LANDSAT Assisted Geostructural Analysis of the Bacon-Manito Geothermal Field

Southeastern Luzon, Philippines

By

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Abstract

LANDSAT imageries covering the Bacon-Manito geothermal field and its vicinity were analyzed and interpreted to define the regional structural framework of the area. Two LANDSAT scenes were utilized. Data formats used were false color composite prints for both scenes and a computer compatible tape (CCT) containing digitized multispectral data. The prints were enlarged to 1:250,000 and analyzed manually. The CCT was processed on the multispectral imagery analyzer of the Natural Resources Management Center (NRMC), photographed on the color CRT screen and interpreted.

The study area covered both the Bacon-Manito area and the adjacent regions in order to take advantage of the synoptic character of the imagery, which in past studies has proven quite useful in providing a regional overview.

Lineaments which may represent faults and fractures as well as circular features which could define potential craters or vents were drawn on overlays. The defined structural sets were correlated with the tectonic setting of the Bicol Region and with the inferred prevailing stress direction.

The preferred orientation of lineaments interpreted from LANDSAT imageries are north-northwest, northwest, north-northeast and northeast. These lineaments are attributed to at least two episodes of deformation. First is the west-northwest shear couple due to a S 75° W primary compressive stress, and the second is due to release of this compressive force combined with the vertical forces resulting from volcanic and magmatic activities. The overall structural framework, therefore, is one of gravity faulting in response to magma withdrawal but the direction of individual fractures is strongly influenced by the regional stress field.

Introduction

This study was conducted by PNOC-EDC and NRMC to determine the regional geostructural setting of Bacon-Manito (BacMan) area through the use of satellite remote sensing data. The study involved regional and semi-detailed analysis of LANDSAT data covering the southern part of Bicol and the entire Bacon-Manito geothermal reservation. A tectonic synthesis of the region was compiled and then correlated with analyzed information from LANDSAT imageries. The study aimed to delineate the major structural lines in southern Bicol and identified the regional stress directions which were responsible for the deformation at BacMan.

Methodology

From the NRMC's LANDSAT data library, two scenes were chosen for this study. These are scenes 1187-01352 taken 26 January 1973 and 315-2001262 taken 3 May 1982. Data formats used for the study are positive transparency of false color composites (FCCs) of bands 4, 5 and 7 and computer compatible tapes (CCTs). Unfortunately, data interpretation was hampered by the partial cloud cover in the LANDSAT scene 1187-01352 of southern Bicol and the inferior quality of the false color composite positive transparency.

False color composite of bands 4, 5 and 7 was chosen to produce the best color contrast on raw data for geologic interpretation. From the positive transparency of the LANDSAT scene (about 180 x 180 kms.) the subscene of the study area was extracted and enlarged photographically to working scale of 1:250,000.

The computer compatible tape on the other hand was run on the Image 100 multispectral imagery analyzer. Subscene covering the area was likewise extracted and generated on the Image 100 CRT screen with a scale of 1:250,000. To emphasize lineaments and other geologic features, the imagery was enhanced using ratioing and linear contrast stretching of the multispectral bands.

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Positive prints of enhanced imageries were reproduced from the Image 100 CRT screen using a large format camera. Prints were enlarged in the color photo library to working scale.

Using conventional airphoto interpretation techniques, positive prints of both raw and enhanced imageries were interpreted for geologic features. Obscure lineaments which were not readily recognizable on the prints were referred to the color CRT display. By varying color combinations and intensities assigned to each band, a better contrast of the imagery is obtained.

Interpretations were drawn on overlays and then transferred to a 1:250,000 scale base map. Structures were later transferred to a 1:50,000 topographic map of the area using a zoom transfer scope. Lineament data were compiled and lineament frequency histograms were generated using the LOTUS program and an IBM PC-XT computer.

The wrench tectonics model by R.E. Wilcox, and others (1973) was adopted by the authors to explain the structural regime of the area.

Regional Geological Setting

Generalized Geology

The topography of Bac Man is typical of volcanic terrains. It is rugged and characterized by numerous cones, domes and crater structures. Surface morphology is very diagnostic of underlying lithology. Areas underlain by pyroclastics are generally gently sloping while lava flows are usually steeply sloping with prominent lobate fronts. Several craters are well preserved signifying very recent volcanic activity while other craters are partly eroded and some have apparently collapsed. Several small lakes occur within well preserved craters. Among these lakes are Osiao, Pulog and Rangas. Intermontane depressions and probable remnants of collapsed craters on the other hand are filled up with eroded materials and pyroclastic debris. A cluster of volcanic peaks rise prominently at the eastern part. The highest peak in the area is Mount Pangas with an elevation of 1082 meters ASL.

Volcanism in BacMan has been active in not too distant geologic past. Travaglia and Baes (1979) and Balce and others (1979) infer that volcanic activity commenced around Late Miocene as evidenced by volcanic flows overlying Upper Miocene sedimentary units. Lawless and others (1983) further suggest that deposition of a certain volcanic formation was active until probably Pleistocene and Recent times.

The most prominent regional structure in the area is the northwest-southeast San Vicente-Linao Fault which obliquely cuts across the Bicol Peninsula. This feature was recognized earlier by Travaglia and Baes (1979) and by the Bureau of Mines (1963). Other structures identified by the previous workers trend east-west and northwest. Lawless and others (1983) also recognized north-south, northwest and north-northeast sets. All these authors used aerial photographs and/or satellite imageries in their structural interpretation. Detailed ground survey by Panem and Alincastre (1985) showed that structures in BacMan are predominantly steeply dipping gravity faults which trend north-south, northwest, northeast and eastwest. North-south faults appear to be the youngest and the most abundant set of structures.

Tectonic Environment

The Bacon-Manito geothermal field is a part of the northwest-southeast trending Quaternary Bicol volcanic belt (Figure 1). Active volcanic centers in this belt include Mayon and Bulusan, while volcanoes presently inactive are Labo, Isarog, Iriga and Pocdol (Phivolcs, 1985).

This belt is paralleled to the east by the Philippine Trench which marks the westward subduction of the Philippine Sea plate beneath the eastern Philippine Islands. The Philippine Trench extends from the vicinity of Talaud Islands in southern Mindanao northwards to the Bicol Peninsula at

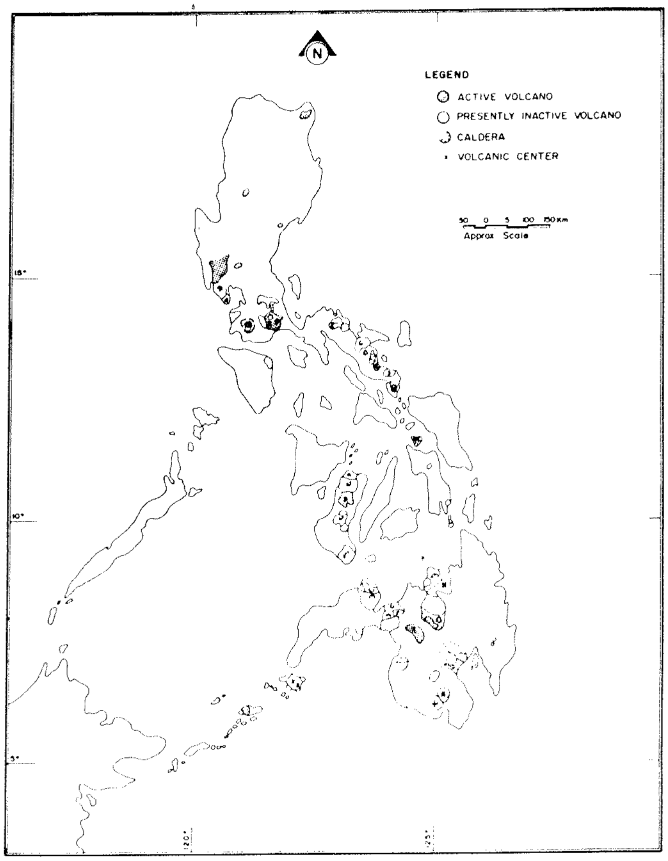

FIGURE 1
Distribution of active and inactive volcanoes in the Philippines
(After Phivolcs, 1985)

about latitude 15°N where it is connected to the incipient East Luzon trench by an east-west left lateral transform fault (Seno and Kurita, 1978; Karig, 1973; Lewis and Hayes, 1980). These tectonic features are shown in Figure 2.

An earlier episode of westward subduction in eastern Luzon has been active from Late Mesozoic to Early Cenozoic as inferred from the presence of Cretaceous and Paleogene volcanics and pyroclastics in the southern Sierra Madre (Gervasio, 1973; Karig, 1973). The magmatic belt of this subduction system extends through northern and southern Sierra Madra, Bicol, Samar and eastern Mindanao (Balce and others, 1979). This phase of subduction is evidenced by the geology of the Pacific Cordillera of eastern Mindanao where the Agusan-Davao trough appears to be the forearc basin of a mid-Tertiary east facing subduction zone (Moore, 1981).

Many geologists agree that this particular episode of westward subduction in eastern Luzon "flipped" to an eastward subduction in western Luzon (Murphy, 1973; Karig, 1973; Bowin and others, 1978; De Boer and others, 1980; Balce and others, 1980). Timing of the polarity reversal, however, is the bone of contention as estimates vary from Early Oligocene to Pliocene (Hamburger and others, 1980). Karig (1973) hypothesized another imminent reversal. He believes that the Philippine Trench-East Luzon subduction system is growing northwards and will replace the Manila Trench as the major plate boundary in the region. Consistently, Cardwell and others (1980) noted the absence of indications of active underthrusting beneath the Luzon Arc.

Recent, seismotectonic activities and other evidences manifest varying subductive scenarios along eastern Philippines. Fitch (1972) suggests that the shallow belt of seismicity east of central Luzon is an indication of incipient subduction along eastern Luzon. Cardwell and others (1980), on the basis of focal mechanism solutions of these shallow earthquakes, likewise believed that deformation beneath eastern Luzon may be an example of rejuvenation of an old plate interface. Hamburger and others (1980) also cited the striking similarity of seismic patterns and focal mechanisms associated with shallow, well developed subduction zones and east Luzon, and thus, interpreted the activity along the latter as a reactivation of subduction along a previously convergent margin.

At the portion of the trench east of the Bicol Region, Hamburger and others (1980) noted that the Benioff zone does not extend westward as far as the volcanic front and that the well constrained intermediate earthquakes are located farther south, beneath Leyte, Samar and Mindanao. These observations cast doubt on the relationship of the Quaternary volcanoes in Bicol and the present subduction activity along the Philippine Trench. In addition, Acharya and Aggarwal (1980) observed that north of latitude 13°N earthquake activity is sporadic and the trench is not well defined by bathymetric data. On this basis they suggest that subduction along this portion is disrupted.

Activity along the Philippine Trench from Mindanao to the south exhibits a different scenario. It is presumed to be propagating southwards from Mindanao to the Talaud Islands. Evidences that support the recent southward propagation of subduction along the Philippine Trench are the absence of Quaternary volcanoes in eastern Mindanao, the absence of accretionary prism in the forearc region (Hamilton, 1979; Karig, 1975), and a shallow Benioff zone that extends less than 200 km. beneath Mindanao and Talaud Islands (Cardwell and others, 1980).

Majority of the earthquakes in the Bicol Region during the period 1962 to 1973 are confined along the trace of the Philippine Fault zone at the back arc and along the trench arc gap. Acharya and Aggarwal (1980) suggest that earthquakes along the Philippine fault in the region are mostly shallow earthquakes with depths less than 70 kms. These were

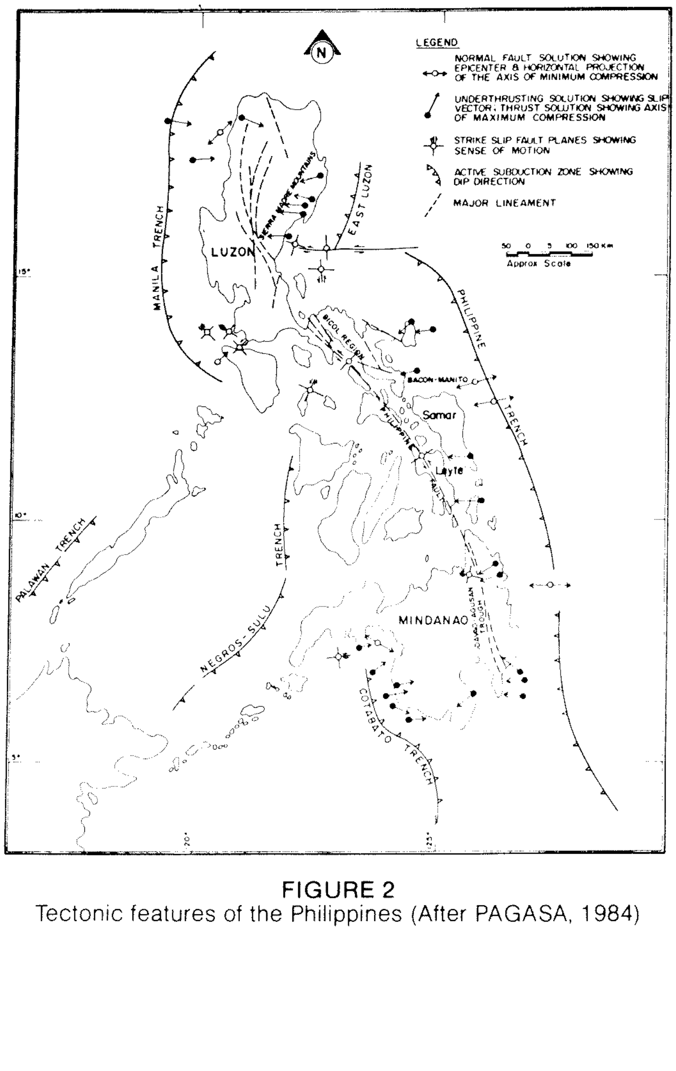

FIGURE 2
Tectonic features of the Philippines (After PAGASA, 1984)

stresses not released in underthrusting. Focal mechanism solutions of earthquakes (between 1963 and 1983) associated with the Philippine Fault zone indicate sinistral wrenching while those located offshore in the trench-arc gap indicates thrusting solution with axis of maximum compression trending west-south-west (PAGASA, 1984; Cardwell and others 1980).

Interpretation of LANDSAT Data

Interpretation of LANDSAT imageries of the BacMan area is greatly hampered by extensive cloud cover. Nevertheless, lineaments were obtained from LANDSAT imageries using the techniques described earlier. Both linear and circular features were mapped and plotted on the base map. Regional lineaments as well as lineaments in the vicinity of BacMan are shown in Figures 3 and 4.

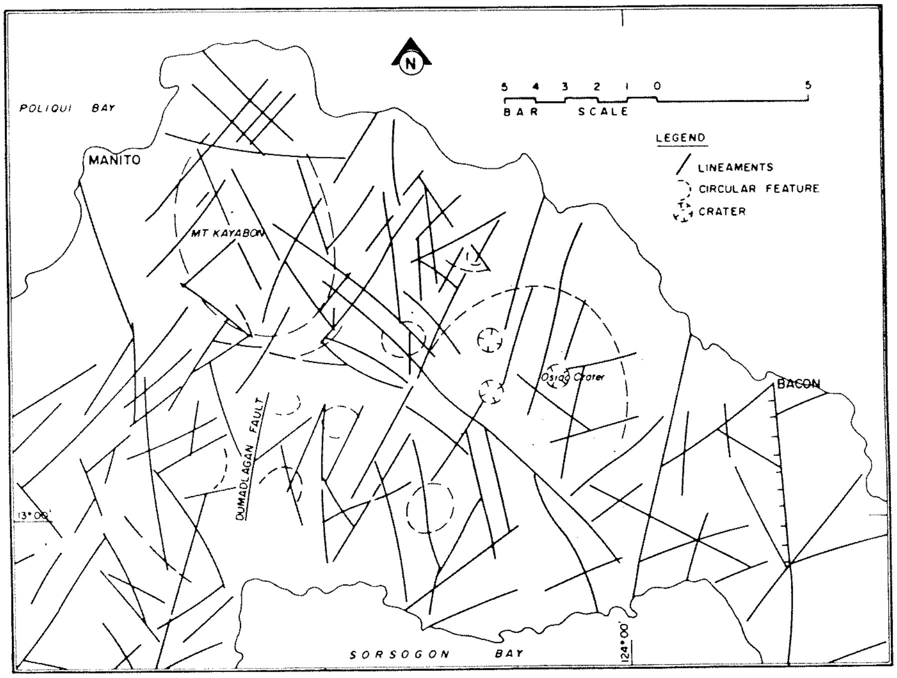

FIGURE 4
Lineament map of Bacon-Manito Geothermal Field (Based on LANDSAT Data)

Linear features were compiled in the form of rose diagrams. Two diagrams were prepared, one for regional lineaments and another for BacMan. From the compilation in Figure 5A, it is evident that the preferred orientation of lineaments in the region are N 10 to 50° W and N 20 to 60° E. Similar lineament pattern was observed in BacMan (Figure 5B) where the N 10 to 25° E structures are locally dominant.

Circular Features

Numerous circular features were identified in the area. Some of them have been identified on the ground either as collapsed caldera, craters or lithological boundaries. A major circular feature occurs south of the town of Manito. It has a maximum radius of approximately 3.5 kilometers. The eastern margin of the circular form is defined topographically by the Manitohan River while the western boundary is defined by an arcuate ridge. This circular feature is associated with the Kayabon volcanic center. Clusters of small circular structures also occur south-southwest of Manito and south of Osiao crater.

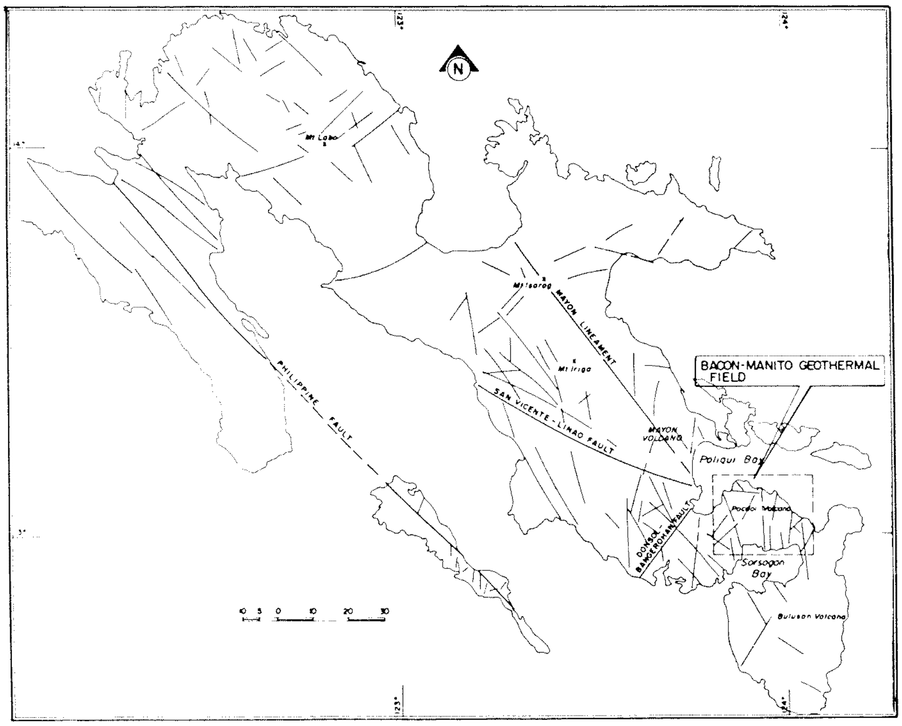

FIGURE 3
Major lineaments in the Bicol Region (Based on LANDSAT Data)

Northwest Set

Based on the rose diagram of the southern Bicol Peninsula, the northwest trending lineaments are the most conspicuous set of structures. The lineaments are preferentially oriented between North 10 and 40° West. The LANDSAT data indicate that these structures are less in number but are long and thorough-going. An important structure in this set is the Mayon Lineament which traverses the volcanic centers in the Bicol Region.

A small number of structures which trend N 65° W is evident in the satellite imageries. A major structure in this set is the San Vicente-Linao Fault, which appears to be a result of

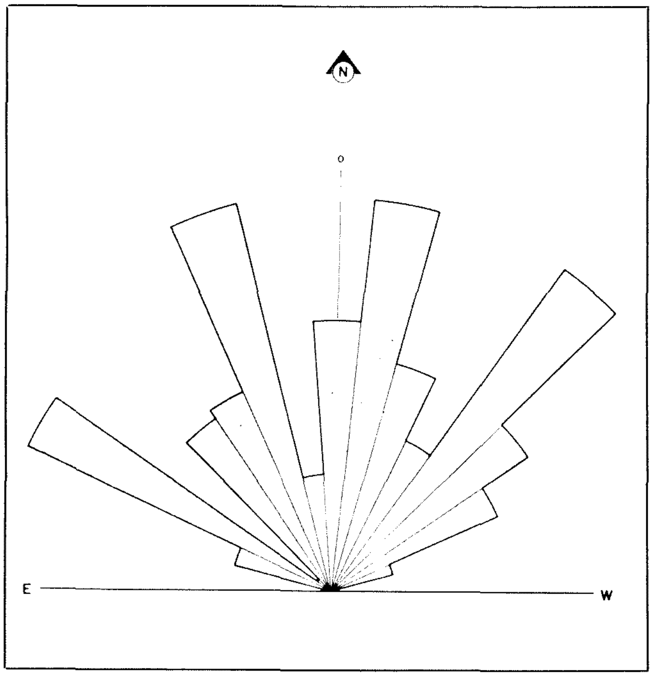

FIGURE 5A
Lineament distribution pattern in Bacon-Manito

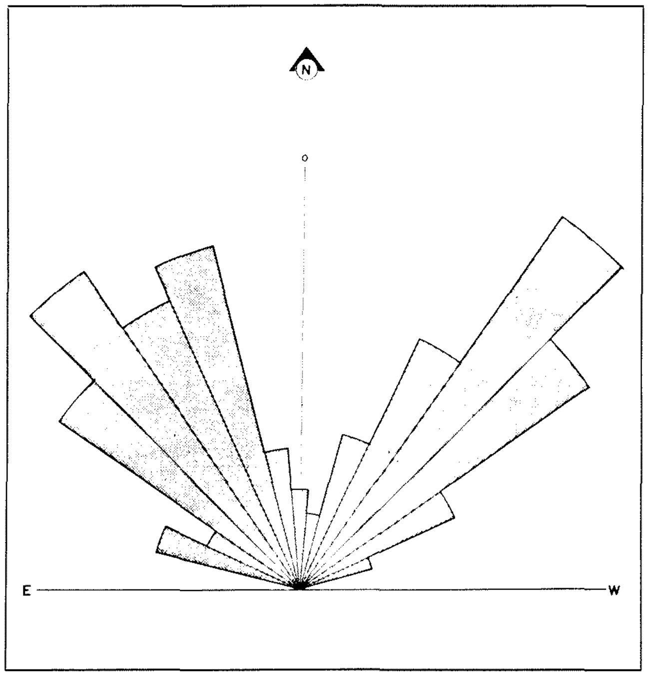

FIGURE 5B
Lineament distribution pattern in southern Bicol

divergent wrenching (Wilcox and others, 1973) along the Philippine Fault. The San Vicente-Linao Fault obliquely cuts across the Bicol Peninsula and probably intersects the Mayon Lineament in Poliqui Bay.

Northeast Set

The preferred orientation of northeast trending lineaments in the region varies between N 20 and 60° E. In contrast, structures within the BacMan geothermal field are preferentially oriented N 5 to 25° E. The local structures trending N 5 to 25° E are presumed to be antithetic, while the N 45 to 55° E and the N 60 to 75° E are believed to be tension and synthetic fractures, respectively. Northeast structures appear to have short traces and are highly disjointed. The most prominent member of this set is the Bangerohan-Donsol Lineament which transversely cuts across the southern part of the peninsula. The lineament passes through the western shore of Poliqui Bay where it possibly intersects the Mayon Lineament and the San Vicente-Linao Fault.

North-South Set

The north-south set is disposed along north-south to N 10° E and N 10° W. This set is not regionally prominent, but it is highly conspicuous in the study area. Major members of this set are: (a) the Dumadlagan Fault which apparently extends from the western shoreline of Sorsogon Bay to the central portion of the area; (b) the segmented north-south structures at the centre of the geothermal field, and (c) the gravity faults east of Bacon. Panem and Alincastre (1985) identified this set as the youngest of the most dominant faults in BacMan.

East-West

There are very few east-west lineaments in the area. The preferred direction of this set varies from N 80° W to EW. The speculated extension of the San Vicente-Linao Fault in BacMan is probably the east-west lineament in the northwestern quadrant of the area. This is where the extension of the fault aligns if it is projected across the Poliqui Bay and assuming it is not displaced by either the Mayon or Bangerohan-Donsol Lineaments. To further verify the extension and alignment bathymetric data of the Bay was studied. There were some topographic alignments noted on the seafloor of the Bay but these are inconclusive.

Structural Analysis

The predicted plate convergence along eastern Philippines is northwest but the generally observed general direction is east-west with slight local variations. To explain the difference, Fitch (1972) suggests that the northwest directed convergence is separated into a normal component which is the westward underthrusting at the Philippine Trench and East Luzon and a parallel component which is manifested by strike-slip movement along the Philippine Fault.

Focal mechanism solutions of shallow to intermediate earthquakes and the orientation of the Philippine Trench in the region indicate approximately a S 75° W directed primary compression generated by the oblique convergence along the Philippine Trench (Cardwell and others, 1980; PAGASA, 1984). Such directed compression would generate a left lateral primary structure (presumably the San Vicente-Linao Fault) causing divergent wrenching (nonparallel displacement of blocks) (Wilcox and others, 1973) along the eastern flank of the Philippine Fault. Sinistral wrenching along the San Vicente-Linao Fault would generate a derived compression directed N 55° E. This compression will produce antithetic shears trending approximately N 15 to 30° E, synthetic shears striking N 60 to 75° E, tension fractures oriented along N 45 to 55° E and fold axes trending N 55° W (Figure 6). This pattern of lineament distribution is reflected in the rose diagram (Figure 5A).

Although the postulated stress orientation accounts for the dominant trend of structures in BacMan, it does not adequately explain the preponderance of gravity faults in the area. Laboratory and field observations by Wilcox and others (1973), however, indicate the antithethic fractures usually inherit some of the tensional component of a wrench deformation and commonly become nearly vertical normal faults with negligible lateral displacement. Furthermore, divergent wrenching favors formation of tensional structures, mainly normal faults.

Alternatively, the lineament distribution pattern and the predominance of steeply dipping gravity faults in BacMan may be attributed to at least two episodes of deformation. The first event involved the south-southwest trending primary compressive stress and the corresponding derived compressional force directed N 55° E. The second episode, on the other hand, involved the release of the south-southwest compressive stress combined with the effects of volcanic activity and the magmatic withdrawal. The general structural picture of BacMan, therefore, is one of normal faulting in response to magma withdrawal but the orientation of individual fractures are strongly influenced by the regional stress field.

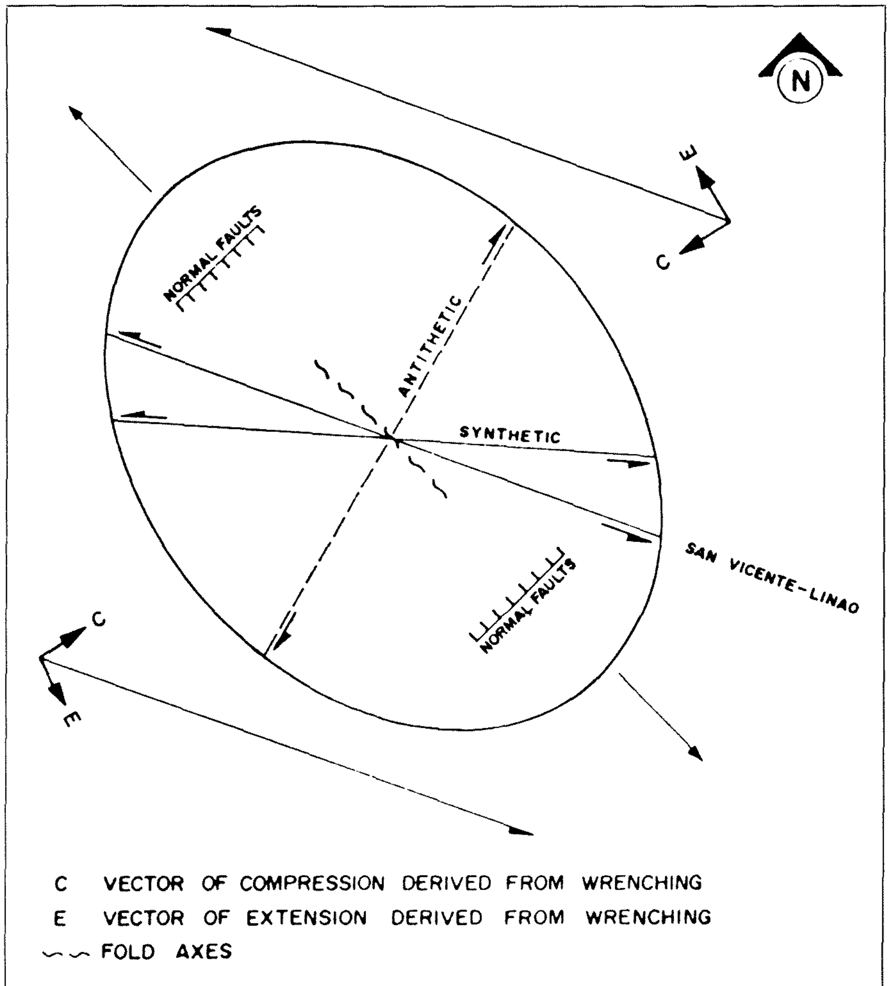

FIGURE 6

Forces and resulting structure from sinistral wrenching along the San Vicente-Linao Fault combined schematically with strain ellipse (After Harding, 1974)

Conclusions

BacMan is in a very young geologic terrain where volcanism probably commenced during Late Miocene and continued until the Recent time. Circumstantial evidences indicate that volcanic activity in the region may not be related to the present subduction activity along the Philippine Trench. As noted by Hamburger and others (1980), the Benioff zone does not extend as far as the volcanic belt. Acharya and Aggarwal (1980) also observed that seismic activity along the trench is sporadic and suggested that subduction along the northern part of the trench is disrupted. Volcanism in the Bicol Region, therefore, is possibly related to an earlier phase of subduction along eastern Philippines

The prevailing primary stress orientation in the area is west-southwest-east-northeast as suggested by the focal mechanism solutions of earthquakes, the trend of the Philippine Trench, and the regional lineament distribution pattern. This primary compressive stress and the associated derived compressional force evidently played a major role in the deformation of BacMan. Their effects are conspicuously manifested by the Bicol fold belt and the predominance of northeast trending gravity faults in the area. The juxtaposition of geologic structures in BacMan, however, suggests the presence of another episode of deformation. This event which generated north-south trending normal faults appears to be related to the combined effects of magmatic withdrawal and the release of the west-southwest compressive stress following the disruption of subduction in the northern segment of the Philippine Trench located east of the Bicol Region. The overall structural framework is one of normal faulting in response to magmatic withdrawal but the direction of individual fractures are strongly influenced by the regional stress field. ☐

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