Geotechnical investigations to assess subsurface stratigraphy of West Coast of Mumbai - A case study

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Abstract: A case study of onshore and offshore geotechnical investigations carried out in Mumbai (Bombay), India for a western freeway sea link project is presented here. 76 boreholes were drilled in soil and rock to assess the geotechnical parameters along a proposed bridge alignment on the west coast of Mumbai. The crucial task of drilling marine boreholes was achieved using a Jack up barge. A geophysical study using a sub-bottom profiler and side scan sonar was also carried out to supplement the geotechnical observations between boreholes. The field data obtained from drilling and in situ testing (including pressuremeter tests) is presented, and correlations with laboratory test results and geophysical data have allowed an evaluation of the geological model of project site. The data available from this investigation is interpreted to reveal the local geology in general and rock mass characteristics and classifications based on Rock Mass Rating. It has been observed from these investigations, in conjunction with other literature, that the sub surface stratum of west coast of Mumbai consists predominantly of westerly dipping basalt along with breccia and tuff with very little or no overburden. Laboratory tests reveal a wide range of strength and other engineering parameters for the characteristic material types present throughout the site area.

Résumé: On présente ici une étude de cas des investigations géotechniques sur terre et par mer qu'on a réalisé à Mumbai (Bombay), Inde destiné au projet d'un lien d'accès occidental libre. On a crusé 76 points d'eau dans la terre rocheuse afin d'évaluer les paramètres géotechniques à côté de la ligne du pont proposé, le long de la côte de Bombay. On a réalisé les travaux critiques de cruser les points d'eau marians en se servant d'une barque à crique. On a aussi établi l'étude géophysique par moyen des profilateurs sous-marians et le sonar de balayage latéral afin de supplémenter les observations géotechniques entre deux points d'eau crusés. Ici on présente les données provenant du terrain d'opération grâce au crusement ainsi que les essais effectués sur place tels que les essais de pressiomètre avec ses corrélations avec les essais de laboratoire et les données géophysiques pour évaluer le modèle géologique du projet sur site. Les données résultant de cette investigation sont interprétées pour déceler la géologie locale en générale et les caractéristiques et classifications de la masse rocheuses selon la Grade. On a remarqué à partir de ces investigations et d'après les témoignages apportés par la littérature technique que le sub-stratum de la côte occidentale de Mumbai comprend pour la plupart la roche basaltique des versants des montagnes occidentales avec Tuf bréchique avec un petit ou nul surchargement. Les essais de laboratoire ont aussi révélé une large gamme des forces et autres paramètres de construction pour signalé la présence des types de matière caractéristiques partout sur site.

Keywords: engineering geology, engineering properties, laboratory tests, rock description, site investigation, soil description.

INTRODUCTION

Maharashtra State Road Development Corporation Limited, India, has planned to construct a bridge under the western freeway sealink (Phase II) along the west coast of Mumbai. This project is an extension of a previous phase, which comprised of a single tower supported Cable Stayed Bridge, 500 meters long, at Bandra Channel, and a twin tower supported Cable Stayed Bridge, 350m long, at Worli Channel, for each carriageway. The total stretch of the Phase-II investigations was 13.66 km from Worli to Nariman Point, about 200 m offshore as shown in Figure 1.

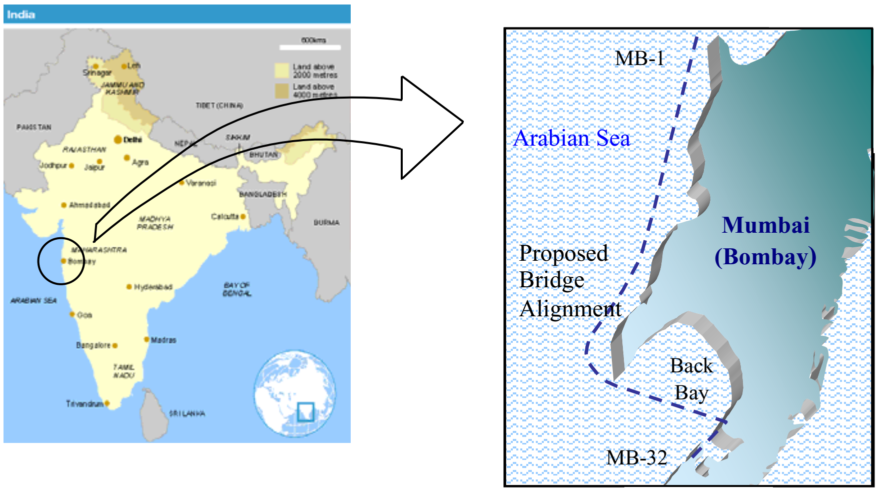


Figure 1. Location of Project Site, Mumbai, India

The objectives of the investigations are to obtain geophysical data along proposed route corridor, and to investigate the geotechnical and geological properties of soil and rock along the proposed bridge alignment and approach roads, to enable a preliminary assessment of a suitable foundation system.

As part of the preliminary investigations, a total of 76 boreholes were drilled along the proposed alignment of the bridge, with total depths varying from 10 m to 53 m. Out of these 76 boreholes, 39 were located in the marine area, 7 were located in the intertidal zone and 30 were located on land along the shoreline. Marine boreholes were drilled in water varying from 1m to 10m in depth. In addition, 200 bar capacity pressuremeter tests were also carried out to assess the in situ properties of rock. Laboratory testing was conducted on various samples, and ranges of representative engineering properties of soil and rock have been derived.

Detailed core logging was carried out to assess geological parameters such as petrography and fracture analysis (fault planes, joints). Data from bathymetry and geophysical surveys was also used to supplement the findings from the geotechnical investigations. A general understanding of the geology of the sea link project site area has been derived from a desk study review of various published references, with the inferred model being validated against borehole information.

SCOPE OF GEOTECHNICAL AND GEOPHYSICAL INVESTIGATION

The geotechnical investigations included drilling onshore and offshore boreholes of varying depth, with detailed logging and carrying out in-situ tests such as the Standard Penetration Test (SPT) and the pressuremeter test. In total, 76 boreholes were drilled using wire line drilling system and PQ coring. Down-hole SPT were carried out wherever a soil stratum was encountered. 200 bar capacity Cambridge pressuremeter tests were also carried out in different boreholes in rock strata, and the data has been analyzed using Cambridge Insitu software to assess different material properties such as insitu lateral stress, limit pressure, shear strength, shear modulus and the behaviour of rock.

The geophysical investigations included carrying out a geophysical survey using side scan sonar, and sub-bottom profiler along a 200 m corridor along the proposed centreline of the bridge alignment. Geophysical investigations, such as a bathymetry survey and a wreckage survey, were also executed but are out of the scope of this paper.

EVALUATION OF ROCK MASS CHARACTERISTICS FROM IN SITU GEOTECHNICAL TESTING

Offshore geotechnical investigations were carried out using three different jack up barges, which had a hydraulic rig mounted for drilling operations (Figure 2). Marine boreholes were started from Worli (MB-1 in Figure 1) and completed at Nariman Point (MB-32 in Figure 1). Detailed borehole logs were prepared for all the boreholes giving information including the type of strata, mineral composition, strength results, and field test results at various depths. The findings of the geotechnical investigations revealed two different principal rock types with overburden, consisting of marine clay or silty sand, at some locations. The predominant rock types observed are basalt and volcanic breccia with intertrappean such as lapilli tuff. The ranges of various properties of Basalt rock based on pressuremeter tests are summarized in table 1.

Figure 2. Jack Up Barges "Commander I" and "Coastal Explorer" during investigation work

Table 1. Pressuremeter Test Results

Type of Rock	Range of RQD, %	Range of Initial Shear Modulus, Mpa	Range of Limit Pressure, Mpa	Range of Insitu Lateral Stress, kpa	Range of Undrained Shear Strength, Mpa
Basalt	NIL-100	1247-2231	118-243	725-800	20-26

EVALUATION OF SOIL AND ROCK MASS CHARACTERISTICS USING LABORATORY DATA

The laboratory testing was carried out to evaluate engineering parameters of soil and rock samples from various boreholes. The soil samples were tested to determine particle size and Atterberg's limits. Tests including Unconfined Compressive Strength (UCS), Point Load Strength Index, Modulus of Elasticity, Poisson's ratio, Dry density and porosity were conducted on rock samples. Tables 2 and 3 show the typical characteristics, based on laboratory testing, of various types of soil and rocks that are encountered within the project area.

Table 2. Laboratory Soil Parameters

Type of Soil	Gravels, %	Sand, %	Silt+Clay, %	Plasticity Index, %
Sandy Clay	0-21	4-22	58-95	27-63
Silty/Clayey Sand with Gravels	0-25	38-89	3-47	NP-32
Silty/Clayey Gravels with Sand	38-56	2-33	11-43	NP-40

Table 3. Laboratory Rock Parameters

Type of Rock	Unconfined Compressive Strength, MPa	Point Load Strength Index, MPa	Dry Density, T/m^3	Modulus of Elasticity x 10^6, kPa
Basalt	38.27-173.66	0.54-6.79	2.50-2.85	30.40-199.07
Volcanic Breccia	1.78-94.58	0.33-3.44	2.29-2.51	35.30
Tuff / Lapilli Tuff	1.10-19.04	0-1.25	1.80-2.47	4.90-14.71

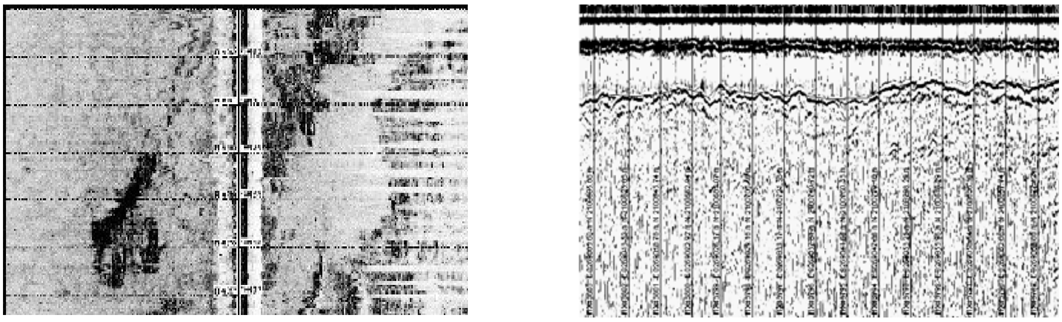
SEABED FEATURES BASED ON GEOPHYSICAL TESTING

Geophysical data was obtained using Side Scan Sonar and Sub-Bottom Profiler to evaluate the lateral variation in seabed features and to provide geological information about the rock mass. This data is used only for qualitative assessment of seabed features and not to determine physical properties of rock. Rock outcrops are seen in Side Scan Sonar as well as Sub-Bottom Profiler at most of the locations along the bridge alignment. Geophysical observations are in close proximity to the actual borehole data obtained and no sudden lateral variation was observed.

Observations from Side Scan Sonar and Sub-bottom Profiler

The Geo Acoustic SS 941 dual frequency side scan system is capable of producing high quality records in either tow fish or ROV mount configuration. The side scan sonar system, along with the navigation system, was interfaced to CODA DA 200 for real time Digital Data Acquisition. The 100 kHz side scan record generally reveals a medium to high reflectivity record because of outcropping rocks throughout the survey corridor. A medium to low reflectivity record was attributed to small patches of silty/clayey sand. Figure 3a shows an extract of side scan sonar record in which rock outcrops are seen as dark patches.

Applied Acoustics Boomer system manufactured by Applied Acoustics Ltd., U.K., is a high-resolution sub bottom profiling system. This is a medium to high power, wide frequency domain (300Hz-14000Hz), electro-dynamic system comprised of a surface towed catamaran, an analogue amplifier and filter, hydrophone array, source element and recorder. At operating powers of 100-300 joules, the power source generates acoustic output of a wide band. The pulse width can be set to allow noise free data even in relatively shallow waters. The data acquired using sub-bottom profiler was studied to gain information about the thickness of soil cap on top of the rock as well as fracture zones in the uppermost part of the rock. The sub bottom profiler record showed a layer of highly weathered/fractured rock, which is observed as outcrop along the alignment. Figure 3b shows the extract of sub-bottom profiler.



(a) (b)

Figure 3. Extracts from Side Scan Sonar and Sub-Bottom Profiler

GENERALIZED SUBSURFACE STRATIGRAPHY

Based on the field and laboratory data, and the various boreholes drilled parallel and perpendicular to the west coast line of Mumbai, the general stratigraphy of west coast of Mumbai has been interpreted to consist predominantly of basalt rock with very little or no overburden. The subsurface strata mainly consist of basalt rock with volcanic breccia with intertrappean such as lapilli tuff. The basalt rock obtained throughout the investigations is dark brown in colour and highly fractured. Basaltic rock was observed in different stages of weathering, from highly-weathered to slightly-weathered. The general tendency of weathering observed throughout the investigation is an upper layer consisting of highly- to moderately-weathered basalt with the severity of weathering changing to moderately- and slightly-weathered with increasing depth. The fracture planes in the basalt are usually filled with minerals including FeO, chlorophaite, Zeolite, Calcite, Chalcopyrite and Pyrite. A limited overburden consisting of marine clay or silty sand is present at a few locations. Though the unconfined compressive strength results for the basalt show very good results at some locations, the discontinuities in the rock mass play a vital role throughout the area under investigation. Some highly fractured zones are also observed a few meters below rockhead, below the zone of intact rock mass. Volcanic breccia along with lapilli tuff are observed as the bridge alignment enters the Back Bay area. The breccia shows various characteristics such as highly-to moderately-weathered, medium- to coarse-grained and medium- to closely-fractured. The overburden of silty sand followed by marine clay is also observed in this region. Tuff and lapilli tuff are mainly observed in the onshore boreholes. The uppermost layers of lapilli tuff are completely- to highly-weathered; further deep the rate of weathering is reduced. The lapilli tuff encountered at the project site is yellowish brown to light grey in colour, fine to medium grainsize, with very close- to medium-spaced fractures, and weak to moderately strong. Fracture planes in lapilli tuff are filled with FeO, Zeolite and calcite minerals. Occasionally, healed fractures or veins filled with Zeolite and Calcite are also present. Figure 4 shows the subsurface stratification at different borehole locations along the main bridge alignment.

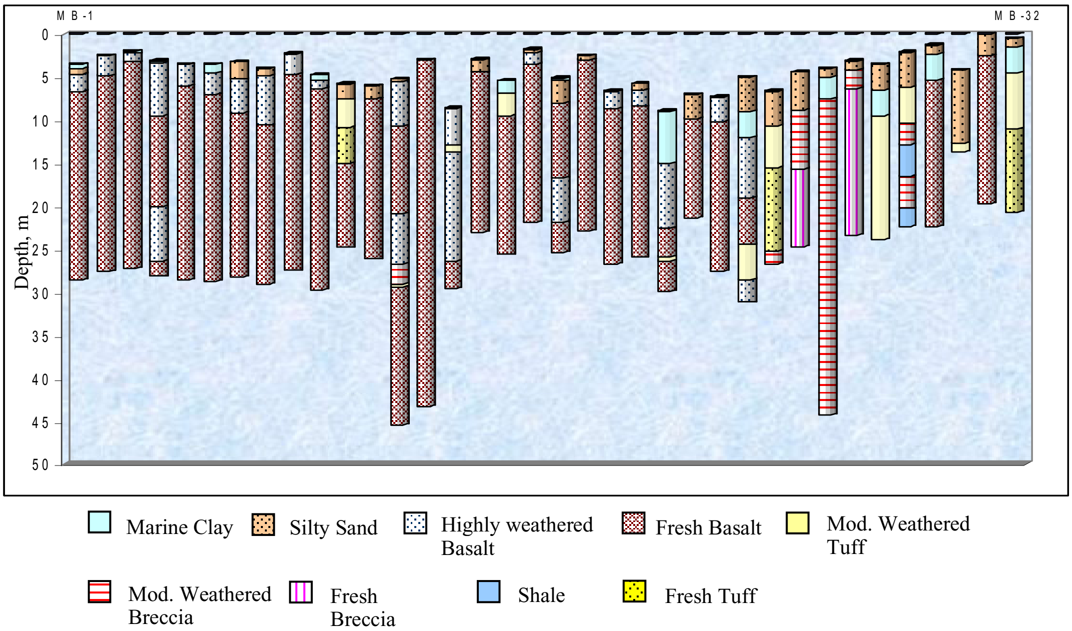


Figure 4. Sub Surface profile at various borehole locations along the bridge alignment

CLASSIFICATION OF ROCK MASS BASED ON ROCK MASS RATING (RMR) SYSTEM

Based on the various borehole data, the rock mass is classified as per the Rock Mass rating criteria as defined by Bieniawki (1989). Information has been gathered from the respective core logging and the corresponding laboratory strength data. Most discontinuities were observed to be rough without significant evidence of preferential, weathering, slickensliding nor the presence of clay gauge. Groundwater conditions are considered as wet (Rating=7). In most of the boreholes the separation of discontinuity is considered as 1-5mm with rating of 1. The rock mass classified along the main bridge alignment falls within Class IV (‘Poor Rock’) and Class III (‘Very Poor Rock’) as shown in Figure 5.

INTERPRETATION AND EVALUATION OF GEOTECHNICAL AND GEOLOGICAL PARAMETERS

Geotechnical Data Interpretations

Various correlations are available in the literature to relate different parameters with each other. Although the RQD is a simple and inexpensive index, it is not sufficient to provide an adequate description of a rock mass on its own because it disregards joint orientation, tightness, and gauge material. The analysis of pressuremeter test data has enabled an estimate of the characteristic undrained rock shear strength to be made from in situ test data. This has been done for all the pressuremeter tests carried out by the Gibson and Anderson and the Palmer subtangent analysis methods. Close agreement was achieved between the two methods of analysis. For undrained conditions the estimated rock compressive strength (UCS) at pressuremeter test pockets was calculated as being twice the corresponding shear strength. Thus giving UCS value in the range of 40-52 MPa, shows a close agreement with laboratory UCS test results. However no comparison could be done for breccia and lapilli tuff as no pressuremeter tests were carried out in these strata.

The value of Poisson’s ratio (ν) was determined on two samples of basalt, with values ranging between 0.11 and 0.24, averaging 0.18. Using standard relationship $E = 2G(1+\nu)$, the pressuremeter shear modulus data is utilized to determine the lateral modulus of elasticity, which ranges from 2943 MPa to 5265 MPa, which is observed to be on lower side compared to vertical elastic modulus obtained from laboratory data.

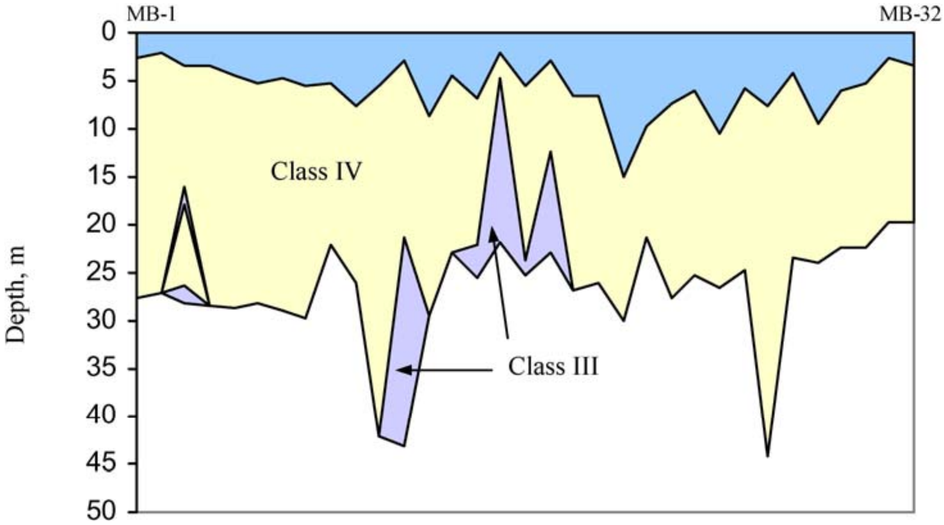


Figure 5. Rock Mass Class based on Rock Mass Rating along the bridge Alignment

The UCS values of basalt and breccia can easily be correlated based on other parameters such as Point Load Strength Index and Dry Density. However it has been difficult to achieve correlations between Point Load Strength Index and UCS values for lapilli tuff. It has also been observed that Point Load Strength Index values can be very low when compared to UCS values for the same sample of lapilli tuff,due to the presence of horizontal laminations. However it is observed that this disagreement is eliminated when lapilli tuff samples are tested for UCS under soaked conditions. The dry density and UCS values show a uniform behaviour in all the rock types as an increase in dry density results in an increase in UCS values.

Geological setting of Mumbai based on literature

The lava flow of Mumbai (Bombay) dips westerly at 5^0 - 10^0 to the west of the Panvel Flexure. The occurrence of two lava flows with a thick sequence of intertrappeans has been previously described at Mumbai Island. The lava flows are seen to be mainly of subaqueous character and do not persist at higher levels in the Western Ghats. These lavas appear to have formed after the rifting of the main plateau basalts, along the Indian west coast, and during the thinning and subsidence of the coastal margin while the subcontinent was moving towards northeast (Sethna 1999).

The lavas of the Mumbai area are believed to represent a much younger phase in the eruptive sequence of the Deccan Volcanic Province. It is proposed to classify these lavas as belonging to a separate sub group- the Salsette Subgroup. In the Mumbai Island area, at least seven distinct lava flows have been recognized. The older Sewri flow and the youngest Malabar Hill lava flow are partly subaqueous and partly subarial, indicating that these lavas erupted under shallow water conditions, possibly during a period of subsidence of the region which followed the rifting of the plateau basalt along the west coast margin of the Indian subcontinent. Although the basalts of Mumbai have not been dated, it is believed that the entire Salsette Subgroup was formed at around 62 Ma, thus predating the main phase of Deccan volcanism (Sethna 1999).

The Malabar Hill flow is of particular significance in connection with the proposed project. The flow is underlain by a substantial thickness of weaker lithified tuffaceous ash debris and volcanic breccia. The gently shelving seabed platform to the west of Mumbai comprises a varied sequence of tuffs, volcanic breccias and carbonaceous shales that overly the Malabar Hill lava flow. These younger deposits are of considerable lateral extent, beneath a thin seabed veneer of recent marine sediments and some completely weathered lava surfaces. In consequence, the strata present at the project site comprise the lower remnants of the Malabar Hill flow beneath which lie a considerable thickness of intertrappean rocks.

Geological Model

It has been observed from the data collected during the investigations that the west coast of Mumbai mainly consists of intrusive and extrusive basalt rock. Generally the rockhead surface ground is very uneven, dark brown in colour with infills of calcite, quartz and other minerals as amygdales. Dark brown-coloured basalt rock is fine to medium grained. The seabed is covered with marine clay and sand at some locations. As the bridge alignment takes a turn towards the east along the southern part (Figure 1), unconsolidated sediments underlain by breccias and tuff are observed. The geological setting in the Back Bay region is different compared with the northern part of the project area, and the principal rock type encountered in this region is volcanic breccia. The tuff encountered during investigations is light yellowish brown in colour, fine to medium grained, slightly to highly weathered and highly fractured with very close to medium spaced fractures. The different layers of rocks are indicative of different lava flows that accumulated at different times. The layer of lapilli tuff gives information about the interval between the two lava eruptions. It has also been observed that the reduced levels of various rocks reflect the westerly dipping rock beds. The angle of dip as actually measured perpendicular to the shore line is 1.4^0 which is less than that mentioned in the literature (Sethna 1999).

Sub-bottom data was examined for faults and other geological hazards that could affect the foundation design. Other than seabed undulations and variable foundation zone soil condition, no additional geological hazards were identified in the study area.

CONCLUSIONS

The economy of any project depends upon the quantum and the quality of preliminary investigations carried out. The data thus gathered through various investigations, including geotechnical investigations, increases the confidence level in the interpretation of the foundation conditions and facilitates the design of appropriate foundation systems. The data presented here is part of the preliminary investigation, part of the development process that plays a very important role in deciding the approach for the detailed investigations to meet site specific engineering requirements.

It is very important to decide the type and amount of detailed investigations required when such complex rock structures are present. As the settlement of foundations is governed by the intensity of jointing, allowable bearing pressure can be assessed as a function of RQD. The Canadian Foundation Manual includes a table of presumed allowable bearing pressure based on a combination of strength and joint spacing together with an equation that gives allowable bearing pressure as one-quarter of uniaxial compressive strength for joint spacing of 1 to 3m. Hence, the design of foundations in such types of rock must include a thorough appraisal of the geological conditions and, especially, possible geological hazards.

Based on the data obtained during the investigations, the principle characteristics of the Mumbai Tertiary Deccan Traps are summarized below:

- Dominance of subaqueous basalts in the form of spilitic lava flows, exhibiting frequent pillow structure
- The presence of volcanic breccias and tuffaceous beds of considerable thicknesses
- Westerly dipping strata inclined between 5^0 and 10^0

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