAPHY

The oldest rock unit ever-exposed in the study area consists of Miocene volcanics interbedded with sandstone facies with limestone lenses classified as the Kalumpang Formation. The formation is a stratigraphic unit introduced by Kirk (1959) to describe the apparently thick sequence of folded and faulted marine sediments and interbedded pyroclastic layers in the Semporna Peninsula area. The facies is characterized by interbedded thick sandstone and shale, with mudstone and lenses of fossiliferous limestone, and tuffaceous beds and agglomerate. Its major outcrop usually shows steeply folded and strongly faulted.

The formation is overlain and extruded by series of Plio-Pleistocene stratovolcanics, and the base of the formation is nowhere exposed. However, an outcrop in Merotai Besar shows that the Kalabakan Formation, dark argillaceous sequence, unconformably underlies the clastic facies of the Kalumpang Formation. The stratigraphy of the area is summarized in Table 1.

The prominent Pliestocene age andesitic-dacitic volcanic rocks of Mt. Pock is in the major mountainous area of Tawau and in the west of Semporna District, Mt. Pock. During the early Pleistocene, the main dacite eruptions were from Mt. Maria building a dacitic cone on top of the older eroded andesite (Kirk, 1959).

Many steep sided volcanic cones of silicified rocks occur in the main volcanic areas, namely: Mt. Andrassy, Glass Hill, Mt. Lucia and Kinabutan Besar Hill. Due to their hard and resistant nature, they formed high ridges and probably formed at the volcanic vents, which would have acted as channels for late stage silica-rich volcanic rocks.

The latest lava flows, olivine basalt, cover an area of about 40% of the peninsula. Prominent olivine basalt lavas erupted during the late Pleistocene period formed three cones aligned NW-SE at Tiger Hill, Bombalai Hill and Quoin Hill. Quaternary olivine basalt lavas also erupted from several volcanic cones as part of the remnants of the volcanic activities of the peninsula.

Table 1: Stratigraphy of Semporna Peninsula.

AGE	Letter Classification	SEDIMENTARY ROCKS	IGNEOUS ROCKS AND TECTONIC ACTIVITY
QUATERNARY		Alluvial deposits	Olivine basalt lava
PLIOCENE	Tgh	Dacitic and andesitic volcanic breccia and tuff with subordinate epiclastic	Dacitic and andesitic volcanic breccia and lavas Dacite and andesite lavas and pyroclastics
LATE MIOCENE	Tf_3	Umas-Umas Fmn.: Interbedded sandstone and mudstone	
MIDDLE MIOCENE	Tf_{1-2}	Kalumpang Fmn.: Tuff, volc. Breccia, tuffite, clastic and limestone	Volcanics (andesite) and tectonic activities associated with the Kalumpang Fmn.
EARLY MIOCENE	Te_5	Kalabakan Fmn.: Interbedded sandstone and shale	
OLIGOCENE	Te_{1-4}		

VOLCANIC TERRAIN

Volcanic rocks of the andesite-dacite-basalt association are found in the area forming the major morphologic features of Semporna Peninsula. The earliest phase of volcanic activities appeared to coincide with the Middle Miocene tectonic movements active during the deposition of the Kalumpang Formation. Semporna volcanisms continued into the Quaternary that resulted in large quantities of mainly dacitic-andesitic lava flows being piled up to form stratovolcanoes. The explosive eruptions of dacites and andesites were culminated during the late Pleistocene, building up the cap of volcanic cones of Mount Maria and some other surrounding areas. During the latest eruptions, olivine basalt lavas were extruded from small cones to form the latest episode of volcanism of the area. The earlier volcanic rocks of andesitic and dacitic composition formed a line of composite volcanoes from Mount Magdalena to Mount Wullersdorf and Mount Pock at Semporna District, while the earliest rocks of the Mt. Magdalena area are hyperstene andesite lavas and pyroclastic rocks of the Kalumpang Formation (Figure 2).

MAGMATIC MODEL

Petrographical and geochemical characteristics of the studied volcanic rocks suggested that; in the evolution of the rocks, fractional crystallization ± assimilation ± magma mixing took place in crustal magma chamber(s), and the parental magmas of basaltic, dacitic and andesitic rocks probably were derived from the same source. Based on the obtained data, the deduced petrogenetic model shows that the Semporna volcanic rocks developed by high to shallow level fractional crystallization of a parental magma derived from subduction induced metasomatised upper mantle. This

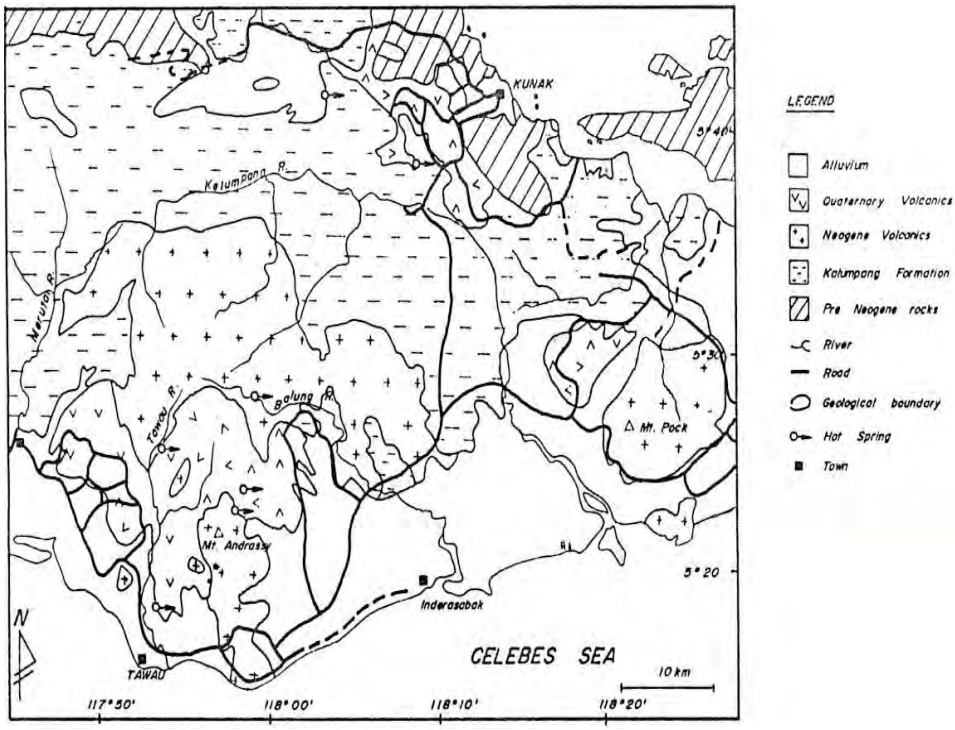

Figure 2: Geological map of Tawau showing the distribution of the rock units.

occurred after thickening of the pre-Semporna Peninsula paleo-oceanic island arc crust during the pre-Middle Miocene time, possibly within a compressional tectonic environment.

Major element studies of island-arc volcanic rocks commonly reveal the importance of crystal fractionation of parental magmas (Hawkesworth *et al*., 2000), and subsequent fractionation of plagioclase–magnetite–amphibole from a basaltic parent magma may be a major process in the generation of more evolved rock types. This array indicates, at first, clinopyroxene and then hornblende controlled fractional crystallization during the evolution of the volcanic rocks. The influence of hornblende fractionation on the chemical variation implies that the fractionation probably took place in the magma chamber located in the shallow-crust.

Many studies on arc magma genesis have provided clear evidence for the assimilation of crustal material as an important process of modification of the trace element and isotopic composition of mantle-derived arc magmas (Hochstaedter *et al*., 2001; Zellmer *et al*., 2005). In a general evaluation of crustal contamination vs. subducted sediments for the volcanics, it is argued for contamination of the primary magmas by arc crust as an important feature of Tertiary arc magmatism. Therefore, before characterizing the source components of the volcanics, it is essential to evaluate the likelihood of crustal contamination of mantle-derived magmas during ascent through the arc crust and possible effect on magma composition.

The production of contemporaneous tholeiitic-alkaline transition and calc-alkaline rocks in the volcanics raises another question: Were the parents of the tholeiitic-alkaline transition and calc-alkaline magmas chemically similar or different. The presence of olivine phenocrysts and relatively low silica contents in the basaltic rocks for the last volcanic eruptions of the area suggest that their parent magmas were mantle-derived basalt (Figure 3), classified as calc-alkaline type.

GEOLOGICAL HERITAGE FEATURES

Selected geological and geomorphologic sites in Tawau are considered to be of unique scientific values to be conserved. This suggestion is another step to see the possibility to develop a programme for the promotion of geological heritage in Tawau. It would be a territory with well-defined limits that has a large enough to promote as such area. The area comprises number of geological heritage sites of special scientific importance. The sites can be linked to the present Sabah Parks and safeguard in a managed park-type situation. The suggested programme would be run by a designated authority that would adopt its own territorial policy for sustainable socio-economic development or can be suggested as part of the Sabah Parks. This would have a direct impact on the areas involved by improving human living conditions and the rural development. Among the area include: Magdalena Mountain, the highest peak (1310 m) followed by Mount Lucia and Andrassy to the south of Mount Maria and some interesting features along major rivers in Tawau. As the highest feature of the landscape, the mountains have naturally become associated with the highest values and aspirations of local residence. The program should also include Bukit Gemok. Some of the geological features are Magdalena Mountain (with the only volcanic crater in Malaysia), volcanic cone of Tiger Hill, columnar basalt of Balong River and various locations of hot springs as shown in Figure 4. Short descriptions are given below.

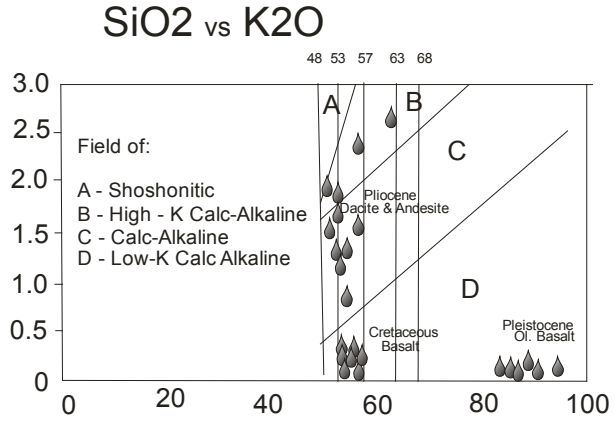

Figure 3: Calc-Alkaline type of volcanic rocks – 25 samples volcanic rocks were analysed from the study area.

Magdalena Mountain

Magdalena Mountain, 1310 m high, is part of the Tawau Hills National Park forming the highest peak of the area (Figure 4A). The rock type exposed along river course is dacite (Figure 4B). Observation from landsat imagery clearly shows an old structure of a crater located at the peak of the mountain. It is located at the Semporna Peninsula in southeastern Sabah and is bounded by the Ulu Kalumpang Forest Reserve on the northern side and Mount Andrassy Forest Reserve on the south. The eastern and western parts are bordered by oil palm plantations. The Magdalena Mountain presents an uneven volcanic landscape with two other peaks, Mount Maria (1067 m) and Mount Lucia (1189 m). This park functions as a corridor between other forest reserves, Ulu Kalumpang in the north and Mount Andrassy Forest Reserve to the south. The area is carved by seven rivers that flow through this 30,000 hectare national park, forming deepwater pools and waterfalls. Among other attractions are waterfalls and Sulphur Spring.

Seven important rivers with water catchment areas are confined largely or entirely within the park boundary are:

1) Sungai Tawau (the main river in the park),
2) Sungai Kinabutan in the centre,
3) Sungai Mantri,
4) Sungai Balung in the east,
5) Sungai Merotai Kanan,
6) Sungai Merotai Kecil and
7) Sungai Junap (a tributary of Sungai Merotai Besar) in the west.

Volcanic cone of Tiger Hill

Tiger Hill is one of the potential geological heritage volcanic landforms (Figure 4C). Series of volcanoes erupted from the Late Tertiary to the Quaternary ages. The controlling geological setting is affected by the oceanic crustal movements of southwestern Circum-Pacific tectonic activities. The relevant natural conditions are the plains, hills and well-developed vegetation. The prominent volcanic features are the volcanic rocks, geothermal springs, volcanic vents and cones and tropical erosion landform. The major geological heritage is the complete volcanic mechanism, volcanic cones, craters and lava flows created by weathering of volcanic rocks.

Columnar Basalt of Balong River

This volcanic feature exposed along Balong River is not found at any other places in Malaysia. The columnar basalt (Figure 4D), of pentagonal and hexagonal columns appears to be of about the same size and uniformly arranged. The surface exposure of each of the column measures about 55cm to 85cm of its perimeters with undetermined depth below surface. The surface view of these volcanic columns appears like piling columns used to prevent erosion along river bank. This structure is due to the fast cooling process from magma when it oozed out to the surface of the earth.

The rock is classified as extrusive igneous with andesitic to basaltic compositions. It is one of the youngest volcanic eruptions during Quaternary.

Hot Springs

Hot spring is a manifestation of geothermal energy from a remaining heat source of igneous activity (Figure 4E). Hot springs found in the Tawau-Semporna region, Sabah, Malaysia (Figure 2), are considered to be of high potential for geothermal energy resources. The initial investigations into the geothermal energy resources have been carried out mainly by the Minerals and Geoscience Department Malaysia (previously known as Geological Survey Department Malaysia) since the late 80s. The preliminary findings hot springs are summarized below :

a) The geology of the area with active geothermal indications consists of Late Tertiary (Pliocene) to Quaternary dacitic to basaltic lava and tuff.
b) Geothermal indications in the Tawau-Semporna region include many hot springs, mud pools and old steaming grounds. Geothermal secondary minerals such as chloride and pyrite are widely distributed in the area.
c) The most active area of the geothermal showings is the Apas Kiri, Tawau area, where the highest water temperature of 84^{o}C had been recorded. Subsurface temperatures in the Apas Kiri area were estimated using Na/K geothermometers to be between 189^{o}C and 236^{o}C and this temperature range shows that there is high potential for harnessing geothermal energy in this area (Fredolin *et al*., 2010).

The volcanic activity was caused by the extension of the Sulu Archipelago Arc-Trench System into the Semporna Peninsula active during the Pleistocene (Fredolin et al., 2010). The hot spring can be located at the following sites:

a) Apas River tributaries at the foothill of Andrassy
b) Southwestern foothill of Maria Mountain
c) Tawau Hot Spring at Kg. Air Panas
d) Sg. Jepun at the foothill of Gunung Pock
e) Kunak Hot Spring

The above mentioned hot springs are the potential geosites for future tourist attractions. Currently, the most visited hot spring is the Tawau Hot Springs. These hot springs had been attracting local visitors, particularly from

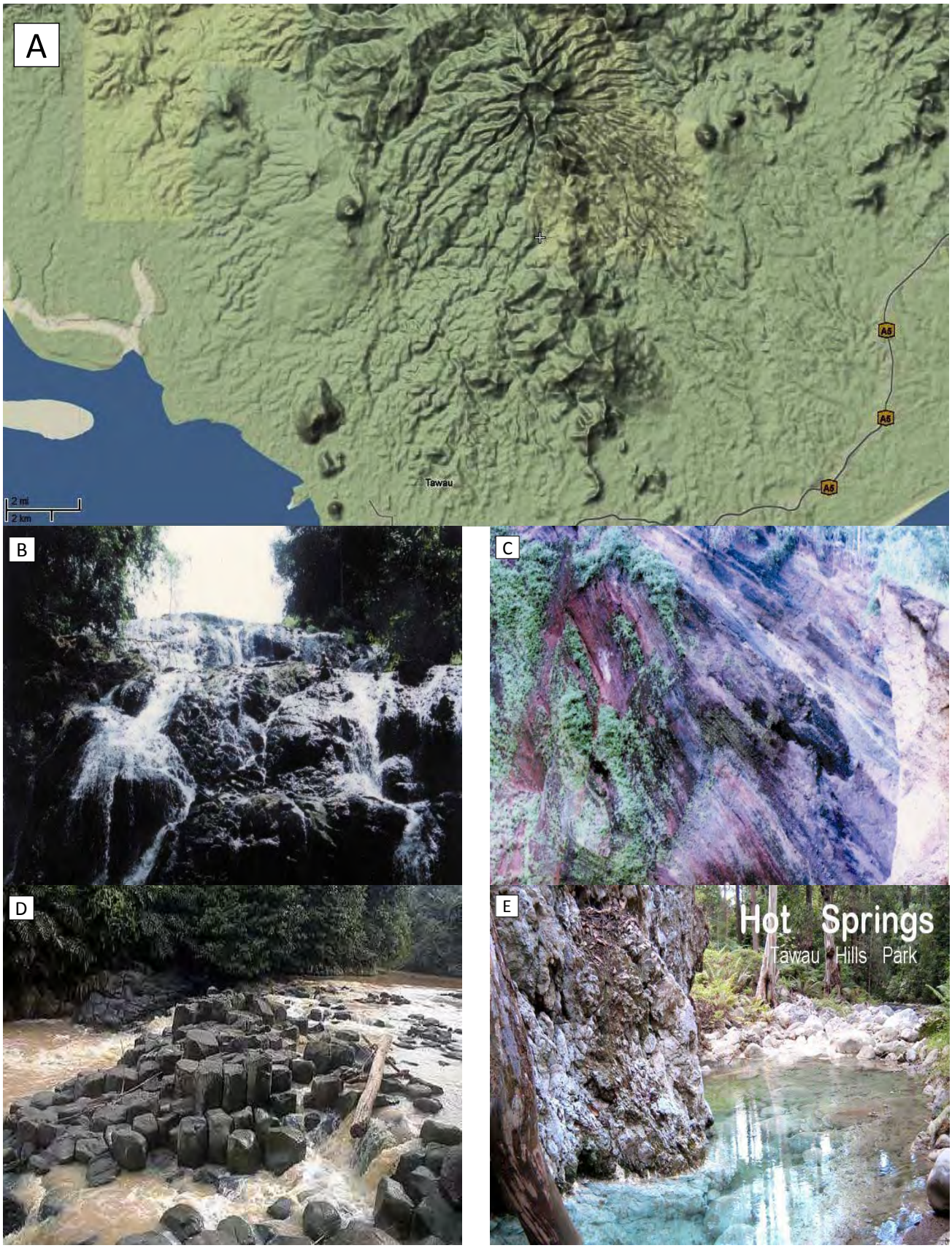

Figure 4: Some outstanding geological heritage features in Tawau area: A – Imagery showing the crater of Mt. Magdalena.; B – Maria dacite largely exposed along rivers and waterfalls within Tawau Hills National Park; C - Tiger Hill, the youngest volcanic rocks in Malaysia consisting interlayers of pyroclastic and volcanic ash of olivine basalt composition; D – rare scene of columnar basalt at Balung River; and E – Hot Spring at the headwater of Tawau River, Tawau Hills Park (courtesy Sabah National Park).

Tawau area and as far as Kunak and Semporna. Local people use the spring water for medicinal skin treatment. Visitors bring along food for refreshment as the place is ideal for picnicking and leisure time.

CONCLUSIONS

The Tawau Mountains, the Neogene-Quaternary volcanic remnants, form the prominent feature of the Semporna Peninsula. Volcanic rocks of the andesite-dacite-basalt association are forming the major mountainous backbone of the area. The Semporna Peninsula Middle Miocene paleo-magmatic arc was represented by volcanic rocks associated with sedimentary rocks deposited in a shallow marine environment. The basaltic rocks contain plagioclase, olivine, clinopyroxene, hornblende phenocrysts and magnetite microcrysts, whereas the andesitic rocks include plagioclase, clinopyroxene, hornblende, biotite phenocrysts, apatite, and zircon microcrysts. The investigated volcanic rocks indicate magma evolution from high transitional to low-K calc-alkaline contents. The Semporna volcanics evolved from a parental magma derived from a source enriched by subduction induced metasomatism.

The area comprises geological features of scientific, historical, recreational, and aesthetic values. It is important to conserve the variety of geological features of the area for the future and to allow research for the advancement of sciences. Geoconservation is necessary as a focus for substantial leisure activities and tourism; this is because the sites have rich geodiversity and wildlife values. The geological heritage programme at Tawau Mountains would prove its specific utility for raising public awareness and stimulating sustainable development on the basis of geotourism. This will help to conserve protected areas and consider them as an essential component for the public in interaction with the environment. Environmentally, the present technology exists to exploit these resources, although at present its cost and benefit is still yet to be determined.

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