Batusatam physical and chemical properties review: A Billitonite tektite in Southeastern Belitung Island, Indonesia

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Abstract. Batusatam considers as Billitonite, a rare Australian strewnfield tektite. Regrettably, the scientific information of this object slightly, especially about the origin, the process of formation, and its uniqueness in the earth's geological history. This paper reviewed the physical and chemical properties of unearth Batusatam in Southeastern Belitung Island, Indonesia. Physical properties are examining based on object shape, surface texture pattern, dimensions, volume, mass, density, and hardness. We also analyzed major and minor elements using portable X-ray fluorescence (XRF) and compared them with another Australian tektite. Rod and tear-drop-shape, the unique shapes of Batusatam, were discovered. It had a higher Fe2O3, CaO, MnO proportion. Also, Sn (tin) is present significantly compared to other tektites. This significant uniqueness of Billitonite could clarify its origin, formation process, and role as a geoheritage.

1. Introduction
Batusatam is a rare stone that can only be found on Belitung Island. This object is black, glassy, and can be found with worm-like cavities patterns on its surface. Several researcher suggested Batusatam was Billitonite (Belitung tektite), a tektite group in Australian strewnfield [1–4]. Tektite is formed as molten debris (in meteorite impact) and scatter throughout from atmosphere then return to the earth surface in hypervelocity [5,6].

The origin and forming of a tektite can be traced based on its shape and chemical composition [3,7,8]. Macroscopically, tektite has various forms, i.e., dumb-bell-shaped, tear-drop-shaped, sphere-disk-shaped, rod-shaped, which had aerodynamical shape. This shape is caused by atmospheric aerodynamic abrasion of the remelting of (debris) glass while it ejected outside the terrestrial atmosphere, re-entry to the earth's surface, and solidified. Tektite chemical compounds could be tracers for revealing the origin, sources, and formation process [9].

This research focuses on examining and analyzing the physical and chemical properties of unearth Batusatam in Birah Village, Southeastern Belitung Island, Indonesia, see figure 1. This research should allow us to better comprehend the significant uniqueness of Batusatam as a rare Billitonite tektite. It would explain and clarify the origin and formation process for further comprehensive studies.

2. Materials and methods
The physical properties measured are dimension, volume, mass, density. Objects' dimensions are measured on the longest perpendicular axis (x, y, z) using calipers. The object's volume, mass, and density measurements were conduct by the non-destructive Archimedian principle method. It uses a graduated-measuring cylinder for volume measurements and a digital scale [10]. We also examined the object's hardness using hardness pens (in Mohs scale). The chemical properties had been analyzed by non-destructive analysis using calibrated Olympus 3 Portable X-ray fluorescence (XRF).
Figure 1. Map of Belitung Island and the location of Birah Village.

3. Results

Batusatam was found in the soil layers around the open-mine at Birah Village, Southeastern Belitung, Indonesia. For this study, we analyzed ten specimens of Batusatam, which had a dark-glassy surface, with irregular-random worm-like cavities pattern, and with unique variation shape. STM-01 is rod-shaped, STM-02 is tear-drop shaped. STM-03 to STM-06 are sub-spherical-disk-shape. STM-07 to STM-10 are spherical-disk-shape. The detail of the physical properties of Batusatam was described in table 1 and figure 2.

Table 1. Physical properties of Batusatam (this study).

| Batusatam Specimens | Dimension (cm) | Shape          | Vol (ml) | Mass (gr) | Density (gr/ml) | Hardness (Mohs) |
|---------------------|----------------|----------------|-----------|-----------|-----------------|-----------------|
| STM-01*             | 7.54 3.41 2.85 | rod-shaped     | 31        | 76        | 2.45            | 6.5             |
| STM-02              | 6.08 3.14 2.58 | tear-drop shaped| 34        | 82        | 2.41            | 7.0             |
| STM-03*             | 3.03 1.85 1.84 | sub-spherical disk | 11        | 29        | 2.64            | 6.5             |
| STM-04              | 3.26 2.65 2.49 | sub-spherical disk | 19        | 44        | 2.32            | 6.5             |
| STM-05              | 2.47 3.07 1.79 | sub-spherical disk | 12        | 28        | 2.33            | 6.5             |
| STM-06              | 3.27 2.64 0.73 | sub-spherical disk | 12        | 26        | 2.17            | 6.0             |
| STM-07*             | 2.85 2.64 1.57 | spherical-disk | 12        | 31        | 2.58            | 7.0             |
| STM-08              | 3.31 3.05 1.52 | spherical-disk | 21        | 46        | 2.19            | 6.0             |
| STM-09*             | 3.35 3.24 1.53 | spherical-disk | 14        | 34        | 2.43            | 6.0             |
| STM-10              | 3.38 3.28 1.83 | spherical-disk | 20        | 43        | 2.15            | 6.0             |

* The specimens that were analyzed for chemical properties.
Figure 2. Batusatam (Billitonite) specimen collection was found in Birah Village, Simpang Pesak, Southeastern Belitung Island, Indonesia.

Considering table 1, Batusatam had an average the density of 2.37 ± 0.168 gr/ml and hardness range 6.0-7.0 on the Mohs scale. We selected four specimens for element distribution analysis, which are STM-01, STM-03, STM-07, and STM-09. For detail of chemical properties data, shown in table 2.

We have limitations in tracing the overall element. Olympus 3 Portable X-Ray Fluorescence is unable to trace sparse elements such as noble gas elements, sodium, fluoride, oxygen, nitrogen, carbon, boron, beryllium, lithium, hydrogen, and other elements in rarity proportion. In addition, the form of oxide is also not traceable. LE proportion in each specimen ranged from 48.3-34.0%; average 39.259 ± 0.1421%. Supposedly, the largest proportions are oxygen as metal oxides and small portions of magnesium, potassium, and sodium [11].

Based on the element distribution analysis, Batusatam in Birah Village, Southeastern Belitung Island, had major elements composition (> 1%) as Si (46.12 ± 0.169%), followed by Al (7.14 ± 0.126%), Fe (4.39 ± 0.027%), and Ca (2.32 ± 0.015%). There are some minor elements (1.0-0.1%) such as are Ti (0.41 ± 0.017%) and Mn (0.10 ± 0.005%). It also had various trace elements (>0.1%) such as Sb, V, Zr, Sn, Cr, Cd, Ni. Although S, Pb, Co, Bi present inconstantly. See table 2 and figure 3 for detail.
Table 2. Element distribution of Batusatam (this study).

| Element | STM-01 (w/w) | STM-03 (w/w) | STM-07 (w/w) | STM-09 (w/w) | Average (w/w) |
|---------|--------------|--------------|--------------|--------------|---------------|
| Si      | 39.125 ± 0.1950 | 50.518 ± 0.1600 | 44.589 ± 0.1580 | 50.262 ± 0.1630 | 46.124 ± 0.1690 |
| Al      | 6.240 ± 0.1450  | 7.316 ± 0.1190  | 7.160 ± 0.1170  | 7.828 ± 0.1220  | 7.136 ± 0.1258  |
| Fe      | 3.756 ± 0.0280  | 4.789 ± 0.0270  | 4.706 ± 0.0260  | 4.307 ± 0.0260  | 4.390 ± 0.0268  |
| Ca      | 1.848 ± 0.0150  | 2.597 ± 0.0160  | 2.550 ± 0.0150  | 2.289 ± 0.0150  | 2.321 ± 0.0153  |
| Ti      | 0.316 ± 0.0180  | 0.429 ± 0.0170  | 0.466 ± 0.0170  | 0.415 ± 0.0170  | 0.407 ± 0.0173  |
| Mn      | 0.091 ± 0.0050  | 0.110 ± 0.0050  | 0.108 ± 0.0050  | 0.096 ± 0.0050  | 0.101 ± 0.0050  |
| Sb      | 0.035 ± 0.0020  | 0.037 ± 0.0001  | 0.041 ± 0.0010  | 0.039 ± 0.0010  | 0.038 ± 0.0010  |
| V       | 0.033 ± 0.0080  | 0.036 ± 0.0080  | 0.057 ± 0.0080  | 0.039 ± 0.0080  | 0.041 ± 0.0080  |
| Zn      | 0.031 ± 0.0005  | 0.035 ± 0.0004  | 0.039 ± 0.0004  | 0.036 ± 0.0004  | 0.035 ± 0.0013  |
| Sn      | 0.025 ± 0.0010  | 0.026 ± 0.0010  | 0.027 ± 0.0010  | 0.025 ± 0.0010  | 0.026 ± 0.0010  |
| Cr      | 0.024 ± 0.0040  | 0.032 ± 0.0040  | 0.026 ± 0.0040  | 0.025 ± 0.0040  | 0.027 ± 0.0040  |
| Cd      | 0.023 ± 0.0010  | 0.023 ± 0.0010  | 0.027 ± 0.0010  | 0.025 ± 0.0010  | 0.025 ± 0.0010  |
| Ni      | 0.022 ± 0.0020  | 0.025 ± 0.0020  | 0.031 ± 0.0020  | 0.026 ± 0.0020  | 0.026 ± 0.0020  |
| S       | 0.075 ± 0.0070  | -               | 0.041 ± 0.0050  | -              | 0.058 ± 0.0060  |
| Pb      | 0.001 ± 0.0003  | -               | -               | -              | 0.001 ± 0.0003  |
| Co      | -               | -               | 0.040 ± 0.0060  | 0.040 ± 0.0060  | 0.040 ± 0.0060  |
| Bi      | -               | 0.003 ± 0.0003  | 0.004 ± 0.0003  | 0.003 ± 0.0003  | 0.003 ± 0.0003  |
| LE*     | 48.379 ± 0.023  | 34.024 ± 0.1780 | 40.088 ± 0.1860 | 34.545 ± 0.1810 | 39.259 ± 0.1421 |

Total | 100.024 | 100.000 | 99.960 | 100.000 | 100.057 |

*LE is other elements that cannot precisely detected by Olympus 3 Portable X-ray fluorescence (limit of detection).

Figure 3. Elements distribution (by 10 base logarithmic scale Y-axis) of Batusatam, in the Birah Village, Southeastern Belitung, Indonesia.

4. Discussion

Batusatam is a local term that refers to rare Billitonite tektite. The study of Billitonite has been conducted since 1897 by Verbeek. R.D.M. He called it "Glaskogels van Billiton" or Glass balls from Billiton [12].
Other researchers [3,6,9,13] began examining and analyzing the properties compared to other tektites (such as Moldavite tektite). They suggested that tektite was molten terrestrial debris that ejected throughout the atmosphere and re-entry the earth's atmosphere in hypervelocity.

Tektite distribution on earth was considered from its origin similarity and age to presume. It is grouped in one strewnfield. There are four well-known tektite-strewn-fields on earth [9], i.e.: (1) North America strewn-field (tektite origin source from 90 km Chesapeake Bay Crater); (2) Ivory Coast strewn-field (tektite origin source from 10,5 Bosumtwi Crater, western Africa); (3) Moldavite strewn-field (tektite origin source from 24 km Ries Crater in Southeastern Europe), and (4) Australian strewn-field (origin source location is yet argued) [14]. Billitonite tektite belongs to the Australian strewn-field tektite. Australian strewn-field is the largest one which is covers 30% of the earth's surface. It covers most of Indochina, South-east Asia (including Belitung Island, Indonesia), far west-out of the Indian Ocean, and Australia, southern Tasmania; it covers about 150 million km². The extent of this coverage strewnfield area reveals the devastating of this catastrophic event that very possibly occurs as an incoming global threat. Presently, the origin and the distribution of the Australian strewn-field tektite are questionable.

Some researchers suggest that the origin of Australian strewn-field tektite comes from a middle Pleistocene meteor impact event in the Indochina region, Kampuchea, South East Asia. It is around 800,000-690,000 BP [15]. However, some researchers are also considering the possible origin of Australian tektite is was ejected volcanic debris from Toba super-eruption Toba activity, which occurs at around 75,000 ± 900 BP [16,17]. There is a gap period of about 700,000 years between those two global catastrophic events. That should be specified accurately by further detailed geological history reconstruction of the sedimentary layers where tektite was found naturally. Thus, it becomes important to describe this rare object comprehensively.

In this study, our Batusatam specimens also had a dark-glossy-glass color with a worm-like cavity pattern on its entire object surface. It had the longest axis at around 7.59 cm. The most striking feature of the tektite is the surface texture pattern which is never more identical in each specimen. It has a worm-like cavity pattern that is significantly diversely distinct. These features are apparent in all specimens examined and appropriated with Billitonite and other Australian tektite shape references.

The most exciting thing is discovering a rod-shaped (STM-01) and a tear-drop-shaped (STM-02) tektite in Birah Village, Southeastern Belitung, Island Indonesia. This form explains the process of the molten debris (the origin of tektite material) shaped due to aerodynamic abrasion when re-entry to the earth's atmosphere in hypervelocity and solidified before reaching the earth's surface. Generally, tektite is found in the form of a disk, which shows that the molten debris that ejected did not have time to crystallize before hitting the earth's surface [18]. Hence, discovering the rod and tear-drop-shaped tektite was remarkable.

The density of these Batusatam was 2.37 ± 0.168 gr/ml and hardness ranging from 6.0 to 7.0 Mhos. This value equaled the typical Australian tektite density, ranging from 2.2 to 2.8 gr/ml. Compared with obsidian density (2.55 g/ml), these Batusatam was less dense. This condition can be affected while the molten debris forms air cavities intensively. These air cavities formed due to high air pressure into the object, atmosphere gas interaction, and glass rapid-crystalization during hypervelocity falling. These Batusatam specimens' hardness is similar to typical glass (4.0 to 7.0 Mhos). Likely with SiO₂ composition majorly. In recommendation, it would be great if Batusatam could be observed in detail using scanning electron microscopy (SEM) in further research. Therefore, we could classify glass mineral characteristics specifically.

In examining chemical properties, we apply elemental distribution data that has been equalized with the estimated oxidation composition. This equalization assumes the most of the detected light element (LE) was oxygen majorly [11,18]. We balanced the LE proportion to every detected element as a Metal-oxide. We also selected noticeable major and minor elements SiO₂, Al₂O₃, Fe₂O₃ (total Fe-oxide), CaO, TiO₂, and MnO. These five oxides are commonly found in tektite. Resulting, SiO₂ is the dominant composition in the range 70–80%, followed by Al₂O₃ (10-14%), Fe₂O₃ (total Fe-oxide 3-8%), CaO (1-4%), TiO₂ (0.6-0.8%), and MnO. (<2%), see table 3.
Table 3. Major and minor oxide comparison between Batusatam and other Australian Strewn-field tektite.

|       | STM-01 | STM-03 | STM-07 | STM-09 | Billitonite | Brunei Tektite | Thaiandites | Indoschinities | Muong-nong | Australites (1) | Australites (2) |
|-------|--------|--------|--------|--------|-------------|----------------|-------------|--------------|------------|----------------|----------------|
| SiO$_2$ | 75.78  | 76.57  | 74.44  | 76.79  | 71.32       | 70.90          | 72.70       | 78.90        | 77.34      | 73.10          | 71.35          |
| Al$_2$O$_3$ | 12.09  | 11.09  | 11.95  | 11.96  | 12.04       | 13.15          | 13.37       | 10.20        | 10.52      | 12.70          | 12.84          |
| Fe$_3$O$_4$ | 7.27   | 7.26   | 7.86   | 6.58   | 5.87        | 5.79           | 4.85        | 3.74         | 3.74       | 4.83           | 5.25           |
| CaO    | 3.58   | 3.94   | 4.26   | 3.50   | 2.95        | 2.35           | 1.98        | 1.21         | 1.76       | 3.75           | 3.31           |
| TiO$_2$ | 0.61   | 0.65   | 0.78   | 0.63   | 0.78        | 1.00           | 0.78        | 0.63         | 0.66       | 0.72           | 0.77           |
| MnO    | 0.18   | 0.17   | 0.18   | 0.15   | 0.14        | n.d            | 0.08        | 0.01         | 0.08       | nd.            | 0.11           |

Total  | 99.50  | 99.67  | 99.47  | 99.61  | 93.10       | 93.19          | 93.76       | 94.69        | 94.10      | 95.10          | 93.63          |

References: 
* Billitonite in this study  
+ Ford (1988)  
* Mueller (1915)  
+ Amare & Koeberl (2006)  
+ Fudali, et al. (1991)

All major and minor elements had a negative correlation vs. SiO$_2$, either on Batusatam or other Tektite ($r = -0.5996$ up to -0.9508). A strong negative correlation is apparent between SiO$_2$ vs. Al$_2$O$_3$ ($r = -0.851$), SiO$_2$ vs. Fe-oxide ($r = -0.888$, in Batusatam and $r = -0.9508$, in other tektites), SiO$_2$ vs MnO ($r = -0.8123$ in Batusatam and $r = -0.8592$ in other tektites); see figure 4. Batusatam and other tektites [1,19–21] have relatively similar correlation trends, as a similar investigation by Amare & Koeberl (2006) [21]. These results indicate a similarity mechanism in its formation and probably its origin also. On the SiO$_2$-Al$_2$O$_3$-Fe-oxide ternary diagram, we noticed that the Batusatam composition is similar to that of another Australian strewnfield tektite. We also notice that the trendline of Fe-Oxide, CaO, and MnO composition of these Batusatam specimens was relatively two points higher than another trendline. This condition seems correlated to Belitung island's alluvial composition, which contains high-Ca ferrous soil and intensely enriched Mn and Sn soil from weathered Mesozoic granite [22]. This alluvial (soil layer) possibility interacts directly with molten glass droplets (origin of tektite material) due to the earth's surface. These major components in this alluvial, concurrently crystalized within tektite molten glass forming. The presence of the Sn element is very rarely found in tektite, even less in large proportions. Sn was a lower volatile element, which is easier to evaporate at high temperatures. It same as Cu, Ce, and Pb. However, we recognized that the proportion of Sn elements in Batusatam specimens was 0.026 ± 0.001% or around 260 ppm. Apparently, the Sn present is significant to distinguish Batusatam (as Billitonite) another tektite. The determination of trace elements for differentiation will help ensure the authenticity of Batusatam as Bilitonite. The discovery of some of these significant differences will help identify-specify properties. We suggest conducting this recommendation further.
Batusatam is currently one of the geoheritage objects in the UNESCO Global Geopark Belitung. Besides that, Batusatam has long been in demand by many collectors and is often sold as tourist merchandise. Meanwhile, Batusatam is a rare object that would deplete even run out if it continues to exploit irresponsibly. Research in geoheritage is fundamental to handle these problems. It could promote experts to routinely review and give recommendations, enhance the geoheritage scientific value, and support expertly in collaborative geoheritage preservation and managing it sustainably.

5. Conclusions

Based on its physical and chemical properties, Batusatam that naturally found in Birah Village, Southeastern Belitung, is Billitonite, a group of Australian Strewnfield tektite. These specimens have a dark-glassy texture with an irregular-random cavity or worm-like pattern in the entire surface object. It had variations in shape that may appear as rod-shaped, tear-drop-shaped, subspherical to spherical shaped. This density is around 2.37 ± 0.168 gr/ml, and the hardness range is 6.0-7.0 Mohs. These objects composition is SiO$_2$ (74.44-76.79 w / w%), Al$_2$O$_3$ (11.09-12.09 w / w%), Fe$_2$O$_3$ (6.58-7.86 w / w%), MnO (0.15-0.18 w / w%), TiO$_2$ (0.61-0.78 w / w%), and CaO (3.50-4.26 w / w%). The Harker diagram shows that all major and minor elements should negatively correlate with SiO$_2$ proportion. It is similar to other known Australian strewnfield tektite. We suggest that Batusatam in Birah Village, Southeastern
Belitung Island, has significant uniqueness as higher concentrations of Fe, Ca, Mn, and Sn than other Australian tektites. It is reasonably related to Billitonite crystalization, which interacts with high Ca ferrous soil from high Mn-Sn weathered Belitung Mesozoic granitic bedrock.

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