Platinum group elements in proximal impactites of the Bukit Bunuh impact structure, Malaysia

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The Bukit Bunuh in Malaysia has recently been identified as an impact structure after the discovery of possible impact-melt-like rocks and impact breccias from this area. The impact event is believed to have occurred around 1.34–1.84 Ma. Twelve impact-related rocks from this suspected impact structure were analysed in the present study for platinum group of element (PGE) content. The sample population includes proximal impactites (two impact-melt rocks and three impact breccias) and possible impact-related rocks (four mylonites) and basement granite (three in number). The results showed no observable clear distinction between the impactites and basement granite. Compared to other asteroid impact sites in the world, the impactites and impact-related rocks in the Bukit Bunuh structure clearly contain a lower concentration of PGEs. Even though previous studies reported possible evidences of shock metamorphism in the Bukit Bunuh structure and electrical resistivity survey favoured the presence of asteroid impact structure in this area as well, the absence of a clear projectile signature in our investigation on PGE hinders further discussion on the existence and nature of the impact. We suggest that the absence of any PGE signature in the Bukit Bunuh impactites could be indicative either of (1) an achondrite projectile, or (2) an oblique impact or (3) the presence of a volatile-rich layer.

Keywords: Basement granite, impact structure, platinum group elements, proximal impactites.

THE platinum group elements (PGEs) are commonly analysed in the impact-melts and impactites from impact craters to confirm asteroid impact events[1–6]. These geochemical data are considered as one of the best indicators of impactor asteroid contribution to terrestrial samples as these elements are strongly depleted in the Earth's crust. For example, the concentration of iridium (Ir) in bulk continental crust is only 0.037 ppb, whereas chondritic meteorites contain at least 300 ppb and Ir concentration in iron meteorite reaches up to 30,000 ppb (ref. 7).

Ir and ruthenium (Ru) are known as the least mobile PGEs, and hence are useful for identification of impactor asteroid components in the impactites[1]. In addition, low concentration of Ir can be determined with more precision than any of the other PGEs[8]. The PGE signature in impact-melt rocks is generally weak because the bulk of the projectile mass is dispersed around the crater area (in cases of smaller impact) by the high-speed ejecta[5].

The Bukit Bunuh, situated in the Lenggong area of Perak, Malaysia (Figure 1) has recently been identified as an impact structure after the discovery of possible impact-melt rocks and several suevite-like boulders in the area[9,10]. The fission track dating on zircons recovered from the impact-melts suggests that the impact event could have occurred around 1.84–1.34 Ma (ref. 11). The electrical resistivity survey of the impact site has shown a crater-like depression reaching down towards the granite basement[9].

Within the vicinity of the Bukit Bunuh structure, impact-melt rocks and polymict impact breccias have been reported[12]. The impact-melt rocks typically contain 50% or more fine-grained matrix and can be described as crystalline, semihyaline, or hyaline rocks containing variable amounts of clastic debris of different degrees of shock metamorphism[13]. The breccias contain at least 50% more clasts than melt rocks. They also often contain unmelted rock fragments. An outcrop of mylonitic granite found near this possible impact structure is suspected to be related to the asteroid impact[14]; however, no thorough petrographic and geochemical studies on this mylonitic rock are available.

To find more evidence to evaluate the Bukit Bunuh impact event, we analysed PGE content of the impact-related rocks using instrumental neutron activation analysis (INAA). Even though the target rocks have low PGE content, it is possible to use PGE analysis to measure meteoritic contributions down to a concentration of 0.1wt% (refs 8, 15, 16).

The suspected Bukit Bunuh impact structure is mainly covered by a palm estate, surrounded by dense forest. Two mountain ranges run in parallel along both sides of the suspected crater structure: the Bintang mountain range to the west and the Titiwangsa mountain range to the east (Figure 1). A large river, the Perak River, runs across the hypothesized crater area. The lithology in the area is represented by alluvium, tephra dust (also known as Toba volcanic ash) and granitic rock. Both alluvium and tephra dust units are Quaternary in age[17], whereas the granitic unit that makes up most of the basement rock is mainly Triassic in age[18].

The granitic rock found in this area, also known as the Buloh Pelang unit, belongs to the Taiping pluton[19,20], a large pluton member within the Bintang Batholith (that makes up the Bintang mountain range). The exposed and cored granitic rock in the Lenggong area can be described

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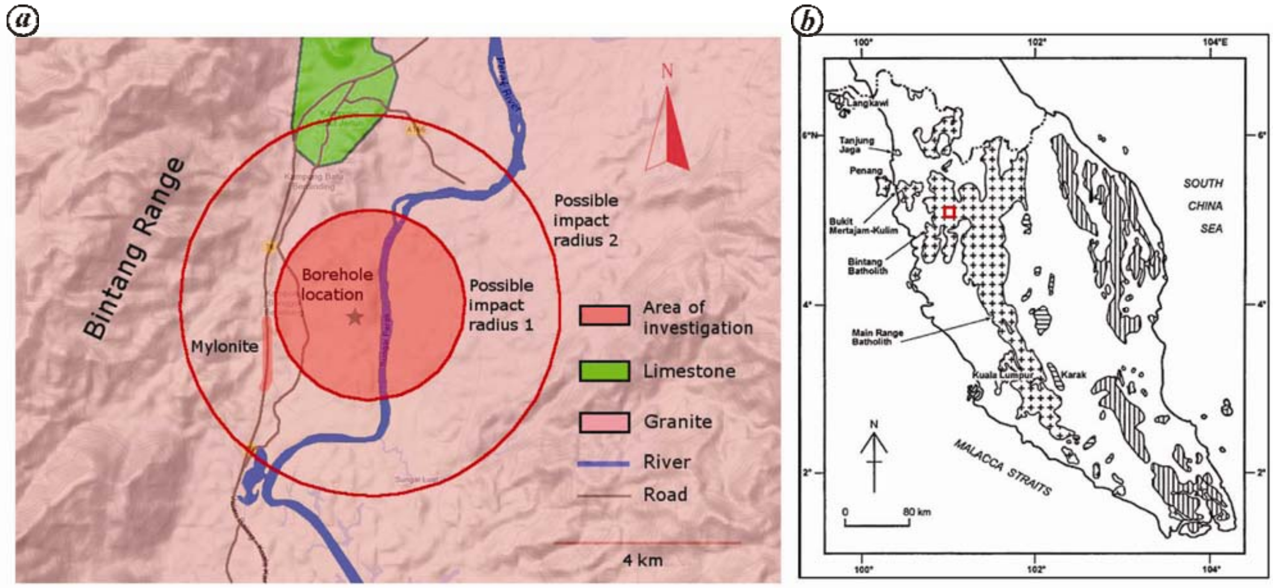

Figure 1. ***a***, The study area in Lenggong, Perak, Malaysia. Radius 1 has a diameter of 4 km, and radius 2 has a diameter of 8 km. Location of mylonite and borehole are also marked. Suevite is collected within the area of radius 1. ***b***, Location of the study area in peninsular Malaysia.

as porphyritic to megacrystic with large euhedral K-feldspar; it is coarse-grained, grey in colour, and contains biotite as its main mafic constituent. Various pyroxene-bearing mafic microgranular enclaves with coarse-grained rims can be found with the granite. The parent rock of the mylonite is believed to belong to the Buloh Pelang pluton, because it is surrounded by this rock unit and shares similar rock texture.

Within some part of the pluton, the biotite content in granite may be as high as 25% (ref. 20). Variations in the K-feldspar porphyry content and the presence of amphibole with pyroxene cores have also been reported. Geochemically, the Buloh Pelang is relatively cafemic (high in calcium [Ca], iron [Fe], and magnesium [Mg]), potassic, and sodium-poor granite with moderate SiO_2 content (minimum 67.3 wt%). It also contains high levels of transitional metals and light rare earth elements (LREEs)[20].

A total of 12 samples (three core samples of basement granites, five impactites, including two impact-melt-like rocks and three impact breccia, and four mylonites) were analysed in the present study. Figure 2 *a–c* shows photographs of cut and polished hand-specimen samples of impactites. Possible impact-melt rocks typically show irregular/distorted shape of the target granite clasts in a fine blackish matrix, while impact breccias are rich in clasts that could originate from either sedimentary or igneous rocks.

The collected rock and core samples were first cleaned with distilled water. After crushing with a hammer wrapped in polyethylene, samples were ground into fine powder using a mild steel mill. This will only induce a small amount of Fe contaminant during pulverization of the sample and will not interfere with the PGE analysis. Approximately 100 g of power of each sample, twice the amount required to optimize the recovery of rare elements, was processed at the Activation Laboratories, Canada, for PGE analysis using INAA. Tables 1 and 2 provides the INAA method detection limit (MDL) and the PGE standard used for the analysis.

Nickel sulphide (NiS) fire assay procedure is used for PGE analysis using INAA. Samples of up to 25 g are fire assayed at 1100°C with borax (sodium borate), soda ash (sodium carbonate), silica, high-purity nickel powder and sulphur. The formed nickel sulphide droplets identifies the PGE from the sample and form a button at the bottom of the crucible. The nickel sulphide button is digested in concentrated hydrochloric acid and the resulting residue, which contains all the PGE and gold (Au), is collected on a filter paper. This residue then undergoes two sessions of irradiation and three separate counts to measure all of the PGEs and Au.

Table 2 provides the PGEs content of the Bukit Bunuh basement granite, suevite and mylonite. The analysis revealed that the following elements: Os (MDL: 2 ppb), Ir (MDL: 0.1 ppb), Pt (MDL: 5 ppb), Pd (MDL: 2 ppb), and Re (MDL: 5 ppb) were below the detection limit for all samples. With the exception of one basement granite sample, the Rh concentration (MDL: 0.2 ppb) of each sample was below the detection limit. Only two elements, Ru (MDL: 5 ppb) and Au (MDL: 0.5 ppb), showed measurable values for all the samples.

Despite the high sensitivity of the instrument, important meteoritic indicators such as Ir are below the detection limit in our analyses. To strongly suggest the presence of an extraterrestrial signature, an Ir value has to be higher than 1–2 ppb (ref. 21). Although a Ru anomaly

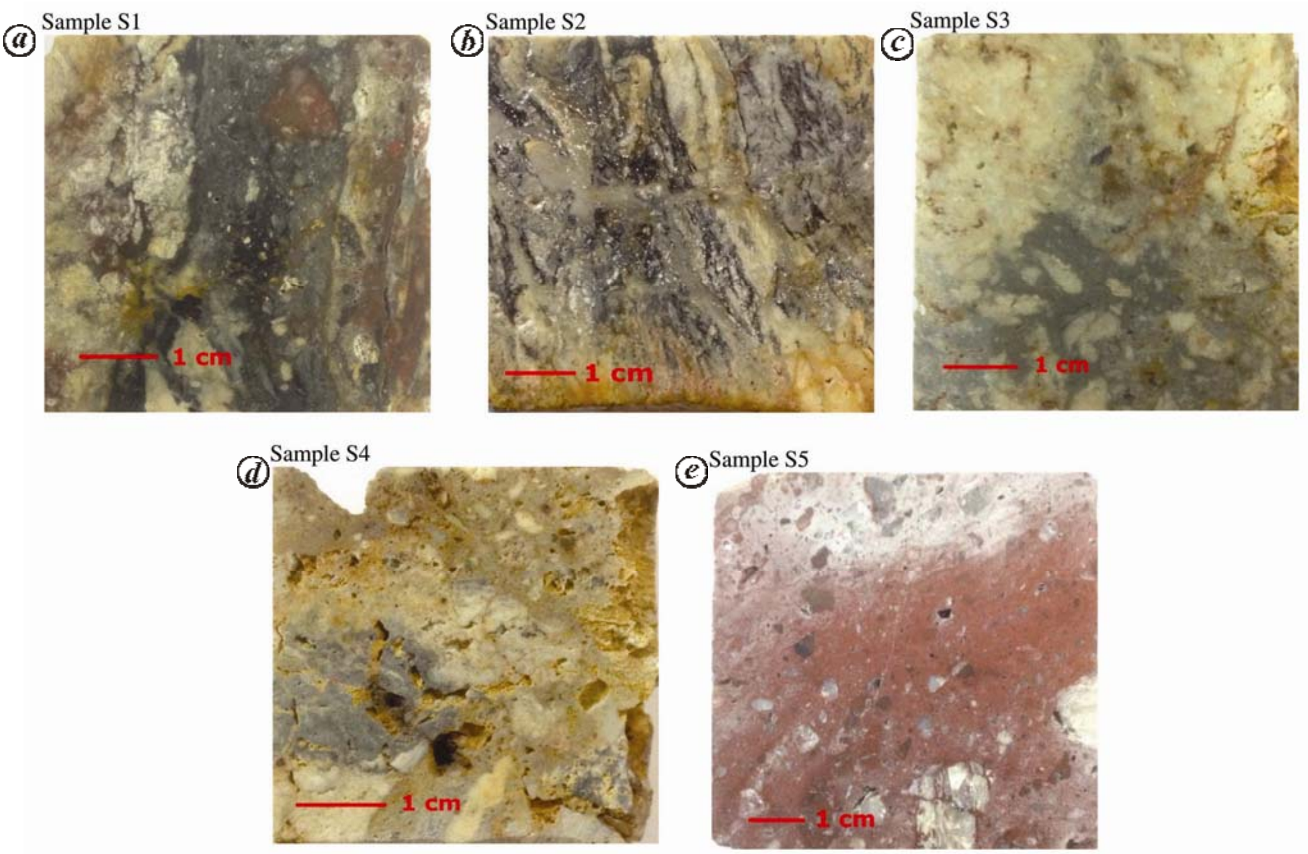

Figure 2. ***a***, Sample S1: A clast-rich impact melt rock. Note the irregular/distorted shape of the white–grey-coloured target granite clasts (which contain quartz and feldspar) in the fine blackish matrix. ***b***, Sample S2: A clast-rich impact melt rock. Contorted banding is prominent in this sample. ***c***, Sample S3: An impact breccias/suevite sample that likely originated from granite. ***d***, Sample S4: An impact breccias/suevite sample with moderate vesicular texture. ***e***, Sample S5: A suevite sample that probably originated from metasedimentary rock. Note this sample has a red matrix.

Table 1. Platinum group elements (PGE) concentration of the Bukit Bunuh samples

PGE Unit	Os ppb	Ir ppb	Ru ppb	Rh ppb	Pt ppb	Pd ppb	Au ppb	Re ppb	Mass g
MDL*	2	0.1	5	0.2	5	2	0.5	5	–
Core 1	< 2	< 0.1	8	0.2	< 5	< 2	1.2	< 5	25
Core 2	< 2	< 0.1	8	< 0.2	< 5	< 2	13.1	< 5	25
Core 3	< 2	< 0.1	10	< 0.2	< 5	< 2	1.9	< 5	25
S1	< 2	< 0.1	< 5	< 0.2	< 5	< 2	4.3	< 5	25
S2	< 2	< 0.1	6	< 0.2	< 5	< 2	9.7	< 5	25
S3	< 2	< 0.1	7	< 0.2	< 5	< 2	3.2	< 5	25
S4	< 2	< 0.1	7	< 0.2	< 5	< 2	4.8	< 5	25
S5	< 2	< 0.1	< 5	< 0.2	< 5	< 2	3.8	< 5	25
My1	< 2	< 0.1	8	< 0.2	< 5	< 2	1.3	< 5	25
My2	< 2	< 0.1	6	< 0.2	< 5	< 2	1.5	< 5	25
My3	< 2	< 0.1	12	< 0.2	< 5	< 2	1.6	< 5	25
My4	< 2	< 0.1	15	< 0.2	< 5	< 2	1.2	< 5	25

*MDL, Method detection limit; Core, Basement granite; S, Suevite; My, Mylonite.

could mean possible asteroid contribution, very low concentrations of other important PGEs (Ir, Pd, Pt and Rh) fail to prove any meteoritic components within the studied samples (Figure 3).

High Ru concentration in the samples could be related to the presence of Ru-bearing minerals, such as laurite (RuS_2). Such minerals are commonly associated with mafic and ultramafic rocks[1], and we postulate that they could come from the basement granite of this area because these granites are moderately contaminated with pyroxene-bearing mafic microgranular enclaves of mantle origin, as shown in the surrounding outcrops and previous studies of the same granite type.

In addition, compared to impact-melt and partial-melt rocks from other confirmed impact sites (examples from Canada[1,3], Namibia[22], South Africa[23] and Mauritania[24])

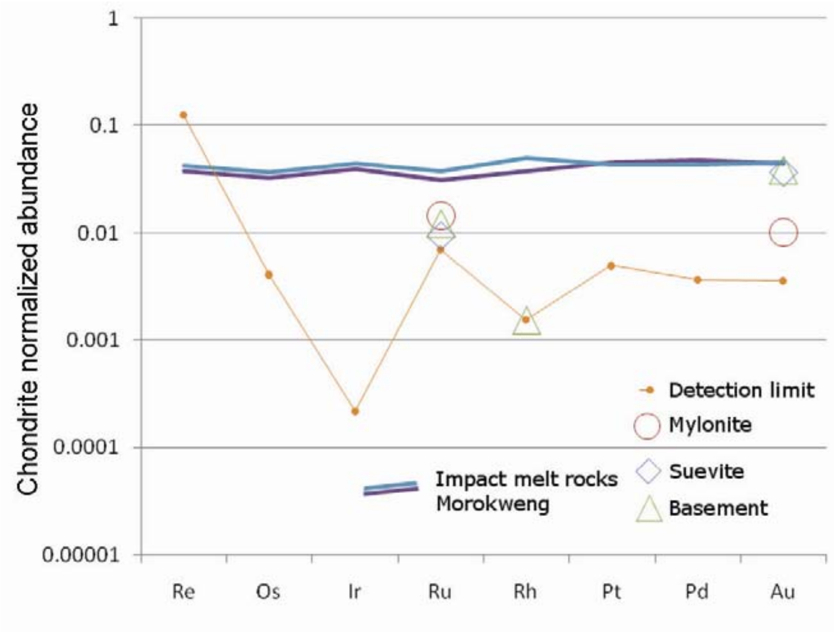

Figure 3. Plot of platinum-group elements and related metal abundances normalized to carbonaceous–chondritic compositions[33]. The impact melt rocks from the Morokweng impact structure, South Africa[23] (MO-43 and MO-48), show a clear meteoritic pattern.

Table 2. Results of PGE concentration in international reference material

PGE Unit	Os ppb	Ir ppb	Ru ppb	Rh ppb	Pt ppb	Pd ppb	Au ppb	Re ppb
MDL*	2	0.1	5	0.2	5	2	0.5	5
Reference material								
OREAS 13b (cert)	12	17.9	78	43	204	134		
OREAS 13b (meas)	12	16.7	73	43.8	211	134		
CDN-PGMS-24 (cert)							806	
CDN-PGMS-24 (meas)							795	
CDN-PGMS-25 (cert)							483	
CDN-PGMS-25 (meas)							443	
Duplicate My2	< 2	< 0.1	6	< 0.2	< 5	< 2		< 5

and well-documented *K–T* boundary clay layers with an impact-induced geochemical signature (examples from the United States and Israel; Table 3), the PGE levels from the Bukit Bunuh samples are clearly more depleted. Although previous studies on the Bukit Bunuh impact area found possible evidence of shock metamorphism (shatter cones, planar deformation features, planar features, maskelynite, kink bands and metamorphism deformation lamella)[14] and geophysical (electrical resistivity survey) evidence of a possible crater[9], our PGE data do not allow definite verification of an extraterrestrial signature. Thus, the nature of the impact event remains ambiguous.

We could, however, suggest several explanations for the absence of PGEs in the impactites of possible Bukit Bunuh structure: (a) the impactor could be an achondrite-type (PGE-poor) projectile; (b) the impactor asteroid could have an oblique impact trajectory, or (c) a volatile-rich layer was present in the impact zone.

(a) If an impact event did occur in the Bukit Bunuh area, it seems that the possibility of both iron and chondritic projectiles, which contain higher concentrations of PGEs, could be ruled out because the impactite samples belonging to the present study are very poor in PGEs. Although it is not possible at present to correlate the impactor asteroid composition with any known meteorite type without clear geochemical evidence, many researchers[5,6,8,25–27] have suggested achondrite projectile for PGE-poor impact rocks. This type of projectile contains only a small amount of PGE elements[28], which could explain the poor PGE levels in the melt rocks. Even so, differentiated achondrites only represent around 2% of the total present meteoritic population[6].

(b) An oblique impact (in which the impact angle is less than about 45°) can lead to a complete escape of the partly vapourized projectile material from the crater area and may consequently lead to complete loss of a

Table 3. Comparison with melt rocks/partial melt rocks from other confirmed impact sites

	Bukit Bunuh			Impact melt rocks					*K–T* boundary layer		
					Canada					USA	
PGE	Impactites	Mylonite	Basement granite	Namibia Roter Kamm[22]	New Quebec[1]	Clearwater East[3]	South Africa Morokweng[23]	Mauritania Tenoumer[34]	Israel Mishor Rotem1	Clear Creek North[1]	Lance Creek[1]
Os	BDL	BDL	BDL			26.94	18	BDL			
Ir	BDL	BDL	BDL	0.87	1.5	25.19	20	3.98	3.2	14.2	2.4
Ru	6.7	10.3	8.7	0.92	3.9	38.12	27	0.21	1.5	8.4	2.7
Rh	BDL	BDL	0.2	0.35	0.069	9.58	6.5	0.69	0.26	0.04	0.19
Pt	BDL	BDL	BDL	2.34	17		43.5	0.7	2.2	26.4	28.8
Pd	BDL	BDL	BDL	2.01	5.4	32.2	24	0.37	4	19.5	12
Au	5.16	1.4	5.4	0.56	3.8	4.9	6.3	BDL		1	9
Re	BDL	BDL	BDL			0.58	1.7	BDL			

projectile signature in impact rocks within the area[29]. In such a case, the impact rocks have a low PGE concentration, but the projectile could either be rich or poor in PGE content[6]. The Chicxulub crater is an example of an oblique impact; there are no detectable meteoritic contaminations[5,30] within the area around the crater, but the worldwide *K–T* boundary ejecta layer is highly enriched in PGE[31]. For an oblique impact, the percentage of meteoritic materials that remain within the crater after the impact is highly dependent on the impact velocity and angle of the impacting meteorites[29].

(c) The presence of volatile-rich layers in the zone during impact could also affect the amount of projectile that is incorporated in the crater lithologies[5,6]. During the impact event, a high amount of volatile ejecting against the incoming projectile will hinder the mixing process between the components from the projectile and the crater[5]. The size of the impactor and the thickness of the volatile-rich layers are correlated to the amount of ejected rock and will determine the contamination of the impact-melt[5]. As the Bukit Bunuh crater is small[32] (less than 4 km across), a sizeable volatile-rich layer would be needed to explain the poor PGE content within the impactites.

The basement granitoid and mylonite from the Bukit Bunuh impact site were analysed for PGEs. The results indicate that the rocks are relatively enriched in Ru but depleted in other PGEs. The absence of a meteoritic geochemical signature in the suevite, basement granitoid rocks and surrounding mylonite in the Bukit Bunuh could be explained by (1) an achondrite-type projectile, or (2) an oblique impact, or (3) the presence of a volatile-rich layer. If this study can be supported by new PGE geochemical and isotope studies around the impact area, it would contribute significantly to the understanding of this impact event.

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