The Ayer Chawan Facies, Jurong Formation, Singapore: Age and observation of syndepositional pyroclastic sedimentation process with possible peperite formation

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Abstract: The Ayer Chawan Facies is one of the volcano-sedimentological facies belonging to the Jurong Formation in Singapore. The geology of the south-western Jurong Island had never been documented before the island was reclaimed in 1998. The present geological, sedimentological and geochronological study of the Ayer Chawan Facies was undertaken as part of an underground rock caverns storage project which was carried out from 2009 to 2014. The Ayer Chawan Facies is composed mainly of grey to black mudstone interbedded with grey siltstone/sandstone. In addition, the pyroclastic rocks of varying thickness are also intercalated with the sedimentary rocks. The pyroclastic rocks yielded an U-Pb zircon age of 240.6 ± 1.2 Ma (Middle Triassic) as determined by Laser Ablation Inductively Couple Plasma Mass Spectrometer (LA ICP-MS). Based on the stratigraphic and sedimentological evidence of the presence of peperitic textures/structures, it is interpreted that the pyroclastic rocks were emplaced into the sediments during deposition which was still in a wet and unconsolidated condition.

Keywords: Ayer Chawan Facies, pyroclastic (lithic tuff) rocks, Peperite, magma-sediment density contrasts, sediment fluidization

INTRODUCTION

Jurong Formation is the second most widely distributed rock formation in Singapore which covers about a quarter of the surface area of the city state. It is well exposed in the western and south-western parts of the island (Figure 1). It is composed of different varieties of sedimentary to meta-sedimentary rocks with minor amount of intermediate to mafic lava and volcanic ash. They were deposited during the Late Triassic to Early Jurassic (PWD, 1976; DSTA, 2009). Although Jurong Formation covers about a quarter areas of the country, almost all surface rock outcrops had been covered by residential and industrial development projects established in the last few decades. The current geological and sedimentological study was made during the construction of the first commercial underground rock caverns for hydrocarbon storage project in South East Asia, namely Jurong Rock Cavern Project (JRC Project) from 2009 to 2014 after the area was reclaimed in 1998. The aims of the present study are to undertake age relationships, geological and stratigraphic mapping of the Jurong Formation focusing on the Ayer Chawan Facies, to document detailed sedimentological and petrological features



Figure 1: Geological map of Singapore (PWD, 1976).

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of the different lithologic units and to determine the nature, setting and origin of the syndepositional pyroclastic rocks and their sedimentation process.

PREVIOUS STUDY

In 1976, the Public Works Department (PWD) of Singapore divided the Jurong Formation into six Facies, namely Queenstown, Jong, Ayer Chawan, Rimau, St John and Tengah. The Ayer Chawan Facies is mainly composed of dark grey mudstones. The type section was defined at the west coast of Pulau Sakra in the south-western group of islands in Singapore (PWD, 1976). The rocks of Jurong Formation were emplaced during the Late Triassic to Early Jurassic in a basin which was formed by uplift of the Bukit Timah Granite to the northeast and the Malayan Main Range Granite to the southwest.

Lim (1974) produced five detailed sections of sedimentary rocks and discussed the stratigraphy and petrology of these units exposed in the south-western part of the Jurong Island. Those sections belonged to the Ayer Chawan Facies with interbeds of the Tengah Facies. The sandstone usually comprises a fine to medium-grained sand made up of quartz with a significant amount of polycrystalline quartz grains, tuffaceous clasts, secondary chalcedony and chert. He described the presence of carbonaceous materials in mudstone. He noted boulders of spillite about 400 m north of Selat Pulau Damar. Earlier Chin (1965) recorded the presence of a volcanic breccia in the Pulau Samulun area and Alexander (1950) recorded lavas associated with chert in the Jurong area and Pulau Sakra. Those volcanic rocks are included in the Ayer Chawan Facies.

The two previous editions of "Geology of Singapore" (PWD, 1976; DSTA, 2009) focused on the main Singapore Island, while the present study focuses in the area of rock caverns storage project that is located offshore. The geological and sedimentological aspects there have never been described and discussed in the literature.

Later, the reclamation project began in 1993 to merge seven southwestern islands - Pulau Merlimau, Pulau Ayer Chawan, Pulau Ayer Merbau, Pulau Seraya, Pulau Sakra, Pulau Pesek and Pulau Pesek Kecil - into one that came to be called Jurong Island.

Between 2001 and 2007, three phases of extensive site investigation works were carried out at Selat Banyan basin by JTC Corporation as the developer for storage rock caverns. They comprised vertical and sub-horizontal borehole drilling, in situ tests inside the boreholes and geophysical surveys. The findings revealed that the sediments are mainly of detrital origin. The accumulation of thick mudstone layers which consist of mud as cementing materials strongly indicated that the Ayer Chawan Facies was formed as mudflows, also called turbid flows. The existence of volcanic minerals (quartz, feldspar), as well as fragments of volcanic rocks in the constitution of the mud, provides a plausible origin of those mudflows as lahars, i.e., volcanic mudflows or debris flows (Geostock, 2007).

PRESENT STUDY AND METHODS

This study was conducted in recently completed underground rock caverns storage project (JRC Project) which was excavated in rock mass of Ayer Chawan Facies. Drill-and-blast rock excavation was carried out at about 100 to 135 m depth below the existing ground surface. The total linear length of excavation was about 18 kilometers with about 3.5 million cubic meters of rock volume. Geology mapping was carried out at the exposed rock face after each round of excavation.

The Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA ICP-MS) U-Pb zircon age dating method was used to determine the age of the pyroclastic unit at CODES, University of Tasmania, Hobart, Tasmania. The LA-ICPMS method is now widely used for measuring U, Th and Pb isotopic data (e.g. Harley & Kelly, 2007).

GEOLOGY OF AYER CHAWAN FACIES, JURONG FORMATION IN JRC PROJECT

Based on location, stratigraphic position and observation of lithology in the study area, the rocks belong to Ayer Chawan Facies. It is composed of well-bedded mudstone and muddy sandstone. A typical example of dark grey to black mudstone exposed on the excavated face in JRC Project, which is the primary rock type of Ayer Chawan Facies is presented in Figure 2 and sandstone interbedded with mudstone type. Limestones are encountered as pocket types at some locations.

OBSERVATION OF PYROCLASTIC (LITHIC TUFF) ROCKS AND ITS BOUNDARY RELATIONSHIP WITH MUDSTONE

The interbedded sequences of mudstone and pyroclastic rock layers were also encountered with the mudstone rock fragments inclusions in the pyroclastic bed. The irregular basal contact boundary between pyroclastic rocks and underlying mudstones was often observed. The flame-like structures were found at the boundary between two rock layers on some exposed faces (Figures 3 and 4). The individual bed thickness



Figure 2: Dark grey to black mudstone interbedded with a minor amount of black sandstone (Ayer Chawan Facies).



Figure 3: Morphology of base of pyroclastic (light) layer with mudstone (dark) showing-flame-like structure; mutual inclusion of both rocks; mudstone inside cracks at the bottom of the pyroclastic rock. (The formation of fluidal peperite is by quenching and magmasediment density contrast.)



Figure 4: Flame-like structure; quench margin of pyroclastic rocks in contact with mudstone and the mutual inclusion of both rocks at the base. (The formation of fluidal peperite is by quenching and magma-sediment density contrasts.)

of both rocks varied widely from a few centimeters to over 2 meters. Mutual inclusions of one type of rock fragments in the other rock type were commonly observed in this area.

Petrography and texture

According to the I.U.G.S classification, the volcanic rocks consisting of ash and lapilli (fragments size from 2 mm to 64 mm in diameter) are called tuff. Lithic tuff refers to one in which rock fragments predominate.

The lithic tuffs are white to light grey with varying thickness from about 10 cm to over 1.5 m interbedded with dark grey mudstone. The thin section analysis reveals that the rock is composed of various kinds of rock fragments (grain size 1 mm to 4 mm) and a minor amount of opaque iron ore minerals (pyrites). Almost all rock fragments are of volcanic origin as evident by their composition and textures (Figures 5a and b). Since volcanic rock fragments predominate, strictly speaking, the rock has to be named lithic tuff or tuffites. Although the occurrence of lithic tuff (pyroclastic rock) was documented in two issues of Singapore Geology, the



Figure 5: Photomicrograph of lithic tuff showing volcanic rock (rhyolite, andesite) fragments embedded in fine-grained groundmass (a) PPL – (b) XPL.

depositional relationship between lithic tuff and sedimentary mudstone was not recorded and remained unclear.

OBSERVATION OF PEPERITES IN THE PROJECT AREA

The definition of "Peperite"

The term 'peperino' was defined by Scrope (1827) to term the clastic rocks from the Limagne d'Au-vergne region of central France that includes mixtures of lacustrine limestone with basalt which look like ground pepper. This area is now placed as the type locality for 'peperite.' Scrope (1858) interpreted the rocks as having originated by a "violent and intimate union of volcanic fragmentary matter with limestone while yet in a soft state," whereas Michel-Levy (1890) particularly interpreted them as having produced by the intrusion of magma into the wet lime mud. The term 'peperite' is now most commonly used to refer to clastic rocks including both igneous and sedimentary components, which were produced by intrusive processes, or along the contacts of lava flows or hot volcaniclastic deposits with unconsolidated, typically wet, sediments.

White et al. (2000) defined as below;

Peperite (n): a genetic term employed to a rock formed essentially in situ by the disintegration of magma

intruding and intermingling with unconsolidated or poorly consolidated, characteristically wet sediments. The term also refers to similar mixtures originated by the same processes activating at the contacts of lavas and hot pyroclastic flow deposits with such sediments.

Peperites are commonly associated with intrusions in submarine sedimentary sequences (Goto & McPhie, 1996), lacustrine successions associated with lavas (Khalaf *et al.*, 2015; Martin & Nemeth, 2007), at the base of pyroclastic flow deposits in subaerial successions (Leat, 1985) and at the base of lava flow in arid setting (Karla *et al.*, 2007). The magma involved in the formation of peperites can have a broad chemical variation, from basaltic to rhyolitic compositions (Skilling *et al.*, 2002) and sediments can vary from fine to coarse-grained (Busby-Spera & White, 1987; Squire & McPhie, 2002).

Gross characteristics of peperites

The volume of peperite body ranges from less than one cubic meter along contacts between sediments and intrusions, lavas and hot volcaniclastic deposits, to several km³ (Snyder & Fraser, 1963; Hanson & Wilson, 1993, Khalaf *et al.*, 2015).

Characteristics of juvenile clasts

Busby-Spera & White (1987) recognized two types of peperite, which were called blocky and fluidal, with reference to the dominant shape of the juvenile clasts.

- Blocky shaped peperites are formed in coarse-grained sediments host
- Fluidal shaped peperites are formed in fine-grained sediments host

In this area, fluidal peperites in elongated globular shape (Figures 6, 7 and 8), tendril and irregular shapes are common since the host sediments are fine-grained mud.

Characteristics of the sediments of Ayer Chawan Facies

In this study area, fine-grained mud and clay with low porosity and permeability are the dominant types of host sediments (Figure 2).

Evidences showing that the host sediments were unconsolidated or poorly consolidated and most likely wet, at the time of interaction with the magma or lava are as follows:

- Mutual inclusions of mudstone and pyroclastic rock fragments in alternate layers at the contact boundaries (Figure 4).
- The scarcity of pyroclastic and mudstone aggregates at the boundary (Figure 6) and the presence of sediment (mudstone) in fractures of the pyroclastic beds (Figure 7).

PEPERITE-FORMING PROCESSES

Peperite formation consists of fragmentation or breakdown of magma/lava to appear juvenile clasts and intermingling of these clasts with a sediment host. Fragmentation and intermingling are probably often synchronized, but some juvenile clasts, particularly those formed by processes such as quenching and auto-brecciation during the intrusion, may intermingle with the adjacent



Figure 7: Wavy boundary contact, mutual inclusions. (The formation of fluidal peperite is by magma sediment density contrast.)



Figure 6: Elongated globule of fluidal clasts at base; mudstone inside cracks at the bottom of the pyroclastic rock. (The formation of fluidal peperite is by quenching and magma-sediment density contrast.)

Figure 8: Wavy boundary contact, mutual inclusions . (The formation of fluidal peperite is by magma sediment density contrast.)

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sediment after initial disruption (Skilling *et al.*, 2002). Thus the mechanisms for fragmentation and intermingling are inter-related and occurred instantaneously.

Fragmentation or breakdown of magma/lava in Ayer Chawan Facies

The main mechanisms for generation of pyroclastic fragments at the contacts after magma/lava intruding wet sediment in the study area are magma-sediment density contrasts (Figures 3, 4 and 6) and quenching (Figures 7 and 8)

Mingling of juvenile clasts and host sediment

The mingling of juvenile clasts and host sediment is promoted by fluidization of sediment, the forceful intrusion of magma, hydromagmatic explosions, magma-sediment density contrasts and sediment liquefaction and liquification (Skilling *et al.*, 2002). The following two mechanisms are the main sources for the mingling of juvenile pyroclastic clasts and host sediments in the study area.

Sediment fluidization process of Ayer Chawan Facies

Fluidization of host sediment, in this sense, is probably an important process accompanying intrusion of magma into wet sediment, and probably gives rise to the mingling of sediment and juvenile components (Skilling *et al.*, 2002). The main evidence of sediment fluidization during peperite formation of the Ayer Chawan Facies observed in the study area is the presence of flame like structures at the base of pyroclastic layers (Figures 3 and 4). The flame-like structure was formed by the upward movement of fluidized wet mud sediments into the hot pyroclastic layer. The flame structure at the contact also developed due to the density contrast between the two layers.

Magma-sediment density contrasts

Mingling may also be motivated by magma-sediment density contrasts at the lower boundary of pyroclastic layers (Figures 3, 4 and 6). The observation that peperite is better developed or restricted to basal contacts was reported by Brooks *et al.* (1982); White & Busby-Spera (1987) respectively. The occurrences show that magma-sediment density contrasts are an essential control on mingling, at least in these contact areas.

Thermal and mechanical effects on host sediment

Hot pyroclastic lava flows with peperite generation resulted in contact metamorphism, local dewatering, cementation and compaction on host sediments which gave rise to the formation of higher strength mudstone (Unconfined Compressive Strength, MPa = 140 MPa) in JRC project than the similar type of typical sedimentary rocks elsewhere on the world (40 MPa; Waltham, 1994). Due to such high strength, the excavation of wide span (20 m width) storage caverns became feasible in the Ayer Chawan facies in the JRC Project.

AGE OF AYER CHAWAN FACIES, JURONG FORMATION IN JRC PROJECT

The LA ICP-MS U-Pb zircon age of the pyroclastic rock, determined at CODES ARC Centre of Excellence in Ore Deposits University of Tasmania Hobart Tasmania, is 240.6 ± 1.2 Ma (Middle Triassic). The results are plotted on Tera Wasserburg concordia diagrams (Figure 9), and the data are given in Table 1.

Fossil was not found during the construction of storage caverns in the study area. However, six stratigraphic columns from Ayer Chawan Facies with collected fossils species recorded by Lim (1974) were reproduced in DSTA (2009). The age of this Facies was given as Late Triassic to Early Jurassic. Based on fine-grained sediments, black coloration and laminated bedding nature, Facies was likely to have deposited in anaerobic conditions with later phases of volcanic activity which were responsible for the elimination of the biota present.

DISCUSSION AND CONCLUSIONS

The geology of the present research area in Jurong Island was first comprehensively studied in 2004 under the feasibility assessment to excavate and construct underground storage rock caverns. Detailed geological mapping and studies were carried out at exposed rock sections after the drill-and-blast excavation during the course of construction works. The Ayer Chawan, belonging to the Jurong Formation, is the single rock facies encountered in the area. The facies consists dominantly of sandstone and mudstone, typically interbedded on a centimetre to meter sacle. The layers of mudstone are typically dark grey to black coloured and laminated. Those mudstone was originated by turbidity sediments at the deep marine environment. Based on field relationship and petrographic studies, it is very likely that the pyroclastic lava intruded into the muddy sediments (Ayer Chawan Facies) while they were deposited in a wet and unconsolidated condition. It gave rise to the formation of peperitic structures at the boundary between the two different rock types. Fluidal peperite having elongated globular, tendril

Figure 9: U-Pb Zircon age determination of the pyroclastic rock sample of the Ayer Chawan Facies, Jurong Formation in JRC Project.

Analysis No.	²⁰⁶ Pb/ ²³⁸ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁸ Pb/ ²³² Th		²⁰⁷ Pb/ ²⁰⁶ Pb	
	Age (Ma)							
	²⁰⁶ Pbcor	+/-1 std. error	Ratio	% rise	Ratio	% rise	Ratio	% rise
AP21C805	232	3.23	0.0370	1.4%	0.0115	3.0%	0.0594	2.7%
AP21C814	234	2.17	0.0371	0.9%	0.0115	1.5%	0.0558	1.6%
AP21C801	237	2.71	0.0377	1.1%	0.0144	2.9%	0.0579	2.7%
AP21C808	237	1.65	0.0374	0.7%	0.0119	1.3%	0.0511	1.2%
AP21C803	237	2.33	0.0377	1.0%	0.0132	1.9%	0.0560	2.2%
AP21C804	238	1.95	0.0377	0.8%	0.0120	1.5%	0.0526	1.6%
AP21C809	238	3.02	0.0381	1.3%	0.0135	2.1%	0.0607	2.5%
AP21C807	241	2.59	0.0381	1.1%	0.0123	2.6%	0.0507	2.4%
AP21C813	241	2.34	0.0382	1.0%	0.0124	2.1%	0.0510	1.9%
AP21C817	242	1.92	0.0382	0.8%	0.0119	1.6%	0.0517	1.4%
AP21C806	242	2.17	0.0383	0.9%	0.0122	2.1%	0.0508	1.9%
AP21C810	243	2.33	0.0385	1.0%	0.0125	2.6%	0.0523	2.3%
AP21C816	243	2.20	0.0386	0.9%	0.0125	1.8%	0.0534	1.9%
AP21C815	244	3.60	0.0394	1.5%	0.0153	3.0%	0.0690	3.1%
AP21C812	244	2.56	0.0397	1.0%	0.0153	1.9%	0.0729	1.9%
AP21C811	244	2.59	0.0387	1.1%	0.0124	3.0%	0.0522	2.7%
AP21C802	251	2.33	0.0398	0.9%	0.0128	2.2%	0.0535	1.9%
AP21C818	278	2.17	0.0441	0.8%	0.0138	1.8%	0.0513	1.4%

Table 1: Detrital zircon U-Pb ages for the pyroclastic rocks (lithic tuff) from JRC Project.

and irregular shaped juvenile clasts were observed. In this study area fluid instabilities within vapour films, magmasediment density contrasts and fluidization of host sediment mechanisms were likely the primary mechanisms to form the fluidal juvenile clasts and mingling with host sediments.

The LA ICP-MS U-Pb zircon age of pyroclastic rocks of the Ayer Chawan Facies is determined to be 240.6 ± 1.2 Ma (Middle Triassic) in this study. It is slightly older but close to the age range assigned after fossil species (Late Triassic to Early Jurassic) collected by Lim (1974).

The host sediments later experienced induration, contact metamorphism, local dewatering, cementation and compaction by simultaneous hot pyroclastic lava flows, leading to the formation of strong mudstone eventually. Due to the high strength (UCS = 140 MPa) attributed to the strength increase associated with the thermal effect on sedimentary rocks by lava emplacement, the safe excavation of 20 m wide span underground storage caverns in the Ayer Chawan Facies became feasible.

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