

Mud volcanoes and the origin of certain chaotic deposits in Sabah, East Malaysia

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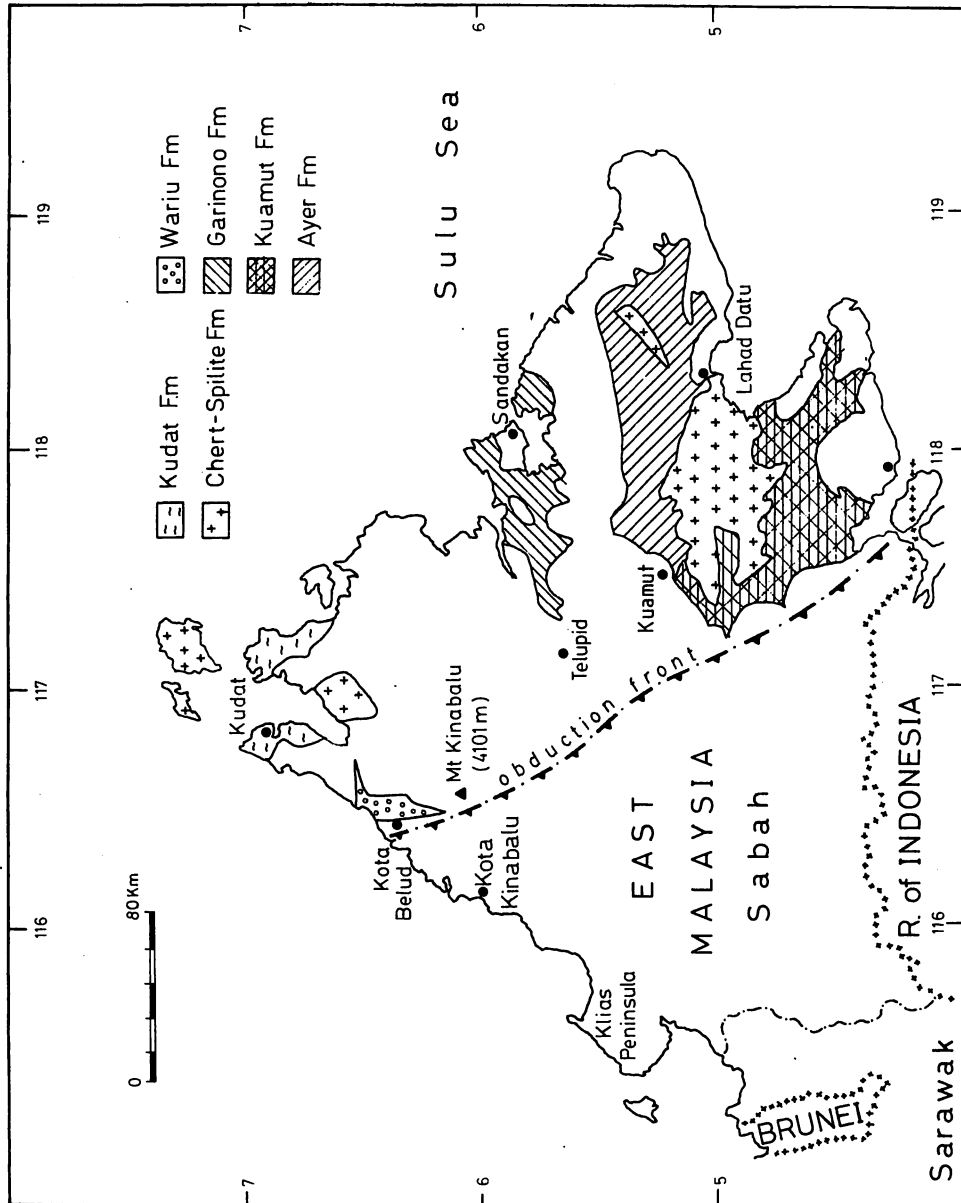
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Abstract: Chaotic and disturbed deposits occur widely in post-Tertiary sedimentary sequences in Sabah and have been mapped as slump breccias in the Garinono, Wariu, Kuamut and Ayer Formations. Some of the breccias are typified by case-hardened, baked arenaceous blocks distributed randomly in scaly clays. Phreatic deposition of silica, gypsum, zeolites and iron sulphides occurs in voids and along joints and shrinkage cracks. The origin of these enigmatic sediments is concerned with the seemingly anomalous depositional conditions in which high energies are required to move large clasts but low energies are indicated by the predominantly clayey matrix, and the presence of low temperature hydrothermal activity. The authors suggest there is a genetic link between mud volcanism and many of the chaotic deposits in Sabah, especially the Garinono Formation. Modern mud volcanoes are distributed across northern Borneo and are composed of lithologies comparable to those in the disturbed rocks. The early development of mud volcanoes is linked to a mid-Miocene collisional event during which obduction of shallow and deep water sediments were thrust from the Sulu Sea onto what is now NE Sabah. Connate water flashing into superheated steam provides the driving force for violent upward movement of hot mud, transporting with it clasts of most rock types including oceanic crust and possibly asthenosphere as well as providing the phreatic activity evident in many localities. Migration of mud volcanic centres which change position regularly could produce, in a 5–6 million year span, a widespread deposit similar to the Garinono Formation. Periods of inactivity would result in the intercalation of chaotic deposits within normal bedded sequences.

INTRODUCTION

Chaotic sediments in which large blocks are embedded in a clayey matrix occur widely in north and east Sabah and have been interpreted as slump breccias. They are reported from the Garinono, Kuamut, Wariu, Ayer and Chert-Spilite Formations (Geological Map of Sabah, 1967) and have been observed also by one of the authors (RBT) in the Kudat Formation (Map 1). They contain blocks of all ages from Tertiary as well as rocks from older Formations including spilite, chert, amphibolite, serpentinite, eclogite and rare glaucophane schist. Some chaotic deposits are noticeably different from others and characterised by the presence of case-hardened, baked arenaceous blocks in scaly clays. Both blocks and clayey matrix show glossy surfaces which in the clays are in the form of discontinuous partings. Phreatic deposition of secondary minerals silica, calcite, gypsum, zeolites and iron sulphides occurs in voids, joint surfaces and cracks. These features have been observed by the authors in the Garinono, Kuamut, Wariu and Ayer Formations but not in the Kudat or Chert-Spilite Formations where a more conventional type of slump deposit is present.

The problematic nature of slump deposits in general rests in the apparent anomaly that transport of larger clasts requires a different energy level to that indicated by the fine-grained matrix. The obvious effects of hydrothermal activity in some of the Sabah examples also requires an explanation as these effects are unusual features not



Map 1. Distribution of chaotic rocks in Sabah.

normally encountered in chaotic rocks. Various possible modes of origin for slump deposits are reviewed briefly below with comments appropriate to the Sabah occurrences.

- a) weathering of ancient conglomerate: there is an absence of ghost stratigraphy in the Sabah examples
- b) talus: generally excessive mud in the Sabah deposits
- c) volcanic mudflows or lahars: this is a possible origin but the quantity of volcanic material in Sabah is much lower than that known from lahars elsewhere
- d) milling beneath thrust sheets: the total thickness of slump breccias in Sabah is greater than that found in cataclastic zones associated with major thrusts and clasts in the Sabah deposits are unshaped. There are also units of complete stratigraphy locally
- e) turbidity current deposit: absence of typical sedimentary structures, notably graded beds
- f) melange associated with subduction at a continental plate margin: this is a possible origin although there is no clear evidence for subduction onshore Sabah

With the exception of modes (e) and (f) above, deposits resulting from all these origins are either very restricted in thickness or lateral extent. Subduction melanges may be both thick and laterally extensive and contain mixtures of material from both volcanic and non-volcanic sources but they do not usually have fragments of oceanic crust. Furthermore, none of the above possibilities satisfactorily explains the low temperature hydrothermal activity in deposits which are largely sedimentary in origin.

To this list origins can be added a phenomenon known to be operating now and in the recent past and encountered at a number of localities in northern Borneo, namely *mud volcanism*. This paper aims to show a connection between the relatively restricted deposits of modern mud volcanoes and the widespread occurrence of the phreatic type of chaotic slump breccia which is found in eastern Sabah.

SEDIMENTOLOGY OF MUD VOLCANIC DEPOSITS

Mud volcanics were first recorded in Sabah in the 1920's and described formally by Reinhard and Wenk (1951) but little detailed research has been conducted on the sedimentology of their products. The clearest descriptions are published by Reinhard and Wenk (*op. cit.*) and no recent data are available except minor observations and analyses added to a repetition of earlier descriptions. (See regional memoirs by Fitch, 1955, 1959; Kirk, 1962, Haile and Wong, 1965, and Wilson, 1964.) The following brief account abstracted from published sources summarises the main features of mud volcanoes and their deposits. The term mud volcano is defined as an outpouring of mud from a vent in a similar way to a normal volcano and although some dictionary definitions imply association with a volcanic environment, the term occurs in the literature more frequently in association with shale diapirs, clastic dykes, mud lumps and mud flows (Braunstein, and O'Brien, 1968). Wilford (1967) comments that most mud volcanoes in Sabah are found in regions where the underlying rocks comprise a large proportion of clay, shale or mudstone. Thus, groundwater when it reaches the surface is heavily charged with mud.

Mud volcanoes occur as roughly circular, shallow cones generally about 180 m to 250 m across and in the humid tropics, are usually heavily forested except where recent activity has deposited new mud. The cones are eroded by small streams and the surface is covered with loose blocks of material left behind after the surrounding clay matrix is removed. The composition of the blocks reflects the nature of the underlying strata through which the mud has erupted and may comprise sedimentary, igneous and metamorphic rocks. There may be several vents near the top of the cone and the mud-charged water is usually saline and accompanied by gas. The surface of the dried mud is encrusted with salts so that new eruptions appear as white patches on aerial photographs. Intermittent explosions sometimes accompanied by local earthquakes provide more spectacular events when large quantities of liquid mud and boulders are hurled into the air. The temperature of the mud may be up to 50°C and clear water hot springs sometimes occur in the same area.

The surfaces of blocks are frequently cracked or burst like volcanic bombs and have a baked appearance; Wilford (1967) attributes the cracking to the effects of heat from burning gas although mud volcanoes in eastern Sabah rarely contain inflammable gas but nevertheless eject boulders with similar cracked surfaces. The mud is usually blue-grey but purplish-red and greyish green clays also occur and it is not clear whether the colour variation is due to primary sediment colour or subsequent alteration. Crystalline deposits of calcite, gypsum, pyrite and marcasite occur in voids or within the body of the clay and many clays have a scaly appearance.

The erupted gas is composed mostly of nitrogen and oxygen with minor carbon dioxide and rarely, hydrogen sulphide; inflammable gas is generally methane and accompanied, in western Sabah, by oil smell and occasionally traces of oil. A waxy material similar to ozokerite is found in some deposits in the Klias peninsula.

Ejected blocks varying from cm- to dm- scale, consist mostly of sedimentary rocks claystone, marl, sandstone and sandy limestone or purer fossiliferous limestone, all derived from Tertiary formations ranging mainly from Tab to Tef. Pre-Tertiary rocks occur principally in eastern Sabah and include chert, spilitic basalt, serpentinite and gabbro from the Chert-Spilite Formation as well as clasts of crystalline schist, volcanics, eclogite and rare glaucophane schist from the Basement. The volcanics are thought by Reinhard and Wenk (*op. cit.*) to be older than the extensive Tertiary to Quaternary volcanism associated with the Sulu volcanic arc.

There are no figures published or estimates given for total thicknesses of modern mud volcanic deposits probably due to poor exposure, inaccessibility and lack of deep erosion. Little is known of their distribution in the stratigraphic column and whereas Recent and modern mud volcanoes are reported from many areas of the world (Freeman, 1968) none has been recognised as such in older rocks. Mud volcanoes tend to be short-lived features active for a few years and subsequently dormant. Haile and Wong (1965) remark that those in the Segama area are said to disappear after a few years of activity to be superseded by new centres erupting in neighbouring areas.

Mud volcanoes in eastern Sabah are underlain principally by chaotic deposits within the Garinono, Kuamut and Ayer Formations but those in the Klias peninsula

are underlain by normally bedded, Tertiary to Recent sedimentary rocks. No mud volcanoes are recorded in areas underlain by the Wariu Formation. Those in eastern Sabah tend to be distributed randomly whereas the Klias occurrences show definite alignment on a NE-trending structural weakness parallel to the Mulu shear zone (McManus and Tate, 1976). It is reported that new islands formed at Pulau Tiga immediately north of Klias following an earthquake centred in Mandanau, Philippines on 21 September 1897 and felt across western Sabah (Wilson, 1964) but curiously not felt in the immediate vicinity of the islands. Violent eruption of mud and strong smelling gas accompanied the creation of a mud cone 20 m in diameter and the gas burned for several weeks. Two years later, the island was 20 m high and 240 m across and was composed of loose accumulations of Tertiary sedimentary rocks. Eventually, three cones were formed to give three islands called, in Malay, Pulau Tiga.

To summarise, modern mud volcanoes in Sabah are ephemeral structures containing in their deposits a wide variety of rock types with ages of sediments ranging from Tab as well as crystalline sialic and oceanic crustal rocks. Many clasts show cracked and polished surfaces and there is deposition from phreatic minerals. Warm, often saline water and mud is accompanied by inert and sometimes inflammable gas which can erupt quietly or with explosive force.

Certain differences enable the Sabah examples to be subdivided into two types. Those in eastern Sabah show mainly random distribution, contain blocks of sialic crust, have moderate to intense secondary mineralisation and are underlain by chaotic rocks. Those in western Sabah are structurally aligned on NE-trending lineaments, are composed mostly of Tertiary sedimentary rocks, have oil smell or oil derivatives associated with inflammable gas and are underlain by Tertiary to Recent bedded sedimentary rocks. Both types show evidence of case-hardening and cracking of blocks but mineralisation in western Sabah is much less intense.

The features shown by modern mud volcanic deposits are almost identical to those seen by the authors in so-called slump breccias described previously from the Garinono, Kuamut, Wariu, and Ayer Formations in north and east Sabah and it is suggested that most if not all slump breccias reported from those Formations are the products of mud volcanism.

ANCIENT MUD VOLCANIC DEPOSITS

Chaotic deposits in Sabah have been interpreted previously as cataclasites or tilloids (Jacobson, 1970), or slump breccias formed by gravity sliding (Collenette, 1965a) similar to *argile scaglioso* of the Appennines, Italy, or to *wildflysch* (Liechti *et al.*, 1960). Attention is now focussed on four Formations in which chaotic rocks are known to occur as they contain features attributable to mud volcanism.

The Garinono Formation was introduced by Collenette (1964, 1965a) to describe a tilloid deposit on the Sandakan–Telupid highway and the type area was designated as the Lokan Plains. Descriptions of the Formation include a list of all rock types found as exotic blocks and Haile (in: Collenette, 1965a) remarks on the presence of curved shear planes with a shiny surface and greasy feel in the argillaceous matrix. The

structure and thickness are unknown although it was thought unlikely that the thickness was less than several thousand feet. The Formation was correlated initially with the Lower- to Middle-Miocene Segama Group but subsequently the relationship was uncertain and on the Geological Map of Sabah, 1967, it is unreferrred and of questionable age (?Tf). The origin of the Formation is ascribed to gravity sliding of material into structural depressions formed during a post- Miocene orogeny.

The Ayer Formation was introduced but not formally defined by Clement and Bisig (Sabah Shell Petroleum Company unpublished report, 1959) to describe sedimentary sequences interbedded with tuffs in the Segama area in eastern Sabah. A more detailed, formal description appears in Haile and Wong (1965) in which highly disturbed tuffs, slump breccias, boulder beds, cherts and pebbly mudstones are reported outcropping mainly south of the Segama river. The best exposures are reported in the Sungei Ayer which serves as the type locality. Identification of the various components of the polymict boulder beds are listed as well as descriptions of slump breccias containing tuff and chert clasts, some of which show polished surfaces ascribed to shearing. Clasts of eclogite are recorded from the Pungulupi valley. An interesting reference is made to Recent mud flows or mud volcano deposits which are interpreted as secondary, almost superficial local features derived from nearby slump breccias. Information concerning the upper and lower boundaries of the Formation is lacking and the thickness is given speculatively as 2,500 m. A Tf age is indicated by foraminiferal determinations and the depositional environment described as neritic or bathyal, accompanied by volcanic activity. The slump breccias are thought to be the product of gravity sliding down a steeply inclined submarine slope.

The Kuamut Formation was introduced by Collenette (1963, 1965b) to describe slump or scree deposits covering a relatively small area around Kuamut in central Sabah. A wide range of exotic rock types occurring as blocks is reported, some are so large that it is difficult to decide whether they are loose boulders or *in situ* exposures. The structure of the Formation is indeterminate although on a regional scale the general strike is roughly perpendicular to that in the Chert-Spilite Formation. A total thickness of 2,500 m is estimated and the deposits are underlain unconformably by Chert-Spilite Formation and overlain conformably by Tanjong Formation, implying a general Miocene age. Incompatible microfaunas and randomly occurring ophiolite masses suggest the deposit is a slump breccia or submarine scree. No details of the matrix are given and in an early reference (Collenette, 1963) similarities with the Wariu Formations are suggested but no specific characteristics are mentioned. It is unfortunate that the type locality chosen for the Kuamut Formation in the Kuamut valley is in an area where major faulting and deformation have caused severe disruption of the deposits. Re-mapping of the Upper Segama and Darvel Bay areas by Leong (1974) has shown the Kuamut Formation to be much more extensive than Collenette (1965b) has indicated and much of the area mapped as Labang Formation (Geological Map of Sabah, 1967) is probably Kuamut or Ayer Formation.

The Wariu Formation was introduced by Bowen and Wright (Sabah Shell Petroleum Company unpublished report, 1957) to accommodate rocks of Miocene age found in the Kota Belud and Kudat Peninsula areas which were similar to the Chert-Spilite Formation described by Fitch (1955) from eastern Sabah and dated as

Upper Cretaceous–Lower Eocene. A concise review of the stratigraphic arguments surrounding earlier classifications of the Chert–Spilite and kindred Formations by Molengraff (1902), Reinhard and Wenk (1951) and Fitch (1955) is given in Leong (1974, pp 104–5). Liechti *et al.*, (1960) in redefining the Wariu Formation describe it as containing slump breccias in part and postulate their formulation by collapse on a hinge zone separating shelf and geosynclinal areas. Unfortunately, rocks with Chert–Spilite affiliations are still included in Liechti and co-workers' view of the Wariu, causing more confusion. In a later synopsis, Wilson (1963) mentions the Wariu contains cataclastic and eugeosynclinal scree deposits. Subsequent assessment of the Kota Belud and Kudat areas resulted in further re-classification of the Wariu Formation by Wilford (1966), restricting the Formation only to slump breccia deposits in a fault-bounded trough N and E of Kota Belud. It is to the latter definition that the present authors refer in this paper. The base of the Formation is nowhere exposed and the top boundary is erosional. The age is questionable.

Thus, the post-1960 interpretations generally regard the Wariu Formation as a slump deposit formed probably by gravity sliding down a submarine slope. Wilford (1966) comments that the Wariu is possibly contemporaneous with the Garinono, Ayer and Kuamut Formations and although palaeontological evidence is equivocal, all four formations may be related to a strong tectonic event in the Middle Miocene, as suggested also by Jacobson (1970) for the Wariu *sensu stricto*. Although Wilford's (1966) reassessment is clearer, more detailed formal definitions are required. However, in the most recent published account of the stratigraphy of Sabah (Geological Survey of Malaysia, 1980, p. 123) the Wariu Formation is not mentioned.

The authors have examined roadside exposures in all four formations and have recorded additional data which are now summarised. West of MP 19 on the Sandakan–Telupid highway, exposures in the Garinono Formation show a non-stratified, chaotic assemblage of angular blocks comprising calcified sandstone containing carbonised plant fragments, mudstone, chert and olivine gabbro. Some fragments of chert, gabbro and volcanic agglomerate are replaced by calcite. Blocks are often cracked and some have smooth, shiny surfaces. Voids and shrinkage cracks in apparently baked blocks are filled with phreatic secondary minerals chiefly calcite and silica with subordinate zeolites, gypsum and marcasite. The clayey matrix is compact, sticky blue-purple grey in colour with conspicuous shaly partings which are continuous, often curved and with a very high gloss. Some of the matrix is reddish purple or greenish in colour suggesting alteration of the original sediment colour but it is not tuffaceous. Agglomerates representing volcanic necks locally project through the chaotic deposits and are thought to be older than the surrounding Garinono which underlies most of the Lokan plains. Exposures further west along the highway contain blocks of immense size, some up to 30 m³, composed mostly of reddish arenaceous sediments belonging to the Kulapis Formation. The blocks are surrounded by grey-green, scaly clays probably belonging to the Garinono Formation. The Kulapis Formation is noticeably shattered in this locality and there are frequent alternations of Kulapis and Garinono sediments towards Telupid.

Exposures examined in the Ayer Formation around Lahad Datu comprise a mixed, non-stratified deposit of purple or grey shales containing angular clasts of de-

chertified radiolarian chert in which the original texture has been altered to a slightly coarser grained crystalline silica and calcite, irregular blocks of carbonate rock which is not a limestone but possibly an altered volcanic rock together with blocks of unaltered lava and mostly arenaceous sediments. The maximum size of the blocks is about 2 m. The purplish-grey clayey matrix has distinctive glossy partings. De-chertified chert is not restricted to the Ayer Formation and similar material is found in the Garinono Formation west of Sandakan. The scaly clays are strikingly similar to the Wariu Formation examined by one of the authors (RBT) north of Kota Belud where massive, greyish black clay and broken shale contains angular blocks of silicified, well-sorted sandstone, red shale and mudstone and occasional bottle-green volcanic rock. Most blocks are cracked and have polished surfaces and the argillaceous matrix has discontinuous glossy partings. The field relationships in this area indicate a thickness of tens of metres.

The features just described show a remarkable likeness to the descriptions of mud volcano deposits given in Reinhard and Wenk (1951) particularly the baked blocks, cracked and burst boulders, fritted clays with shiny partings and exotic content. Secondary deposition of minerals is recorded infrequently but nevertheless crystals of pyrite and calcite have been noted at some mud volcanoes in eastern Sabah. The authors contend that the chaotic deposits reported from the Garinono, Wariu, Kuamut and Ayer Formations which have been interpreted mostly as a slump breccias formed by gravity collapse are in fact the products of mud volcanism. This new interpretation is based upon the authors' field observations together with a critical assessment of published data on modern mud volcanoes. However, it is emphasized that only the chaotic parts of the four formations are derived from mud volcanism, the remaining sections within the formations being normal stratified sedimentary and volcanic sequences. For example, descriptions of the Kuamut Formation (Leong, 1974) indicate clearly that slump breccias form only part of the stratigraphic sequence which also includes bedded clastic sediments and *in situ* limestones.

ORIGIN OF MUD VOLCANOES

A volcanic origin was assumed by Reinhard (1924) but this interpretation was later discarded by Reinhard and Wenk (1951) in the absence of widespread evidence of solfataric and other volcanic manifestations. Mud volcanism could not be explained by Tertiary tectonics and a deep-seated origin was required although no details of how the mechanism operated were given. The mud volcanic structures in Segama were attributed by Fitch (1955) to the last vestiges of Quaternary volcanism and although Haile and Wong (1965) give additional descriptions of field occurrences, no firm conclusions on origin are given.

Sedimentary volcanism with examples from other parts of Asia and North America is discussed in detail by Freeman (1968) who also gives a resumé on possible origins including gas-driven migration along weakness planes. Metasomatism and diastrophism also are introduced but no universal mechanism fits all occurrences. More recent physical data obtained largely by the oil industry, indicates that a buildup of fluid pressure in shales either by generation of methane, overpressuring due to increase of pore pressure caused by compaction disequilibrium or undercompaction as

a result of inability to exude pore water is the principal cause of a phenomenon known as '*shale tectonics*' leading to the formation of shale diapirs, mud volcanoes and clastic dykes (Hedberg, 1974, Miffin, 1970).

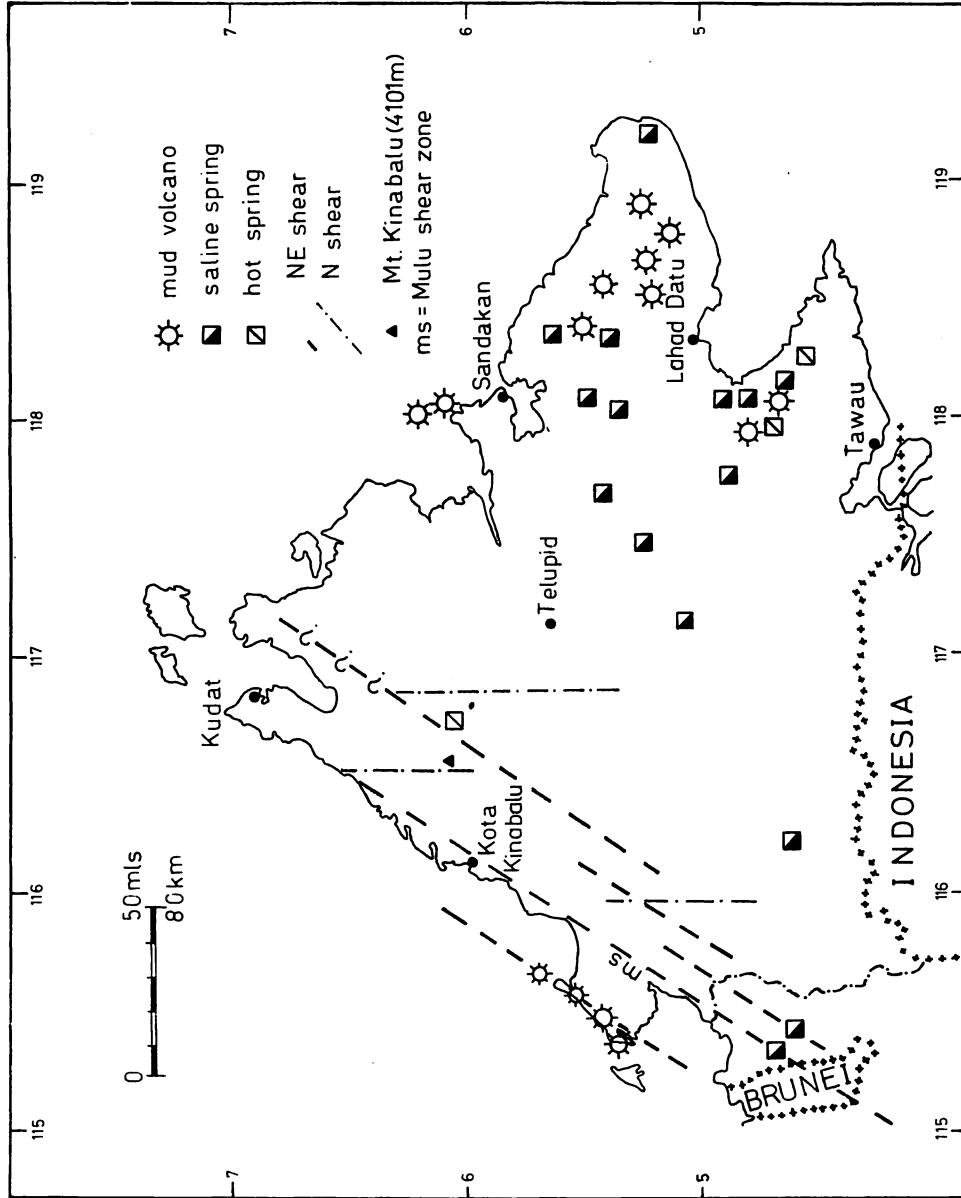
The fluid pressure hypothesis is acceptable as an origin for mud volcanoes on the Klias peninsula where they occur in Tertiary sequences typical of the NW Borneo hydrocarbon province and the presence of shale diapirs offshore is corroborative. However, the hypothesis cannot reconcile entirely the features shown by mud volcanoes in eastern Sabah, particularly phreatic activity. Nor indeed does the fluid pressure hypothesis explain similar features found in chaotic deposits in that part of the country. Clearly a different mechanism is required and the authors believe it is related to a major tectonic event affecting eastern Sabah during the Middle Miocene.

MECHANISM FOR THE FORMATION OF MUD VOLCANO AND PHREATIC CHAOTIC DEPOSITS IN SABAH

The sedimentological descriptions detailed already imply that a de-watering phenomenon is involved in the formation of mud volcanoes and their deposits. Connate water, much of it occurring as interparticular in muds and interstitial in coarser clastics, is released at rates controlled largely by the permeability and heterogeneity of strata. Mud has a very low permeability so the presence of structural and textural weaknesses is an important factor in water release. The alignment of mud volcanoes in western Sabah suggests that structural control is a major influence in their distribution along the Klias peninsula which is itself a structurally controlled block aligned parallel to a major shear zone trending NE. Further south in Brunei, mud volcanoes are associated with mud and shale diapirs developed along N and NE trending weaknesses (Wilford, 1961). In eastern Sabah, most mud volcanoes show random distribution except perhaps a small cluster in the lower Segama valley where they appear to be related to NE—trending faults; the remainder are unrelated to structural alignment or mud diapirism and are controlled probably by textural inconsistencies in the underlying rocks (Map 2).

If it is accepted that most slump breccias in eastern Sabah are due to mud volcanism, the total area of disruption is therefore very large, at least 10 000 km². The quantity of water expelled in the creation of a huge volume of mud volcanic deposits is correspondingly large and far greater than that which would be expelled normally by mud compaction during de-watering of most common sediments. There is therefore a need to explain how this superfluous quantity of water can accumulate and also a need to explain the conditions in which a relatively low but continuous supply of heat is maintained enabling phreatic activity to continue for several million years.

In an earlier publication (McManus and Tate, 1983) the authors suggested that an obducted mass of sediment including ocean floor material has been thrust southwest across eastern Sabah onto *in situ* early Tertiary sediments and older rocks. It is envisaged that the obduction event would create conditions in which large quantities of water are entrapped within an abnormally thick pile of partially consolidated sediment. In this event, higher pressures caused by increased thicknesses, depression of the pile due to loading or a combination of those conditions coupled with higher



Map 2. Distribution of mud volcanoes, saline and hot springs and shear zones, Sabah.

thermal gradients in hot obducted material or heat generated by thrusting could produce a continuous supply of superheated steam. The advent of a steam-pressured phase permeating a dominantly argillaceous mass could become a powerful subterranean force which would give the immense energy needed to disrupt overlying bedded sequences into blocks of almost any size (q.v. the shattered Kulapis Formation). Superheated steam also would provide a penetrative phreatomagmatic agent capable of mobilisation and deposition of epigenetic minerals. Water condensed from steam would mix easily with the clayey sediments and upward migration of mud-laden liquid would erode and transport material from all stratigraphic layers through which it passed. Mud, saline water, exotic blocks and gasses would be erupted quietly or explosively through vents at the surface. The overall effect across a wide area is analogous to a bubbling cauldron where points of effusion are distributed randomly across the surface. Extrapolated in time, the eruption of mud volcanoes in a sporadic and random manner would produce a widespread deposit of substantial thickness similar to the Garinono Formation. It is suggested that the accumulation of extensive mud volcanic deposits has occurred throughout much of the area occupied by the obducted mass and it is perhaps significant that the southwest limit of the slump breccias coincides with the postulated position of the obduction front (Map 1).

The authors suggest that the obduction hypothesis provides a suitable mechanism to explain the phreatic mud volcanism in eastern Sabah and the presence of exotic fragments of ocean floor spilite, chert and serpentinite in the Garinono, Ayer and parts of the Kuamut Formations is undisputed supporting evidence. Moreover, the presence of high pressure/low temperature rocks, eclogite and glaucophane schist, in the chaotic sequences indicates a profound tectonic event which involved partly the asthenosphere and possibly also indicates the intensity with which collision and obduction took place.

Other features explained satisfactorily by the hypothesis are mineralisation, exotic content of clasts, disparity in particle size between clasts and matrix, case-hardening, baking, explosion patterns in some clasts, shrinkage cracks and glossy surfaces on both clasts and partings in the clay matrix. The unusual shattering of strata in the Kulapis sediments is the result of particularly violent explosive volcanicity. Some phreatic mineralisation is related to the chemical nature of entrapped water and its composition is probably closely allied to that of water presently issuing from modern mud volcanoes and saline springs. The few analyses published indicate a close relationship between entrapped water and modern seawater and most of the phreatic minerals identified in slump deposits also occur in soluble form in seawater with the possible exception of iron sulphides which could have been mobilised from iron-rich organic mud or shales in older rocks.

A more extreme example of phreatic mineralisation occurs close to Mamut copper mine east of Mount Kinabalu where local zones of intense metallic sulphide enrichment are present in porous sediments. The rocks contain substantial amounts of pyrite and chalcopyrite covering joint and bedding surfaces as well as disseminated throughout the rock and other sedimentary rocks nearby show dark, mud-infilled fractures. It is interesting to speculate on the origin of the Mamut deposit in the context of phreatic mud volcanism. Chemical analyses given by Jacobson (1970) suggest that copper and zinc occur in roughly equal proportions of 270 and 220 parts per million

respectively and lead is subordinate in quantity, only 13 ppm. These are approximately the same proportions as those which occur in seawater, namely copper 5 ppm, zinc 5 ppm and lead 0.03 ppm.

Kosaka and Wakita (1978) in their description of the detailed geology of the Mamut deposit show that mineralisation is associated clearly with an adamellite stock suggesting an igneous origin in a continental setting. Other evidence is conflicting, island arc and collision-related environments are also discussed but no firm conclusions on origin are given. The present authors suggest that mineralisation may be related to hydrothermal activity involving sea water and the geochemical and fluid inclusion evidence seems to be corroborative (Jacobson, *op. cit.*, Nagamo *et al.* 1977). The role of convective circulation of connate or marine waters in mineral deposition has been described by both Fyfe (1984) and Hutchinson (1984) (Keynote papers, this conference) and by earlier workers, notably Sillitoe (1972). Convective circulation is often related to thermal gradients generated at subduction or spreading centres but at Mamut, thermal gradients could have been provided by obduction.

A search for economic mineralisation within the phreatic chaotic deposits may be justified particularly in the light of more recent theories concerning the movement through rocks of large quantities of water (W.S. Fyfe, 1984; keynote address, this Conference). In the various scenarios described by Professor Fyfe, it seems that whenever large fluid volumes are pumped through rocks there is a potential for local mineral enrichment. The authors suggest further that if unconsolidated sediments are involved in a process which comprises high volume aqueous flow driven by thermal energy, they may also undergo mud volcanism.

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