# PALEOENVIRONMENT RECONSTRUCTION OF THE GAYONG SEDIMENTARY FORMATION, BACMAN GEOTHERMAL FIELD, PHILIPPINES

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## ABSTRACT

The field-wide occurrence of Gayong Sedimentary Formation (GSF) in the Bacon-Manito geothermal field (BGP) in the Philippines was evaluated to refine the stratigraphy of the geothermal system, and to reconstruct the paleoenvironment of this specific lithologic formation, as well as the geomorphology of its depositional basin. Based on paleoanalysis, the GSF is the oldest stratigraphic unit encountered in BGP with an established Late Miocene to Early Pliocene age. It is predominantly composed of carbonaceous and fossiliferous limestones, reefal carbonates, calcareous sedimentary breccias and fine-grained clastic rocks. Downhole well data correlation results combined with paleoanalysis and lithofacies characterization indicate a paleoenvironment gradation – from shallow neritic to shallow open marine in Botong and Palayang Bayan sectors, and deepening towards the south in Tanawon, possibly reaching the abyssal plains of deep marine setting. Observed lateral and vertical changes in lithofacies of GSF are attributed to natural deepening of ocean basin morphology, historical sea level fluctuations, and tectonic activities.

The GSF has widespread occurrence in BGP except in Cawayan sector. The wells drilled in Cawayan did not observe GSF probably because of either of the following: deep occurrence of formation due to downfaulting; obliteration of sedimentary units due to Plio-Pleistocene intensive volcanism; or non-deposition of sediments attributed to a paleo-high configuration of the region in pre-Miocene to Pliocene. In Tanawon sector, the presence of non-calcareous laminated fine-grained sediments indicates that the area was once submerged in deep marine environment. Its present high elevation at ~912 mASL, however, suggests that the area was uplifted after deposition of the GSF. Accurate subsurface depiction and reconstruction of depositional environments of GSF aims to aid particularly in delineating permeable zones and in predicting areas that are prone to calcite scaling.

## 1. INTRODUCTION

The Bacon-Manito Geothermal Field (BGP) is located within the Pocdol range in the southern end of the Bicol Peninsula, Luzon Island, Philippines (Fig. 1). Commenced for power generation in 1993, it has a combined 150 MWe production capacity from three producing sectors, namely: Palayang Bayan, Botong, and Cawayan (Ramos, 2002).

Existing regional extension and transtention stress regimes in response to a second-order shear of the Philippine Fault (Lagmay et al., 2004) creates numerous fault splays such as those traversing the Pocdol range which are collectively part of the Bacman Fault Zone (BFZ). These structures are considered to be the predominant controlling factor for permeability in BGP (D'amore, 1993).

The Gayong Sedimentary Formation (GSF) is the oldest stratigraphic unit intersected by geothermal wells in the BGP (Fig. 2). It is unconformably overlain by the Pocdol Volcanics Formation (PVF) and intruded by the Cawayan Intrusive Complex (CIC). A paleosol horizon separates GSF from the overlying PVF.

Collation and integration of data from existing geothermal wells in Palayang Bayan, Botong, and Tanawon sectors show variation in GSF across BGP in terms of rock assemblage and character, lateral and vertical extent, and depth of top of formation. Nevertheless, GSF lithofacies in general, is mainly composed of multi-lithologic calcareous breccia, fossiliferous limestones, and carbonaceous clastic sedimentary units. Its age, based on paleoanalysis of core samples ranges from Late Miocene to Early Pliocene (N18-21 undifferentiated) (Tebar, 1988), coinciding with widespread deposition of carbonates in the shallow neritic to open marine setting of the Bicol basin.

The GSF is a probable production zone target. As confirmed in several wells, the GSF-PVF stratigraphic contact and intraformational boundaries within GSF lithofacies are sources of primary permeability. Interconnection of spaces between fragments of volcanic and calcareous breccias, for instance, makes these lithofacies permeable. Circulation losses encountered in some wells are attributed to primary permeabilities associated with the formation.

However, GSF also poses several challenges on production and development of the BGP geothermal resource. Although it can be a good source of permeability, there are calcareous and carbonaceous fine-grained clastic siltstone and claystone sub-units which possess inherently low permeability. Furthermore, carbonate lithofacies and calcareous breccias are expected to have high non-condensible gas (NCG) levels (Ramos, 2002), such as $CO_2$. Hydrothermal fluids passing through these reservoir rocks, therefore, are prone to calcite scaling.

This paper aims to delineate the extent of GSF in BGP and reconstruct its depositional environment by reconciling existing geologic data from geothermal wells; and eventually coming up with a refined lithostratigraphy of this sedimentary complex. The various lithofacies encountered in existing wells were characterized, and major structural controls were also integrated to be able to reconstruct paleoenvironments.

Depiction of horizontal and vertical distribution of GSF lithologies will be useful in anticipating zones that are prone to calcite scaling and in designing future wells to target permeable zones associated with this sedimentary rock formation.

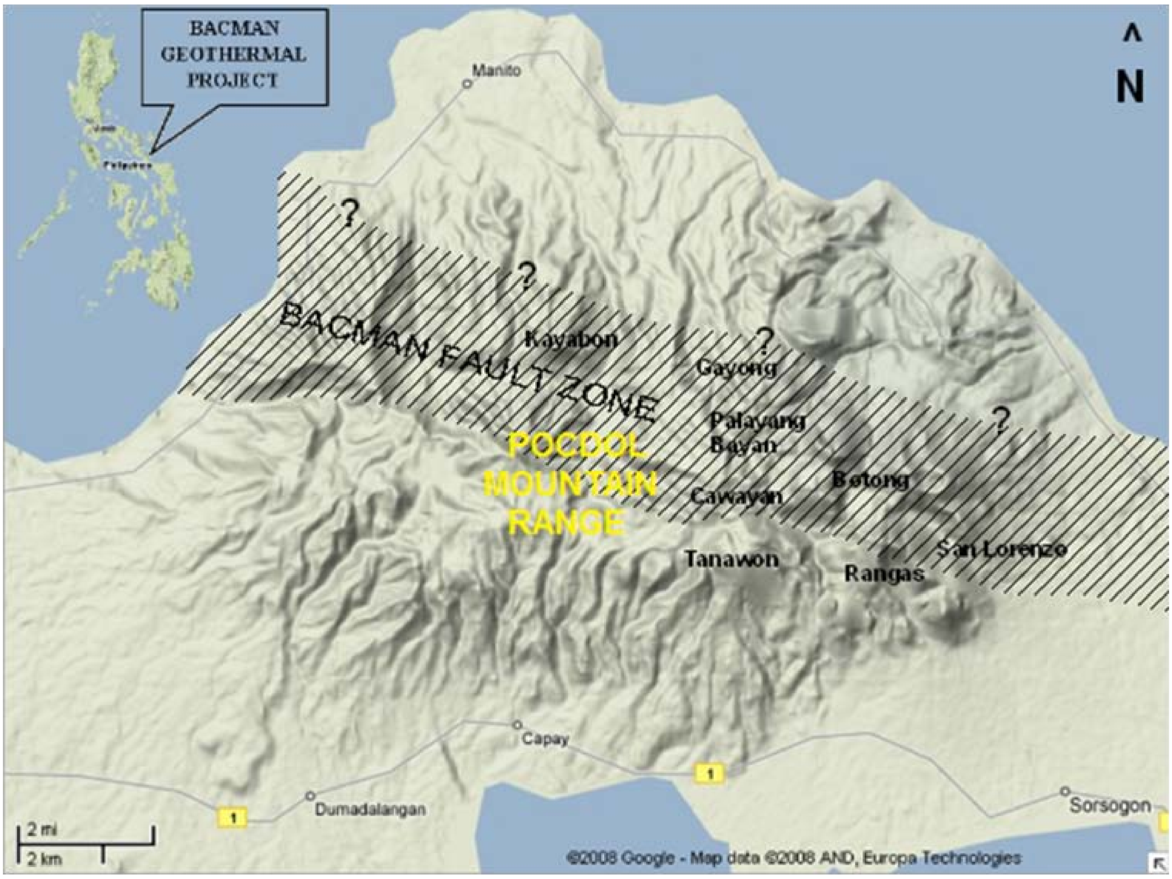


**Figure 1: Regional setting of the Bacman Geothermal Project.**

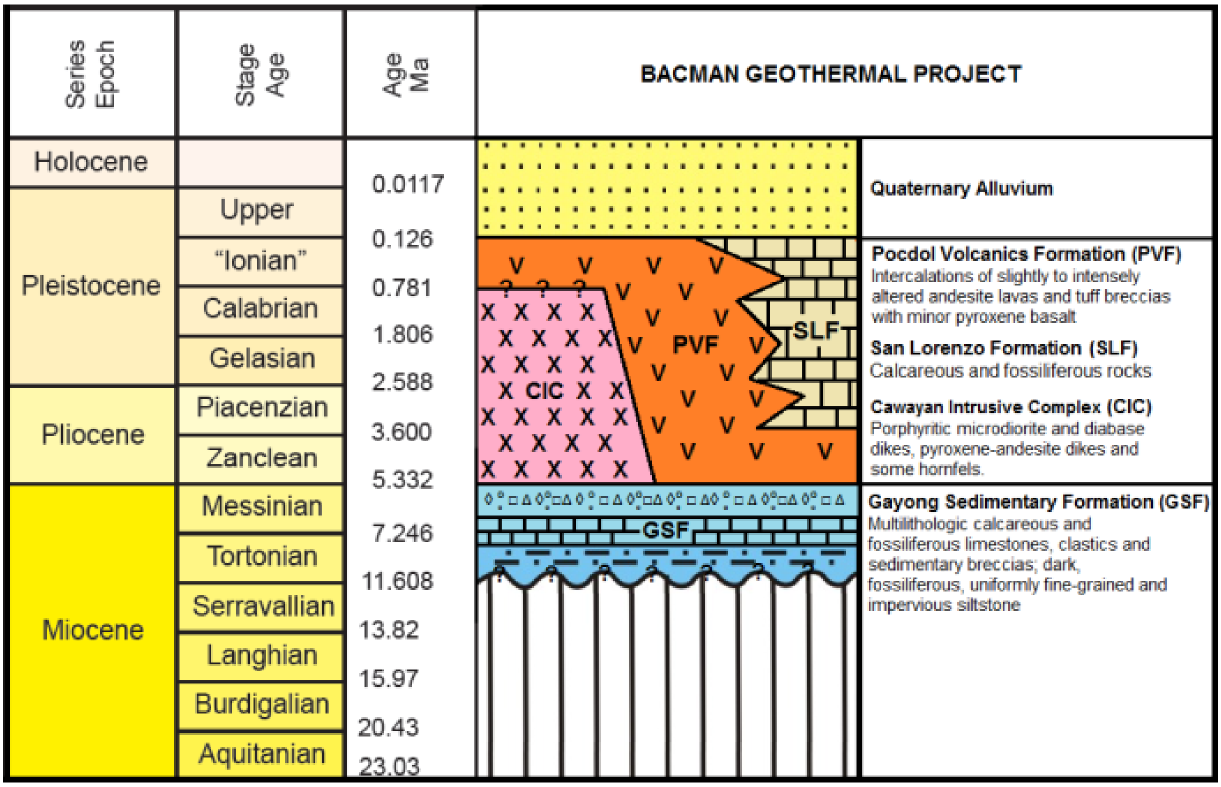


**Figure 2: General stratigraphy of the Bacman Geothermal Project**

## 2. REVIEW OF WELL DATA

The GSF was previously called the San Lorenzo Formation (SLF) based on exposures mapped in San Lorenzo area and Rangas sector to the southeast (Fig. 3). Comparable to GSF lithology, SLF is also predominantly composed of fossiliferous limestones deposited in shallow neritic environment during Late Miocene to Early Pliocene (Robinson, 1987). The name GSF was derived from the occurrence of correlated sediments previously encountered by the first well drilled north of Palayang Bayan. GSF was formally named after a subsequent well pointing to an intersected sedimentary breccias unit and a fine-grained dark-colored unit, which exhibits a different lithologic character from the mapped SLF surface samples. Sedimentary samples from these two wells where GSF designation was based displayed similarity in color and composition, stratigraphic relationship with overlying PVF, and age and environment of deposition.

Upon availability of more downhole geologic and paleontologic data from other drilled wells, the demarcation between GSF and SLF was drawn more clearly. Calcareous and fossiliferous rocks reflecting lagoonal environment of deposition were confined to younger Late Pliocene to Pleistocene SLS. Conversely, older sedimentary rock assemblage consisting of limestone, breccias and fine-grained sediments, which are indicative of shallow neritic to open marine environment, were clearly labeled as GSF. Based on paleoanalysis of rock samples in selected BGP wells, GSF was assigned a Late Miocene to Early Pliocene age. Table 1 shows a summary of lithofacies in BGP wells with interpreted paleoenvironment based on faunal content and lithologic characteristics.

GSF covers a wide area of BGP, although geothermal wells in the Cawayan sector did not penetrate the formation. It was encountered shallowest in well OP-1D and deepest in well OP-5D. The true thickness of GSF, however, cannot be ascertained since wells that intersected the formation have either been terminated within the formation or drilled blind until total depth.

### 2. 1 Palayang Bayan Sector

Collected data from some Palayang Bayan wells revealed that GSF was comprised primarily of sedimentary breccias with volcanic clasts, carboniferous and fossiliferous limestones, and usually intercalated with volcaniclastics and lava flows. The GSF lithology encountered in the north is predominantly composed of fossiliferous limestones and volcanic breccias with minor calcareous sandstones. The occurrence of foraminifera with minor echinoid fragments in limestones indicates an open marine environment.

In central and eastern Palayang Bayan, the GSF consists mainly of multilithologic calcareous sedimentary breccias. Core samples of dark impervious and fossiliferous siltstones were recovered from the deeper sections. These rock units represent the deep portion of GSF and were probably deposited during the Late Miocene to Early Pliocene in a deep marine environment.

### 2.2 Botong Sector

Among the wells drilled in BGP, the top of GSF was intersected shallowest in well OP-1D and deepest in well OP-5D. Well OP-1D, the first exploratory well in Botong sector drilled through predominantly calcisiltite, calcarenite, limestones, and shale lithofacies of GSF. Paleoanalysis of faunal content in well OP-1D calcisiltite cuttings suggested vertical variations in environment of deposition—changing from reef lagoon to shallow neritic, deepening towards open marine, and back to shallow reef lagoon environment near the well bottom. This reflects a sequential transgression and regression of sea level through time.

GSF in well OP-1D contains red algae and more planktonic and benthonic foraminiferal markers, which narrowed down its depositional environment to shallow neritic. Moreover, presence of large foraminifera in well OP-5D also implies lagoonal-submarine to shallow neritic environment of deposition. Thus, the recovered sediments from Botong wells were likely deposited in shallower areas, most probably lagoon or subaerial to shallow neritic.

### 2. 3 Tanawon Sector

In Tanawon, the top of the GSF was intersected at an average depth of -1,000 mRSL. In one well, this rock formation consists of fossiliferous limestone, calcareous andesite breccia, andesite and basalt hyaloclastites, similar to lithofacies encountered in Palayang Bayan wells. At deeper levels below ~1000 m RSL, a pyroxene microdiorite cuts the GSF producing contact metamorphism in calcareous host rock units. On the other hand, the GSF in another well is composed of highly carbonaceous siltstones, sandstones, and laminated claystones. Fossiliferous limestones and breccias imply deposition along slope in shallow open marine, while fine-grained carbonaceous clastic rocks and laminated claystones denote deeper marine conditions. This marked contrast in lithofacies implies an abrupt shift in the depositional environment of the GSF within this sector of the geothermal system:

## 3. DISCUSSION

The GSF lithofacies encountered in all drilled wells in BGP were gathered, and their depositional environment was interpreted initially based on paleoanalysis (Table 1). To ensure consistency and reliability in reconstructing the paleoenvironments, lithologic characteristics of paleoanalysed rocks were compared with global sedimentary facies distribution in ocean depositional setting. Generated lithofacies assemblage was then used to identify and correlate the lithology and corresponding paleoenvironment for all the wells drilled in various sectors.

Paleoenvironment reconstruction revealed that the natural configuration of marine depositional setting and sea level transgression and regression cycles are the prevailing controlling parameters on the deposition of GSF, as well as on the lateral and vertical variations within its lithologic sequences. However, volcanic and tectonic activities also proved to have remarkably contributed to the resultant variation in lithology. Such dynamic geologic events may have transpired during and after widespread deposition of calcareous GSF sediments in the Late-Miocene to Early Pliocene.

### 3.1 Lithofacies and Paleoenvironment

Correlation of well data in BGP suggests a general deepening of GSF top boundary from Botong to Palayang Bayan and Tanawon sectors. This trend coincides with the interpreted paleoenvironment and basin morphology based on paleoanalysis results and lithofacies characterization. Figure 3 illustrates a continuing transition of depositional

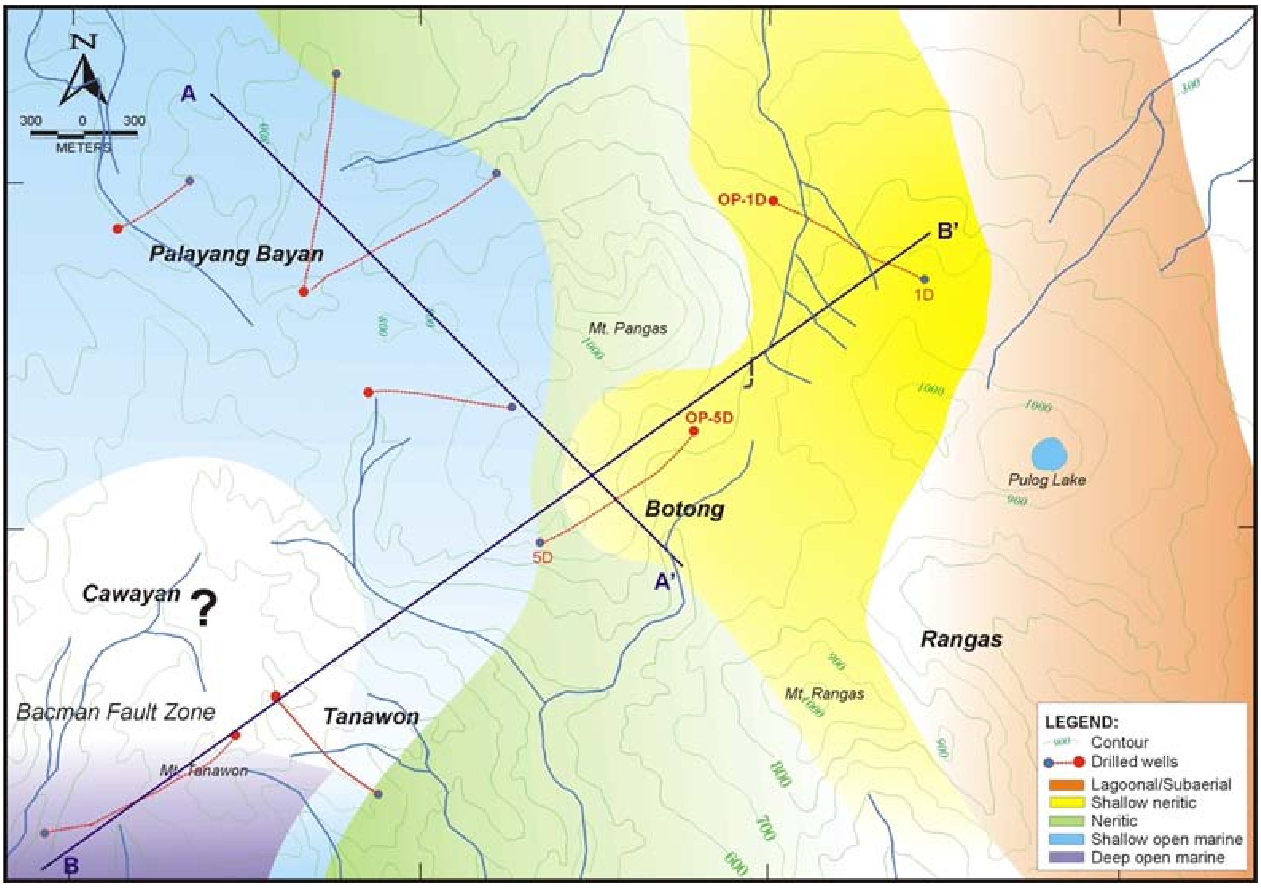


**Figure 3: Sectoral Map of the Bacman Geothermal Project showing its paleoenvironment distribution.**

| Paleoenvironment/ Sea level (m) | Wells | Lithology | Faunal Content | Geologic Age |
|---|---|---|---|---|
| Lagoon / subaerial | **OP-1D** | **calcsisiltite, biocalcarenite,** *marl, clay and organic-rich fine-grained clastic rocks* | *O. Universa*<br>*Gs.Obliquus*<br>*Gq.Altispira*<br>*Amphistegina*<br>red algae<br>echinoid | Miocene (?) - Recent |
| Shallow neritic / littoral ~5-10 | **Botong** | **carbonaceous/fossiliferous** limestone, calcsisiltite, calcarenites, calcareous clastics (sandstone, siltstone, shale, claystone) | *Globorotalis tumida*<br>*Orbulina spp.*<br>*Gs. Trilobus*<br>ostracods | Pliocene |
| Neritic / sublittoral ~200 | **Botong**<br>**Palayan Bayan** | **reefal carbonates,** limestones, calcareous/fossiliferous siltstone (with planktonic foraminefaral and coral fragments) and sandstone | *Gs. Spp.*<br>*Globorotalia sp.*<br>*Pseudorotaliids* | Late Miocene to Pliocene |
| Shallow open marine ~700-1000 | **OP-5D**<br>**Palayan Bayan**<br>Central Tanawon | **Slope deposits, calcareous sedimentary breccia,** fossiliferous/calcareous sandstone and dark laminated siltstones | *O. Universa*<br>*Gq. Altispira*<br>*Globigerinoides*<br>*Globorotalia tumida* | Late Miocene to Pliocene |
| Deep open marine ~4000-4500 | South Tanawon | **Fine-grained carbonaceous claystones** with fine parallel laminations, siltstones, and sandstones | - | Miocene to Pliocene (?) |

**Table 1: Paleoenvironment and GSF lithofacies in BGP wells (Wells in bold have paleoanalysis).**

environments from lagoonal to shallow neritic in Botong, slightly deepening toward Palayang Bayan, which reflects shallow neritic to shallow open marine; and further deepens down to the abyssal plains of ocean basin toward the south-southwest in Tanawon sector.

Based on lithofacies character and paleoanalysis, GSF in Palayang Bayan was deposited in varied zones of marine setting from neritic to shallow open marine (Fig. 4). The occurrence of carboniferous and fossiliferous limestones and thin, fine-grained clastic units in Palayang Bayan wells represent lulls in volcanic activity and tectonic quiescence in neritic setting, and accompanied by sea level rise and fall. Usually intercalated with sediments, volcaniclastics and lava flows suggest that sedimentation was accompanied by intermittent volcanism during Late Miocene to Early Pliocene. The presence of volcanic breccias denotes deposition in localized slopes where volcanic materials fall due to gravity. In central and eastern Palayan Bayan, paleoanalysis of dark calcareous siltstone core samples at deeper levels confirmed a neritic depositional environment, possibly grading to shallow open marine. Other wells drilled in the sector encountered similar dark calcareous fossiliferous siltstones with prominent laminations and abundant planktonic foraminifera, which also indicates a shallow open marine environment.

Botong wells, similar to those in Palayang Bayan, encountered lithofacies generally concentrated on shallow neritic to neritic environment (Fig. 5) based on predominance of reefal carbonates and calcisiltites; except for occurrence of volcanic breccias in well OP-5D, which implies change in environment from neritic to sloping regions in shallow open marine. Presence of terrestrial-influenced sediments in Botong suggests that the area most likely defines the easternmost boundary of the Bicol basin.

Going south towards Tanawon, GSF occurrence and appearance imply deeper depositional setting based on its finer claystone unit, abundant clay minerals, and thin parallel laminations. Such characteristics are all distinctive of a deep marine depositional environment. Moreover, the fine clastic units are devoid of calcareous matrix and fossils. This strengthens the concept that southwest Tanawon sediments were most probably deposited in deep marine environment below the Calcite Compensation Depth (CCD), possibly within the abyssal plains, the bottom of which contains mostly clay-rich sediments with no fossils at all since calcareous ooze can no longer survive at these depths.

Although thinly-laminated fine-grained sediments can also be found in subaerial conditions, all lagoonal rock samples in BGP are calcareous and fossiliferous, making them totally different from the carbonate-barren clastics in Tanawon. Also, indications of deposition along slope break in open marine segments derived based on the presence of volcanic breccias suggest deepening of ocean floor towards the southwest. Furthermore, GSF in central Tanawon showed characteristics similar to Palayang Bayan GSF lithologies, which were accurately established as open marine deposits based on paleoanalysis. This inference by association advocates a deep marine deposition of the GSF for southwestern Tanawon. Thus, the marked contrast of lithofacies in wells within Tanawon sector implies a sudden shift in depositional environment, most probably due to steeply dipping shelf break plunging down the abyssal plains: a typical ocean floor landscape in Philippine archipelagic setting.

The depth and extent of GSF suggest that sediments were laid within a single depositional basin. Thus, it demonstrates spatial continuity from lagoonal towards deep marine, simultaneously displaying lateral and vertical variations in lithologic characteristics, which in turn reflects the eclectic blend of changing zones in ocean basin morphology, sedimentation conditions, and sea level fluctuations.

### 3.2 Tectonics

Dynamic movement of geologic structures provides plausible explanation on the anomalous occurrence of GSF top boundary in wells drilled across BGP. Abrupt deepening of the formation in adjacently drilled wells along Botong-Palayan Bayan and Tanawon-Botong sectors suggests tectonic subsidence due to extensional forces. Similarly, Cawayan wells did not intersect GSF most probably because of downfaulting; although intensive volcanism or existence of a paleo-high configuration may also explain why GSF was not observed in this sector. On the other hand, Tanawon sector south of the Bacman Fault Zone suggests upliftment of the area based on the presence of sediments with deep marine characteristics.

In Palayang Bayan, most geothermal wells generally intersected GSF at around -1000 to -1500 m RSL, although some wells encountered the formation at greater depths. In Botong, it could be seen in Figure 5 that the GSF generally occurs at shallower levels, but it is also where deepest occurrence of GSF was observed in well OP-5D at ~1,500 m RSL. Average depth of top of formation across section from Palayang Bayan to Botong sector in Figure 4 shows a relatively even surface for GSF. Minor anomalously deep GSF intersections, however, suggests that geologic structures—parallel to sub-parallel to the section—could have influenced the vertical displacement of the formation. Aside from subsurface downfaulting, surface geomorphology of Palayang Bayan which defines a NW-SE graben-like structure may support this claim.

The interpreted cross section from Tanawon to Botong sector in Figure 5 illustrates a possible subsurface deepening of GSF probably due to the influence of the Bacman Fault Zone (BFZ) or the southeastern end of the Palayang Bayan graben structure in Rangas area further south of Botong. To the south of BGP, Tanawon sector rests on the uplifted block at the southern boundary of BFZ. BGP aerial photographs visibly capture Tanawon as an elevated sector, bounded to the north by the downthrown BFZ block. This prominent elevated tectonic feature possibly explains why the southwestern Tanawon well intersected deep marine sediments, which are supposedly located at relatively deeper horizons.

In Cawayan, the wells drilled did not intersect GSF. In this case, the downward movement of fault block most likely displaced the sediments at deeper levels. Thus, wells drilled in the area may have been terminated at shallow depths and did not reach the top of GSF further beneath. On the other hand, GSF could have been intersected but was not observed, probably because sediments were already completely obliterated by episodes of intense Plio-Pleistocene volcanism. Alternatively, it can also be speculated that the area was a paleo-high during the

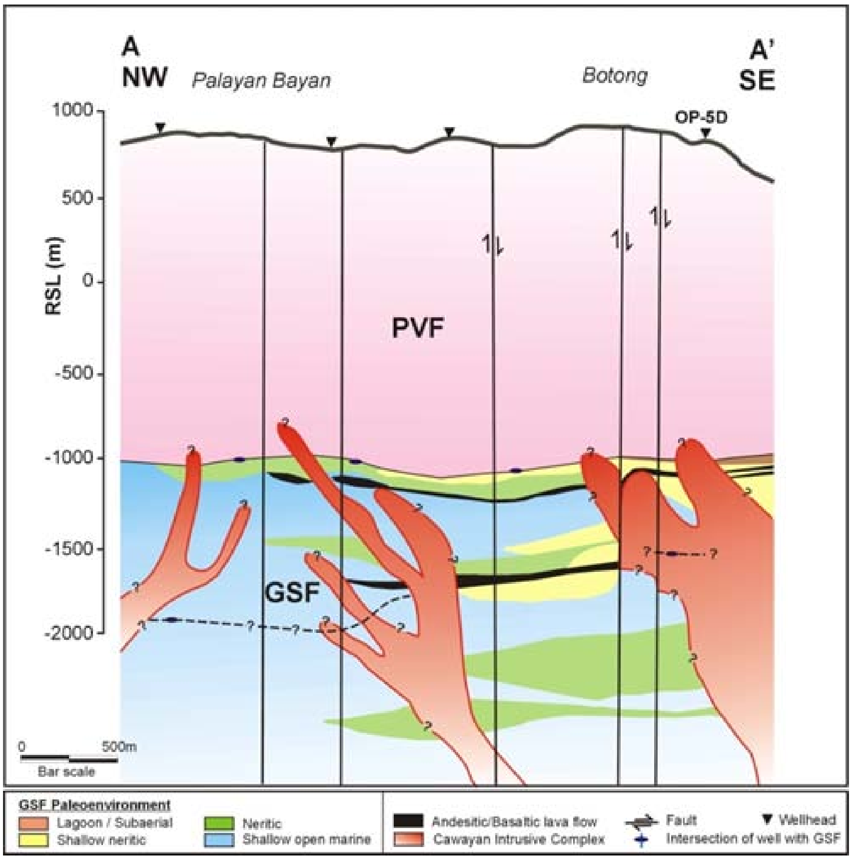


**Figure 4: Interpreted cross section of Palayang Bayan and Botong sector, BGP**

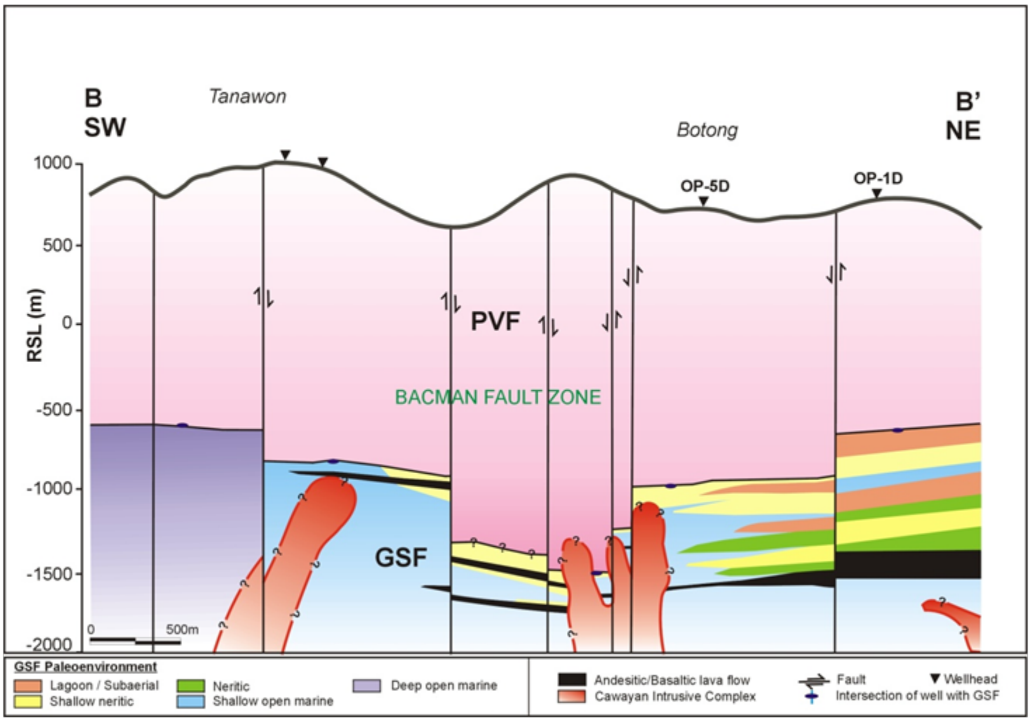


**Figure 5: Interpreted cross section of Tanawon and Botong sector, BGP**

Miocene to Early Pliocene, hence, GSF deposition may not have actually taken place.

## 2. CONCLUSION

Characterization of GSF lithofacies observed in BGP wells helped establish the different depositional environments and morphology of paleobasin across BGP. The dominant lithologies and faunal assemblage determined the paleogeographic location of wells in different zones of marine depositional setting. At the same time, each lithologic variation in an individual well suggested specific change in conditions of environment of deposition. Having considered all these concepts, evident lateral and vertical variations in GSF lithofacies indicate probable deepening of depositional basin in Palayang Bayan to the west, and towards south-southwest in Tanawon sector.

Recent geological, geophysical and structural data must be integrated with this study to refine stratigraphic correlation, characterize and subdivide lateral and vertical lithofacies, and determine the true depth of GSF. Additional subsurface geologic data to the west of BGP could elucidate on the extent of the formation. Exploration activities in Rangas sector in the east will also help delimit the lateral extent of GSF lithofacies towards the southeast. Furthermore, future drilling expansion in Tanawon and Kayabon sectors could confirm the deepening of paleobasin to the west and south. This will help define the morphology of the BGP depositional basin and help associate lithology with permeabilities within GSF.

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