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U–Pb Geochronology of the Baguio Area, a Major Mining District in Northern Luzon (Philippines)

Monika Walia[1,2] | Rolando Pena† | Ulrich Knittel[2,3]

[1]Department of Earth and Environmental Sciences, National Chung-Cheng University, Chiayi, Taiwan | [2]Department of Geosciences, National Taiwan University, Taipei, Taiwan | [3]Research Unit Petrology and Fluid Processes, RWTH Aachen University, Aachen, Germany

Correspondence: Ulrich Knittel (knittel@rwth-aachen.de)

Received: 12 December 2023 | **Revised:** 25 June 2024 | **Accepted:** 26 August 2024

Funding: Department of Earth Sciences of the Taiwan National University (funds of Prof. T.Y. Frank Yang), the National Institute of Geological Sciences of the University of the Philippines and private funds of the authors.

ABSTRACT

The Baguio District, located in northern Luzon (the Philippines), is one of the major gold and copper mining districts in the Philippines and SE Asia. U–Pb zircon ages for igneous rocks and for detrital zircons extracted from sediment samples of the principal formations of the Baguio District reveal major magmatic pulses at ca. 1, 3, 16, and 20 Ma. The oldest zircon dated in this study has an age of $27.3 \pm 1.6\,(2\sigma)$ indicating earlier activity which has, however, left only a small imprint on the zircon inventory of the sediments. The absence of older zircons suggests that northern Luzon formed as an intra-oceanic arc. Zircon Hf isotope data suggests that the magmas, from which the zircons crystallized, were derived from time-integrated highly depleted mantle sources, compatible with an intra-oceanic origin of the island. The results of the U–Pb dating of zircons mostly confirm previous estimates of the ages of the rock units. Mid-Miocene ages obtained for samples thought to represent the Pugo Formation, the lowermost unit, which is thought to be Cretaceous-Eocene in age, most likely date magmatic rocks that intruded the Pugo Formation.

1 | Introduction

The Baguio area, located at the southern end of the Central Cordillera of Northern Luzon (Philippines), is one of the world's prime mineral districts and has been one of the most important gold-producing districts in the Philippines (e.g., Waters et al. 2011). Despite its economic importance, there is little agreement between published accounts of the geology of the Baguio area and—in particular—between published maps of the area. Likewise, the geochronology of the area is to some extent uncertain due to the fact that available radiometric age determinations were mainly carried out by the K-Ar method (e.g., Wolfe 1981; Bellon and Yumul 2000; Polvé et al. 2007), which is prone to erroneous results in areas of repeated magmatic and hydrothermal activity as a result of argon loss and/or excess argon. Shannon (1979) reported fission-track ages that date, however, generally only the most recent thermal event. More recently, Waters et al. (2011) reported $^{40}Ar/^{39}Ar$ ages that are considered to be more reliable. Encarnacion, Mukasa, and Obille (1993) dated a sample using conventional U–Pb dating of zircon and Liu et al. (2020) and Nakajima et al. (2023) presented ages for altogether five samples based on single grain zircon dating.

Here we report further single grain U–Pb zircon ages for igneous rocks and the first data for detrital zircon of sediments from the area. These data allow us to date several igneous complexes with confidence and to refine the age assignment of the sedimentary formations sampled. We also determined the Hf isotopic composition for a subset of the dated zircons which provides us with an insight into the sources of the magmas from which

†Deceased. R. Pena made significant contributions to this work including planning and organization of the fieldwork and writing of large parts of the initial draft.

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the igneous zircons crystallized (e.g., Bodet and Schärer 2000; Wang et al. 2010; Tsai et al. 2019).

2 | Geological Setting

The Philippine Island Arc system is composed of two major terranes (Figure 1), the Palawan Continental Terrane (PCT) that formed at the margin of the Asian continent and rifted southwards from the SE China margin as a consequence of the opening of the South China Sea (e.g., Taylor and Hayes 1980; Holloway 1982), and the Philippine Mobile Belt (PMB) composed of a collage of ophiolites and arc systems (e.g., Yumul, Dimalanta, Maglambayan et al. 2008 and references therein). The PCT and the PMB collided in the late Miocene (McCabe, Almasco, and Diegor 1982; Yumul et al. 2009; Walia et al. 2013).

Luzon is the largest island of the archipelago and forms the northern part of the PMB. North Luzon, which is separated from the remainder of the island by the Philippine Fault, is largely composed of the North–South trending Northern Sierra Madre situated on the eastern side and the Cordillera Central at the western side of the island. These mountain chains are separated by the Cagayan Basin and merge to the south in the Caraballo Mountains (Figure 1).

The basement of the Northern Sierra Madre consists of ophiolites that seem to be part of an ophiolitic belt that runs along the eastern margin of the Philippines down the Pacific Cordillera of Mindanao. Magmatic arcs that generated copious effusions of basaltic to andesitic lavas and intrusions of batholitic dimensions during Paleogene time include the oldest known diorites and quartz diorites found in Northern Luzon. These form the Coastal Batholith of the Northern Sierra Madre dated at 49–43 Ma (K-Ar ages, Metal Mining Agency Japan 1977; Pena et al. 2009). The Paleogene magmatism is thought to be the result of westward subduction of the West Philippine Basin. Westward subduction ceased at the end of the Oligocene when the Benham Rise accreted to eastern Luzon blocking the subduction zone (Pena et al. 2009). For an alternative view see Hollings et al. (2011).

The eastward subduction of the seafloor of the South China Sea probably started in late Oligocene or early Miocene and generated magmas that led to the formation of the Central Cordillera and the Caraballo Mountains (e.g., Polvé et al. 2007). In the Caraballo Mountains, the quartz diorites and granodiorites of the Dupax Diorite Complex are thought to have Late Oligocene to Early Miocene age (K-Ar ages: 33–22 Ma, Metal Mining Agency Japan 1977). Wolfe (1981) proposed a two-stage model for magmatism in the Central Cordillera based on the then available K-Ar age data: an earlier phase from Late Oligocene to Early Miocene and a later phase from Middle Miocene to recent. Based on additional K-Ar ages, Polvé et al. (2007) proposed three episodes of Neogene magmatism at 21–18, 15–8, and 3–1 Ma that are of critical importance for the evaluation the minerals potential of the area. Older magmatic episodes are indicated by an U–Pb age of 32.5 ± 0.7 Ma obtained by Nakajima et al. (2023) for a biotite hornblende diorite from the Chico River in the North-Eastern part of the Baguio area and a conventional U–Pb age of 26.8 ± 0.4 Ma by Encarnacion, Mukasa, and Obille (1993). Even older zircons (35–42 Ma) were found by Tsai et al. (2019) in sediments of the Chico River, but the exact source of these zircons is not known.

So far, no continental basement has been shown to exist in the PMB (Rangin and Pubellier 1990; Tsai et al. 2019), hence, the

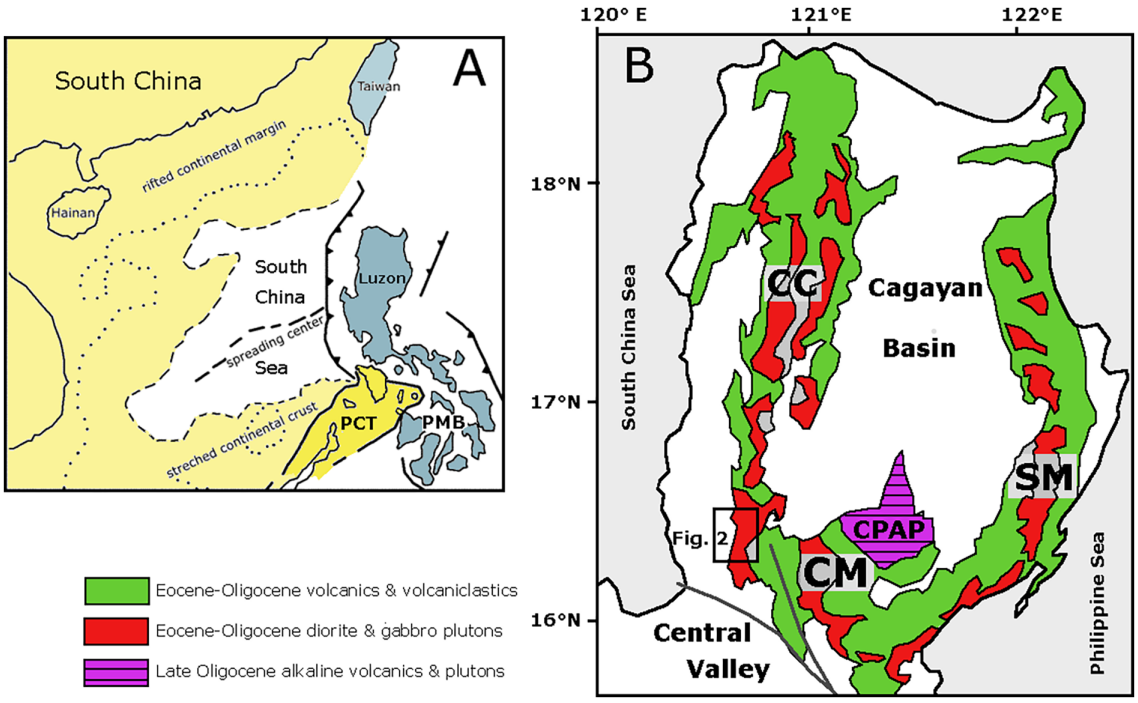

FIGURE 1 | (A) Geologic setting of the northern part of the Philippine archipelago. Dotted line in the South China Sea is 2000 m depth, dotted line shows the extent of stretched continental crust. (B) Simplified geological map of northern Luzon. CC = Central Cordillera, CM = Caraballo Mountains, CPAP = Cordon-Palali Alkaline Province, SM = Northern Sierra Madre.

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PMB is considered to be an intra-oceanic arc. However, the nature, origin, and age of several complexes of metamorphic rocks occurring along the eastern margin of the PMB and in the Caraballo Mountains are not known (Metal Mining Agency Japan 1977). In several cases they are assumed to be part of ophiolite complexes. However, felsic meta-sedimentary metamorphics also occur (for example on Rapu-Rapu Island) and their age and nature are unconstrained.

3 | Geology of the Baguio District

The Central Cordillera that forms the western part of Northern Luzon is a volcano-sedimentary belt about 300 km long, 50 km wide and up to ~3000 m high. At its southern end, the Baguio Mining District is located (Figure 2), which is the most important gold-producing district in the Philippines in terms of economic value (e.g., Waters et al. 2011). Mineral deposits comprise a wide variety of deposit types, including epithermal gold-base metal veins (e.g., Antamok: Sawkins, O'neil, and Thompson 1979; Acupan: Cooke, Mcphail, and Bloom 1996), copper-gold porphyry deposits (e.g., Santo Tomas II, Imai 2001). As well as proximal copper-gold, distal gold-base metal skarn (e.g., Thanksgiving Au-Zn skarn; Callow 1967), and sediment-hosted gold deposits occur, along with an unusual style of sediment-hosted copper mineralization (Wildcat: Damasco 1979).

The Baguio area is underlain by magmatic and sedimentary rocks that were deposited from Late Cretaceous (?) to Pliocene (e.g., Payot et al. 2007; Yumul et al. 2008). They were intruded by a variety of igneous rocks during several episodes (Bellon and Yumul 2000; Polvé et al. 2007). While most authors agree with the general stratigraphy described below, there is little agreement on the areal distribution of these units (Figure 2).

The Pugo Formation, including the Dalupirip Schist, is considered to form the exposed basement in the Baguio area by most authors (Peña 1992; Yumul et al. 2008; Dimalanta et al. 2013) and consists of basaltic and andesitic lava flows with occasional interbeds of sandstone, chert, and pyroclastic rocks. In an alternative interpretation, the so-called Itogon Ophiolite that covers large parts of the area mapped as Pugo Formation (Figure 2C) is considered to form the basement of the Baguio area (UNDP 1987; Florendo 1994; Encarnacion 2004).

Crispin and Fuchimoto (1980) report an imprecise K-Ar age of 83 ± 20 Ma, equivalent to Late Cretaceous, for a sample of the Dalupirip Schist whereas Bellon and Yumul (2000) report two K-Ar ages of 15 and 20 Ma for the schist. As these are K-Ar ages, they may date the metamorphic overprint of the schists. However, it is also possible that these ages are meaningless as K-Ar ages do not give an indication whether or not they really date a geological event. In any case, the Dalupirip Schist is now considered to be a low-grade metamorphic equivalent of the Pugo Formation by most authors (e.g., Balce et al. 1980; Yumul et al. 2008).

An andesite sill, the Emerald Creek Complex of Schafer (1953), which may be a part of the Pliocene Mafic Dyke Complex of Waters et al. (2011), separates the Pugo Formation from the overlying Zigzag Formation. The latter is a sequence of sandstone, siltstones, and mudstones with local lenses of limestone. The upper section of the Zigzag is characterized by intercalations of pyroclastic rock in the sedimentary beds, andesite flows, and conglomerates with basalt cobbles. The geochemistry and sedimentology of this formation has been studied by Tam et al. (2005), Dimalanta et al. (2013), and Suzuki et al. (2017). Geochemical discrimination diagrams show the affinity of the felsic components of the Zigzag to an active continental margin or evolved island arc setting and overall more evolved geochemical signatures compared to the younger Klondyke Formation. Sedimentological features indicate deposition by high-density sandy debris flows in a slope environment.

The Zigzag Formation is overlain by the Kennon Limestone which has a thickness of around 240 m. On top of the limestone, the clast-supported conglomerate sequence of the Klondyke Formation was deposited. Clasts attain dimensions of more than 0.5 m. Sandstone interbeds are notable along the Bued River section of this formation. The Kennon Road section, with a predominance of conglomerates, is considered by De Leon et al. (1991) as the lower member of the Klondyke, while the exposures of mudstone-shale with subordinate sandstone and conglomerate and occasional calcarenite beds and limestone lenses of the Marcos Highway section are considered to be the upper member. Estimates of the thickness of the Klondyke Formation are up to 3600 m (De Leon et al. 1991). Sedimentological features suggest rapid deposition by high-concentration turbidity currents, whereas ungraded massive parts are thought to be of debris-flow origin in an inner fan depositional environment (Suzuki et al. 2017). In terms of geochemistry, the sandstones of the Klondyke Formations exhibit the signatures of a primitive arc setting (Tam, Suzuki, and Yumul 2007; Dimalanta et al. 2013).

Capping the sediment pile is the Baguio Formation, consisting of tuff, volcanic conglomerate, volcanic breccia, and pyroclastic flow deposits. The Baguio Formation was originally defined by Smith and Eddingfield (1911) but the term was practically abandoned until it was resurrected by De los Santos (1982) for the pyroclastic rocks around Baguio which apparently rest on the Mirador Limestone and is considered to be of Late Miocene to Early Pliocene age.

The oldest igneous unit in the Baguio area is the Central Cordillera Diorite Complex (CCDC) that intrudes the Pugo Formation as stocks and batholiths of diorite, quartz diorite, and granodiorite. The oldest U–Pb ages obtained for this complex are 32.5 ± 0.7 Ma (Nakajima et al. 2023) and 26.8 ± 0.4 Ma (Encarnacion, Mukasa, and Obille 1993). K-Ar ages of 19–22 Ma (Polvé et al. 2007; Waters et al. 2011), and the U–Pb zircon age 15.6 ± 0.4 Ma obtained for the Itogon Quartz Diorite (Liu et al. 2020) indicate further intrusive episodes. Later intrusions include the Balacbac Andesite (K-Ar ages: 3.5–5.1 Ma; Maleterre 1989), the Black Mountain Quartz Diorite (Late Miocene) with a K-Ar age of 2.1 ± 0.1 Ma (Imai 2002) and Ar-Ar ages of 2.81–2.98 (Waters et al. 2011), and the Balatoc Dacite (Ar-Ar-ages: 0.5–1.1 Ma, Waters et al. 2011).

The Black Mountain Quartz Diorite was formerly exposed along the Kennon Road/Bued River at Camp 6, but the exposure has been covered by landslides and mined for copper

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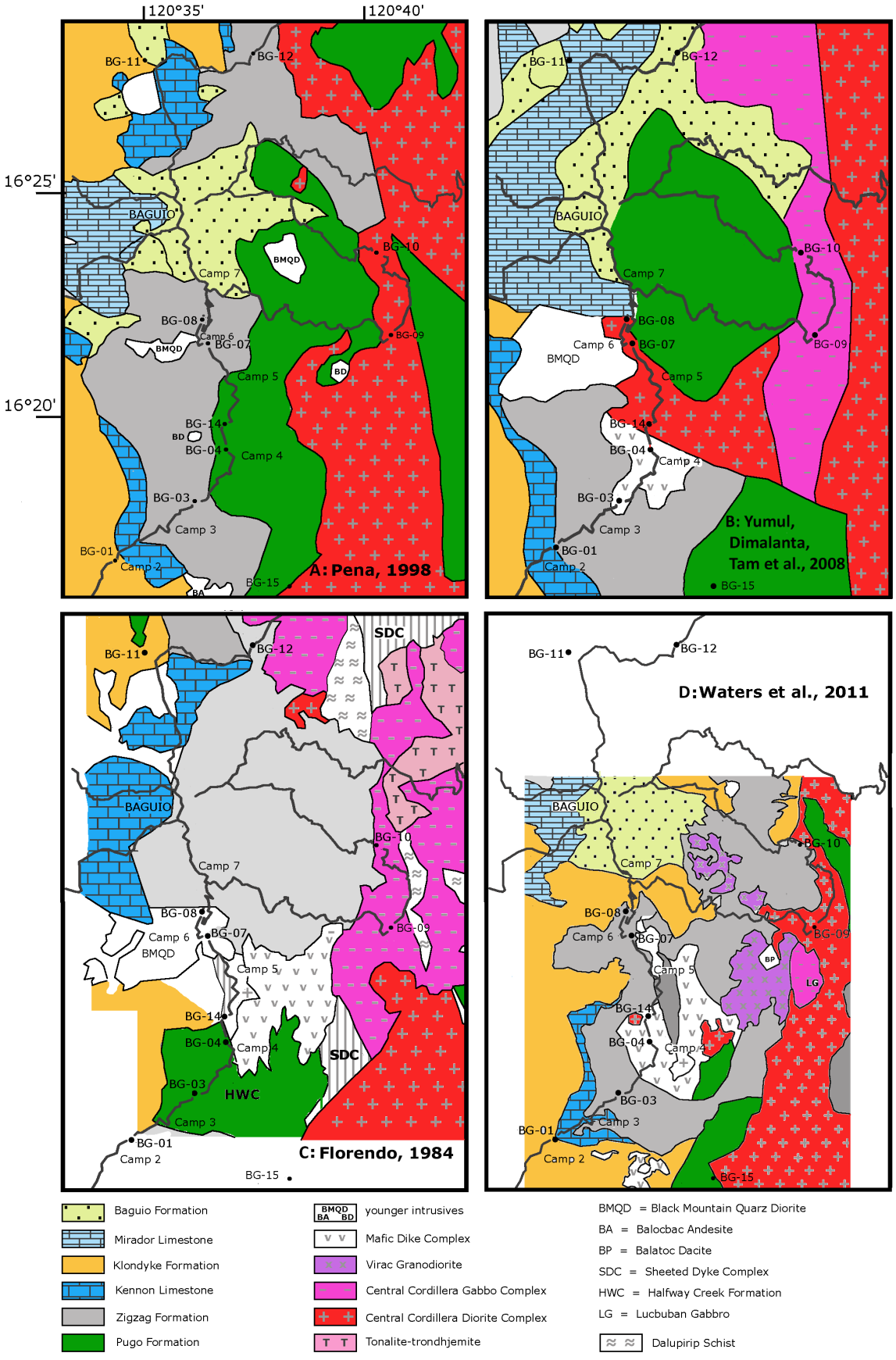

FIGURE 2 | Published geological maps of the Baguio area based on A) Pena (1998), B) Yumul et al. (2008), C) Florendo (1994) and Encarnacion (2004), and D) Waters et al. (2011). Note that the units and their interpretation of Florendo (1994) only roughly match the stratigraphic units used by the other authors.

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in the 1970s as it hosted a small porphyry type deposit. The mineralization of the complex gold-sulfide skarn deposit at Thanksgiving Mine adjacent to the Black Mountain deposit is also ascribed to the intrusion of the Black Mountain Quartz Diorite. The Balacbac Andesite (part of the Mafic Dyke Complex of Waters et al. 2011) occurs as dikes and small intrusive bodies consisting mainly of andesites with prominent phenocrysts of hornblende or plagioclase, and occasionally, pyroxenes. In places they form a dike swarm. Where they occur as small intrusive bodies as in Philex mine, they have the appearance of fine-grained diorite. The Balatoc Dacite in Acupan is a diatreme which was mined for gold over several decades until the early 2000s.

4 | Samples

Samples were collected from all major formations exposed along the Kennon Road and from locations around Baguio City (Figure 2, Table 1). The initial assignment of the samples to the various formations is based on the map of Pena (1998), but review of published maps indicate for some samples different assignments as discussed below (Table 2). Photos of outcrops, samples, and thin sections are provided as Data S1.

4.1 | Sedimentary Units

Two samples, BG-04 and BG-05 were collected from the area mapped by Pena and Reyes (1970) and Peña (1992) as part of the Pugo Formation. On the map of Yumul et al. (2008) (Figure 2B); the area is shown to be underlain by the Atake Creek Basalt and on the map of Waters et al. (2011) by the Mafic Dyke Complex, which is a general term for several dike complexes (Figure 2D; Waters et al. 2011). BG-04 was collected just North of Camp 4, South of Maramal Bridge and comes from a massive lava unit characterized by large plagioclase phenocrysts and plagioclase glomerocrysts. The abundance of plagioclase and scarcity of mafic minerals suggest an andesitic composition. Based on its field characteristics and petrography, the andesite could be a part of the Pugo Formation.

BG-05 was collected just North of Maramal Bridge and is a lava or dike rock containing amphibole megacrysts over 1 cm long and abundant xenoliths of volcanic and plutonic rocks. Amphibole occurs at all sizes and many crystals have colorless rims. Plagioclase is the second most abundant mineral. The petrography suggests that the primary magmatic component of the rock is of dacitic composition. It therefore appears possible that BG-05 comes from the Mafic Dyke Complex that separates the

TABLE 1 | Sample locations and summary of U–Pb age data.

Sample	Location	Altitude		U/Pb age	U/Pb age range	YC1σ	K-Ar and/or $^{40}Ar/^{39}Ar$ age
BG-01	16°16′58.5″N 120°34′42.8″E	433	Conglomerate	—	12–23 Ma	14.0 ± 0.9 Ma	
BG-03	16°18′00.8″N 120°36′12.2″E	548	Sandstone	—	15–27 Ma	17.4 ± 0.8 Ma	
BG-04	16°19′11.4″N 120°36′53.8″E	652	Andesite	16.3 ± 0.4 Ma	15–19 Ma	—	
BG-05	16°19′17.3″N 120°36′54.3″E	656	Dacite	—	18–24 Ma	18.0 ± 0.8 Ma	
BG-07	16°21′34.6″N 120°36′29.7″E	821	Diorite	3.2 ± 0.1 Ma	2.6–4.4 Ma	—	2.81 ± 0.24[a]
BG-08	16°22′04.0″N 120°36′19.4″E	926	Conglomerate	—	11–25 Ma	13.6 ± 1.2 Ma	1.70 ± 0.16[b]
BG-09	16°21′43.2″N 120°40′46.9″E	731	Quartz diorite	15.3 ± 0.4 Ma	11–19 Ma	—	0.97 ± 0.11 Ma[b] 15.6 ± 0.4 Ma[c]
BG-10	16°23′34.0″N 120°40′26.2″E	926	Diorite	16.0 ± 0.4 Ma	15–18 Ma	—	
BG-11	16°27′52.7″N 120°35′01.9″E	1331	Tuffaceous	—	10–23 Ma	9.7 ± 0.5 Ma	
BG-13	16°13′49.3″N 120°30′18.4″E	—	Sediment	—	2.7–24 Ma	—	
BG-14	16°19′44.4″N 120°36′54.8″E		Diorite	20.3 ± 0.3 Ma	18–23 Ma	—	
BG-15	16°15′53.5″N 120°37′23.8″E		Diorite	1.2 ± 0.1 Ma	0.8–2.2 Ma	—	

[a]Waters et al. (2011).
[b]Polvé et al. (2007).
[c]Liu et al. (2020).

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TABLE 2 | Assignment of the samples to the various formations based on published maps.

Sample	Formation based on Pena (1998)	Yumul et al. (2008)	Waters et al. (2011)	Florendo (1994)
BG-01	Klondyke Formation	Klondyke Formation	Klondyke Formation	Klondyke Formation
BG-03	Zigzag Formation	Atake Creek Basalt	Zigzag Formation	Halfway Creek Formation
BG-04	Pugo Formation	Atake Creek Basalt	mafic dyke complex	Halfway Creek Formation
BG-05	Pugo Formation	Central Cordillera Diorite Complex	mafic dyke complex	Halfway Creek Formation
BG-07	Black Mountain Quartz Diorite Porphyry	Central Cordillera Diorite Complex (just east of Black Mountain intrusive complex)	Black Mountain Quartz Diorite Porphyry	post-Zigzag
BG-08	Zigzag Formation	Central Cordillera Diorite Complex	Zigzag Formation	post-Zigzag
BG-09				
BG-10				
BG-11	Baguio Formation	Kennon Limestone	—	Klondyke Formation
BG-13	River Bued			
BG-14	Intrusion into the Pugo Formation	Atake Creek Basalt	mafic dyke complex	Halfway Creek Formation
BG-15	Diorite from Philex Mine			

Pugo and Zigzag Formations and from which Waters et al. (2011) describe rocks with large amphibole phenocrysts though BG-05 is not a mafic rock.

Two samples, BG-03 and BG-08, are a conglomerate and a sandstone, respectively, collected from the Zigzag Formation along the Kennon Road. Sample BG-03 was taken between Camps 3 and 4 and sample BG-8 just north of the exposure of the Black Mountain porphyry. On the map of Yumul et al. (2008); (Figure 2B) the sampling site of BG-03 is underlain by the Atake Creek Basalt, whereas on that of Waters et al. (Figure 2C; Waters et al. 2011) by the Zigzag Formation. The sampling site of BG-08 is located at the border between Mirador Limestone and Pugo Formation on the map of Yumul et al. (2008) (Figure 2B) and in the area underlain by the Klondyke Formation of the map of Waters et al. (Figure 2D; Waters et al. 2011), but close to the boundary to the Zigzag Formation. Sample BG-03 is a heterogeneous sediment containing fragments of minerals (in particular plagioclase, both rounded and angular quartz), rocks (including volcanics and ignimbrite), and calcareous fossils. Sample BG-08 consists largely of fragments of plutonic rocks (quartz-+plagioclase = quartz−diorite), (polycrystalline) quartz grains, and plagioclase grains. Fragments of (mafic) volcanic rocks, quartzite, and sandstone are also recognized. Biotite and chlorite flakes occur. Mafic minerals are mostly replaced by epidote, rarely also by chlorite.

The Klondyke Formation, is represented by sample BG-1 collected from a conglomerate unit.

The Baguio Formation is represented by sample BG-11 collected in La Trinidad. In thin section at least two fragments of more altered volcanic rock of similar composition can be recognized. Phenocrysts are plagioclase, strongly pleochroic brown amphibole (very rarely also green amphibole that may be xenocrystic), and pyroxene in decreasing order of abundance.

Sample BG-13 is recent river sediment of the Bued River collected downstream and should represent the complete zircon inventory of the exposed lithologies in the catchment area. It was taken where the Bued River enters the plain in Barrio Bangar.

4.2 | Intrusive Rocks

Sample BG-09, collected in Itogon represents the CCGC (the Central Cordillera Gabbro Complex of Yumul et al. (2008), Figure 2) and is part of the Antamok Diorite of Shannon (1979). The sample is an amphibole-bearing quartz diorite composed of euhedral to subhedral plagioclase, anhedral green amphibole, and quartz. Plagioclase crystals may attain sizes of > 1 mm and quartz likewise sometime forms large (> 1 mm) grains.

Sample BG-10 likewise represents the CCDC and is part of the Itogon Quartz Diorite of Shannon (1979). It is an amphibole-bearing quartz diorite largely composed of plagioclase and green amphibole with some quartz. Most quartz occurs in the

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interstices between the other minerals and forms large poikilitic grains. All minerals are relatively fresh.

Sample BG-07 is a (sub-) volcanic quartz diorite porphyry. The sample was collected at the margin of the Black Mountain Intrusive Complex (Figure 2). Phenocrysts are largely plagioclase that forms up to mm-sized crystals. All mafic minerals are replaced by epidote whereas plagioclase is only partially replaced by epidote and carbonate. Based on the shape of the pseudomorphs, the mafic minerals might have been pyroxenes. A sample (PH01-08) collected north of our sampling site has a K-Ar age of 1.7 ± 0.2 Ma (Polvé et al. 2007) and Waters et al. report somewhat older ages of 2.81–2.98 (Waters et al. 2011).

Sample BG-14 is a gray colored granodiorite collected along Kennon Road (Figure 2). The medium grained phaneritic diorite is composed dominantly of quartz and plagioclase crystals with slight chlorite-epidote disseminations. Its age was uncertain until this dating.

Sample BG-15 is a fine grained diorite drill core sample from Philex Mine which hosts late copper mineralization in the area (K-Ar ages: 2.3–3.0 Ma; Polvé et al. 2007). The sample was collected at a depth of 453–459 m from the mine. The diorite has slight to moderate vein density of quartz, biotite, chlorite, magnetite, and anhydrite alteration assemblage.

5 | Analytical Procedures

Approximately 3–4 kg of the rocks were collected at each sampling point. Care was taken to collect as fresh a sample as possible. Prior to further processing, the samples were washed thoroughly to avoid contamination. Then, they were crushed, sieved, and processed using conventional methods of mineral separation including magnetic and heavy liquid separation followed by hand picking under the microscope.

The internal structure of zircon grains was examined using cathodoluminescence (CL) imaging using a scanning electron microprobe JSM-7100 at the Institute of Earth Sciences, Academia Sinica, Taipei, in order to recognize any inclusions present and to choose an area of the grain for U–Pb dating and Hf isotope analyses.

U–Pb dating of the zircon grains was done following the methods described by Knittel et al. (2014) using an Agilent 7500 s quadruple Inductively Coupled Plasma–Mass Spectroscope equipped with a New Wave UP213 laser ablation system at the Department of Earth and Environmental Sciences, Chung Cheng University in Chiayi, Taiwan. Laser ablation was performed using a helium carrier gas resulting in reduced deposition of ablated material onto the sample surface and improved transport efficiency, and thus in increased signal intensities (Günther and Heinrich, 1999). During the experiments, the gas blank was measured for about 60 s and the signals for the sample were measured for about 70 s. External calibration was performed using the GJ-1 zircon standard that is well established for its precise $^{207}Pb/^{206}Pb$ age determined by isotope-dilution thermal ionization mass spectrometry (ID-TIMS) at 608.5 ± 0.4 Ma (2σ) (Jackson et al. 2004). Since all zircons are younger than 100 Ma, only $^{206}Pb/^{238}U$ ages were considered.

The ability of the instrument used to date very young zircons has recently been demonstrated by Shao, Chung, and Chen (2014) who obtained reliable U–Pb ages as young as ~1.24 Ma for andesite samples from Lutao Island, Taiwan, using the same instrumentation.

All U–Th–Pb isotope ratios were calculated using the GLITTER 4.4.2 (GEMOC) software. Correction for common lead follows the procedures in Andersen (2002). Calculation of weighted mean U–Pb ages probability density curves as well as the plotting of concordia plots were carried out using Isoplot v.3.0 (Ludwig 2003). Each run started and ended with at least two analyses of the GJ-standard. The accuracy of the analyses was checked by analyzing the Plešovice zircon (Sláma et al. 2008) at the start of each set. If the value for the Plešovice zircon was found to be unsatisfactory, the run was restarted by recalibration of GJ. The average value for the PL during the period of analyses was 341.0 ± 3.1 ($n = 30$) as compared to the accepted value of 337.1 ± 0.4.

The Hf isotopic measurements were carried out using the Nu Plasma HR Multi-Collector Inductively-Coupled Plasma Mass Spectrometry connected to the Photon Machines Analyte G2 laser system at the Institute of Earth Sciences, Academia Sinica, Taipei. Each measurement took 120 s including the blank time of 30 s and ablation time of 80 s, with a 5–8 Hz repetition rate and laser energy density of ~8–9 J cm^2. The laser ablation was carried out with He carrier gas of ~0.9 L min^{-1} (MFC1 = ~0.7 L min^{-1} and MFC2 = ~0.2 L min^{-1}) which would then mix with Ar gas of ~0.7 L min^{-1}.

Mud Tank (MT) zircon standard was analyzed to evaluate the accuracy of the data in the beginning and end of each run comprising 10 spot analyses. The average $^{176}Hf/^{177}Hf$ ratio obtained during the analyses was 0.282501 ± 28 ($n = 17$). This value is in good agreement with the average $^{176}Hf/^{177}Hf$ value reported in literature which is 0.282504 ± 44 (Woodhead and Hergt 2005). Additional details of the analytical procedures can be found in Zhang, Takeuchi, and Lee (2019). For the calculations, we adopted the value of ^{176}Lu decay constant as 1.865 X 10^{-11} y^{-1} (Scherer, Münker, and Mezger 2001).

6 | Results

All zircons analyzed are bigger than 40 μ in size. In CL picture they all exhibit zoning (Figure 3). Concordia diagrams are shown in Figure 4A,B. U–Pb analytical data and $^{206}Pb/^{238}U$ ages and the Hf isotope data are provided as Tables S2 and S3, respectively.

6.1 | Pugo Formation?

Only 18 zircon grains could be dated for sample BG-04. Zircon ages range from 15.1 to 21 Ma. Omitting the oldest grain, which is slightly discordant, an average of 16.9 ± 0.5 Ma [MSWD = 2.0] can be calculated for 17 grains. As indicated by the somewhat high MSWD, the average age is almost incompatible with the youngest grain and the two oldest grains. A "shoulder" in the probability density diagram suggests that the main peak might comprise two populations (Figure 5) and indeed, for the 12 youngest grains an age of 16.3 ± 0.4 Ma can be calculated with

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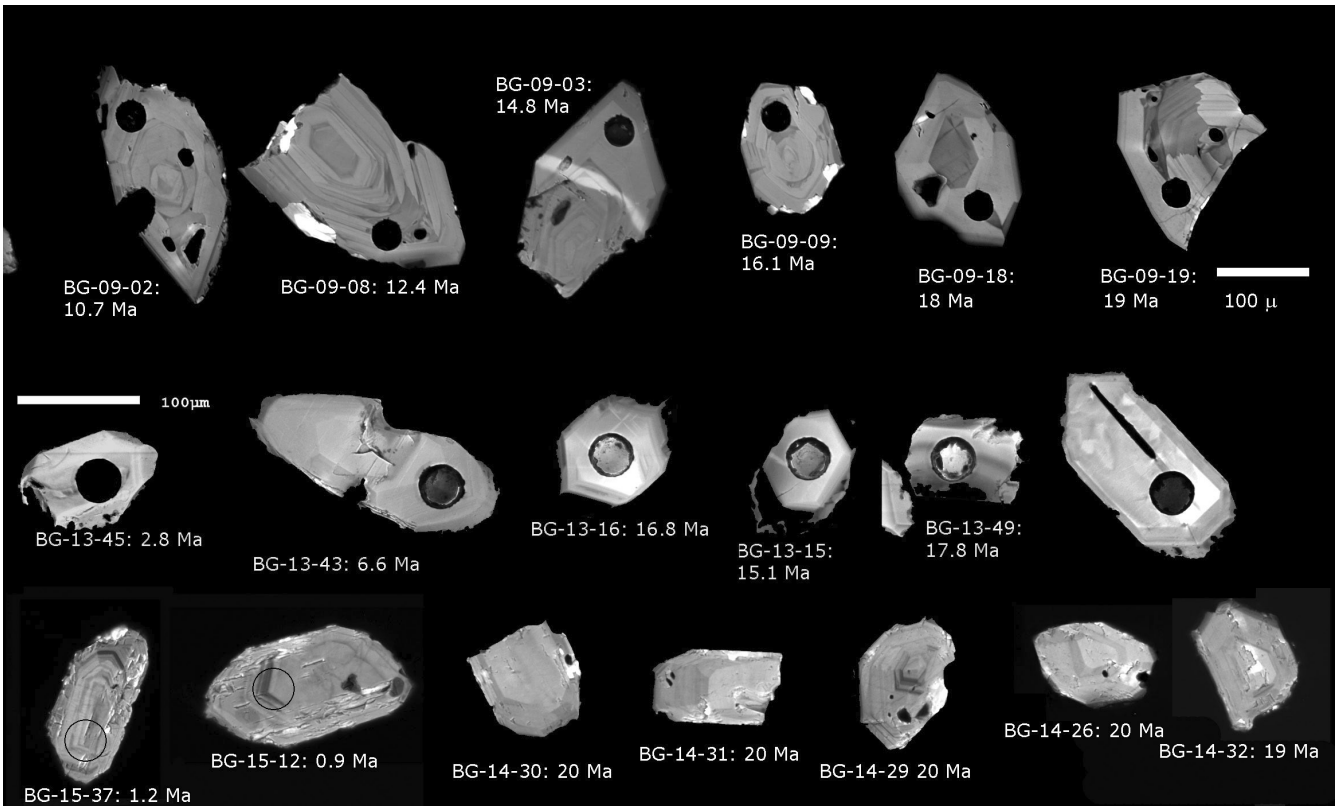

FIGURE 3 | CL pictures of selected zircons.

a much decreased MSWD of 0.71 and this is taken as the age of the lava. For the remaining zircons an age of 18.1 ± 0.6 Ma (MSWD = 0.40) can be calculated. These grains are probably xenocrysts. Hf isotope ratios were analyzed for 6 grains and the εHf(T) values are between +15.9 and +18.2.

Twenty-two zircons could be analyzed for dacite sample BG-05. Their $^{206}Pb/^{238}U$-ages range from 17.6 to 24 Ma. All ages are concordant (Figure 4). The five youngest grains give an average of 17.9 ± 0.7 Ma (MSWD = 0.08) and the remaining grains, except the 24 Ma grain, an average of 19.8 ± 0.4 (MSWD = 1.2). For 10 grains the εHf isotopic values vary between +13.3 and +18.0.

6.2 | Zigzag Formation

BG-03 and BG-08 are a conglomerate and a sandstone sample, respectively, from the Zigzag Formation. Thirty-four grains were dated for sample BG-03, where the ages spread from 14.9 to 27.3 Ma excluding the youngest age that has a large analytical error (Figure 5). The YC1σ age is 17.4 ± 0.8 Ma. Five slightly discordant grains were excluded from further consideration; their ages are 20.3–21.2 Ma, that is, within the age range that is also represented by the concordant zircons. Only 2 zircon grains could be analyzed for their Hf isotopic composition and both grains have εHf(T) values of +17.7.

BG-08 produced 84 datable zircon grains. Sixty-nine analyses gave concordant ages covering a range from 11 to 25 Ma. The YC1σ age is 13.6 ± 1.2 Ma. A major, broad peak at ca. 20 Ma comprises 59 zircons (Figure 5). Twenty-two grains were analyzed for their Hf isotopic composition and their values are restricted between +15.9 and +19.1.

6.3 | Klondyke Formation

Sample BG-01 is a conglomerate sample collected from the Klondyke Formation. Fifty-two analyzed zircons have an age range of 12–23 Ma (Figure 5) excluding three grains that are discordant or have very large errors. The YC1σ age is 13.8 ± 1.1 Ma. The probability density curve shows a maximum at ca. 16 Ma. Hf isotopic values were obtained for 12 grains and are all positive. The εHf(T) values range from +15.5 to +18.6.

6.4 | Baguio Formation

BG-11 is a tuffaceous rock. Thirty-two grains were dated for this sample, 2 ages are discordant and are not considered further. The 12 youngest zircons (9.5–11.1 Ma) form a coherent group with a mean age of 10.2 ± 3 Ma. The low MSWD (0.99) suggest this is valid age, which is then considered to be the maximum age of the sediment. The probability density plot suggests further maxima at ca. 19.3 Ma and at ca. 22 Ma (Figure 5). The 19 Ma peak corresponds to peaks in our Zigzag samples and one of the Pugo samples. The 22 Ma peak does not correspond to a peak in other samples, but zircons of that age are found in other samples too. Hf Isotope analyses were done on 12 grains and the values vary between +12.2 and +17.8.

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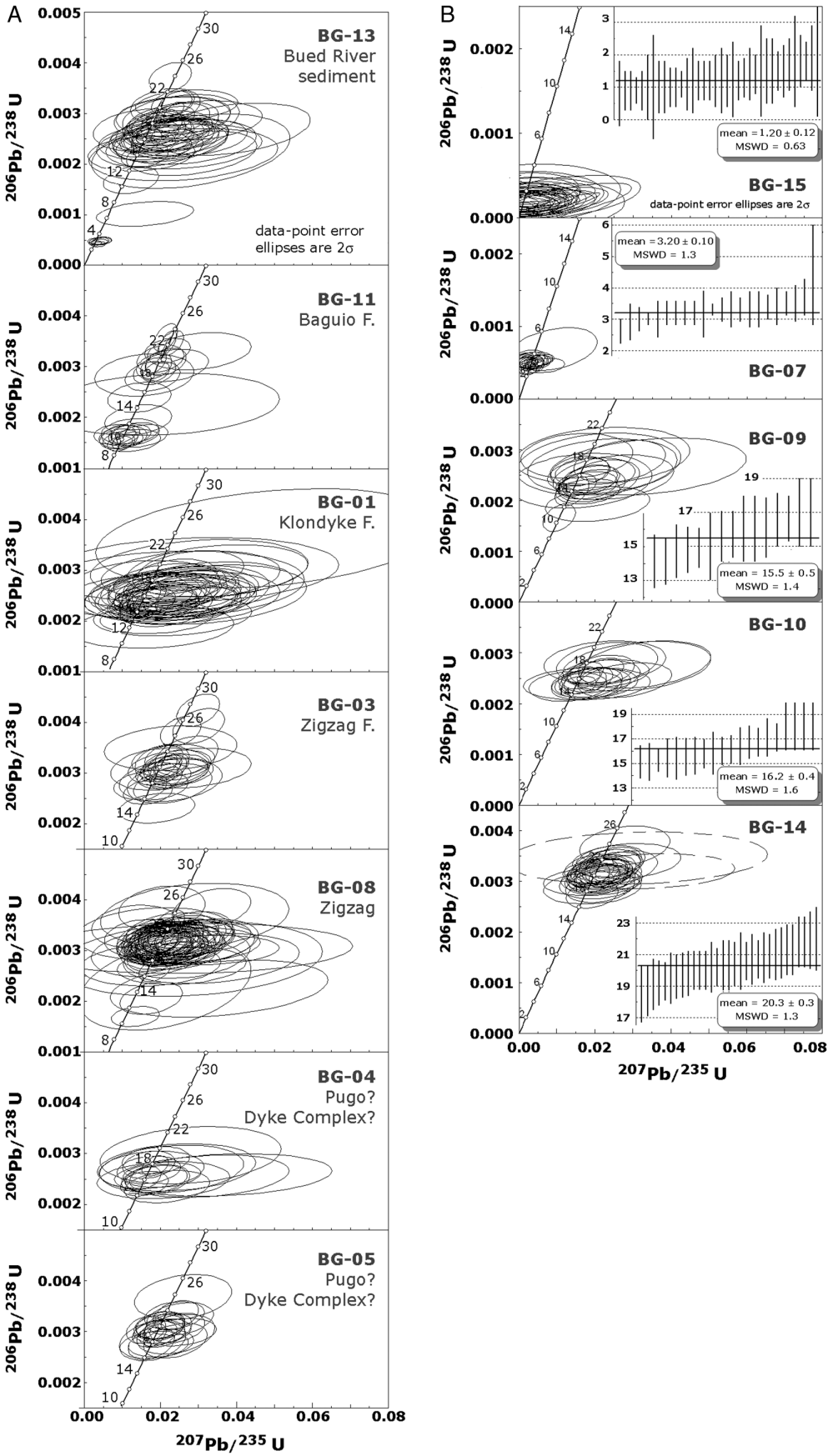

FIGURE 4 | (A) Concordia diagrams for detrital zircons; (B) Concordia diagrams for zircon from igneous rocks.

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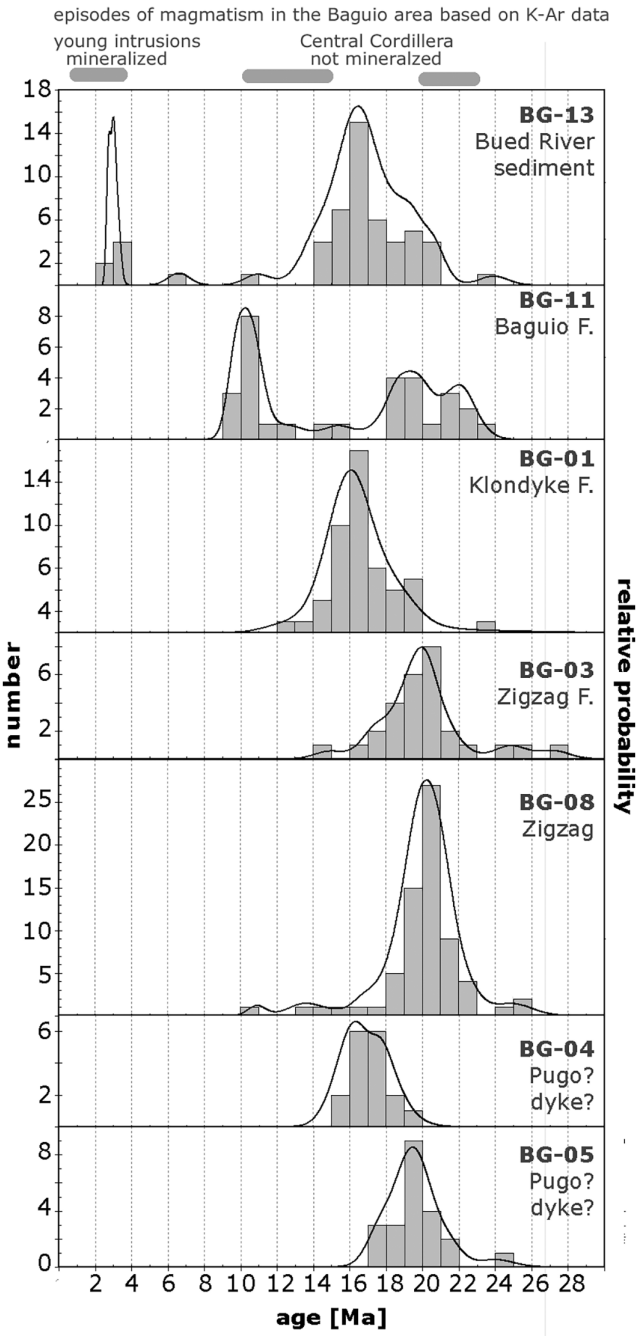

FIGURE 5 | Histograms for detrital zircon.

6.5 | River Sediment

Sample BG-13 is river sand collected from downstream of Bued River. The river drains all the lithologies mentioned above and has produced ages which can be related to the samples collected in this area. Fifty-six zircons were analyzed for the U–Pb dating. All but the oldest one have concordant U–Pb ages.

Several age groups are recognized (Figure 5). The youngest group comprises 6 grains in the range 2.7–3.2 Ma. The second group is centred at 16–17 Ma. A mean age of 16.5 ± 0.3 Ma can be calculated for 30 grains with a value of MSWD = 0.99. Zircons of that age are also found in our Pugo sample and in our Klondyke sample. The "shoulder" in the probability density curve at ca. 19 Ma corresponds to major peaks in our Zigzag samples and in our second Pugo sample. Nineteen grains were analyzed for their Hf isotope ratios and the values range between +12.1 and +19.8.

6.6 | Intrusive Rocks

21 out of 22 zircons analyzed form diorite sample BG-07 form a coherent group. The weighted average age is 3.2 ± 0.1 Ma (MSWD = 1.2) and is considered to be the magmatic age. One grain is slightly older but has a large attached error and hence is compatible with the average age. Ten grains were analyzed for their Hf isotopic ratios and the εHf(T) values are high, ranging from 15.5 to 18.2.

For BG-09, 22 zircons were analyzed. Of these, 17 fall into the range 14.1 ± 1.4 to 18 ± 2 Ma. The average age that can be calculated for these zircons is 15.6 ± 0.6 Ma. The MSWD is somewhat high at 1.7. Two grains are slightly older at 19 ± 1 Ma and could xenocrysts. Hf isotope values for the analyzed 8 zircon grains range between +14.0 and +18.7.

Twenty-two grains were dated for diorite sample BG-10. The youngest grain has a large error attached (13 ± 4 Ma) and is not considered here. One grain is slightly discordant and is also not considered here. The probability density curve has a maximum at 15.8 Ma and for the 12 youngest grains an average age of 15.6 ± 0.6 Ma [MSWD = 0.35] is obtained; for all grains the average age is 16.2 ± 0.4 Ma [MSWD = 1.6] (note: due to its large error, the age of the youngest grain is compatible with these average ages). The εHf(T) values for 8 grains are 15.0–19.2.

BG-14 is a granodiorite collected along the Kennon Road North of Camp 4. Thirty-four zircon grains were analyzed for this sample. The obtained ages range between 17.6–23.8 Ma. A mean age of 20.3 ± 0.3 Ma can be calculated with somewhat high MSWD = 1.3 excluding the oldest (23.8 ± 1.0 Ma), the youngest (17.6 ± 1.4 Ma) grains a well as a discordant grain.

BG-15 is a fine grained diorite drill core sample from Philex Mine. Out of the 41 analyzed zircon grains, the ages for the 40 grains range from 0.4–2.3 Ma and one grain is dated at 6 Ma. A mean age of 1.21 ± 0.11 Ma can be obtained with MSWD = 1.0.

7 | Discussion

There are several aspects of the data. The zircon dates help to clarify the deposition period of some units and/or confirm previous correlations. They then help to identify major periods of magmatism in the Baguio area and to refine the purported gaps in igneous activity. Finally they contribute to the discussion of the age and nature of the oldest basement of the Baguio area.

7.1 | Significance of the New Age Data for the Sedimentary Units

Two samples of the purported Pugo Formation were taken. However, the zircon ages of 16.3 ± 0.4 Ma for BG-04 and of

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17.9 ± 0.7 Ma for BG-05 clearly are much younger than the assumed late Cretaceous to Eocene age of the formation. Bellon and Yumul (2000), however, report a similar K-Ar age of 18.1 ± 2.0 Ma for a meta-andesite from the Pugo Formation North of the Santo Tomas II mine site. There are two possible explanations: the current age estimate for the Pugo Formation is wrong or the samples do not belong to the Pugo Formation.

The field aspect and petrography of sample BG-5 suggests that it is part of the dike complex exposed between the exposures of the Pugo and Zigzag Formations. The similarity in age would then suggest that BG-04 is also part of the dike complex though its petrography and field aspect also allow to consider it as part of the Pugo Formation. On the map of Schafer (1953) our sampling sites are part of the Emerald Creek Dyke Complex. The ages between 16 and 18 Ma are younger than those obtained for the older intrusives of 20–33 Ma and hence they cannot date the host rocks of these intrusives. As they fall into a major episode of magmatic activity in the Baguio area (Figure 6) we consider both samples to be derived from the dike complex separating the Pugo and the Zigzag Formations. Therefore, the age of the Pugo Formation could not be constraint in this study. Waters et al. (2011) determined $^{40}Ar/^{39}Ar$ plateau ages of 4.1 ± 0.2 and 3.5 ± 0.2 Ma for the mafic dyke complex and this suggesting that dike complexes formed during more than one period.

The Zigzag Formation that overlies the Pugo Formation is thought to be of Late Oligocene to Middle Miocene age (ca. 30–15 Ma, based on paleontological evidence summarized by Pena 1998). YC1σ ages of samples BG-3 and BG-8 are 17.4 ± 0.8 Ma and 13.6 ± 1.2 Ma, respectively, compatible with the paleontologial age. The abundant zircons with ages scattering around 20 Ma suggest that they are derived from older units of the Central Cordillera Batholith.

The age of the youngest zircon in Klondyke sample BG-01 is 12 ± 1 Ma and this agrees with the Middle Miocene to early Late Miocene age (15–7 Ma) determined by De Leon et al. (1991) on the basis of nanofossils. Most zircons are derived from igneous activity at 15–18 Ma, that is, from younger components of the Central Cordillera Batholith.

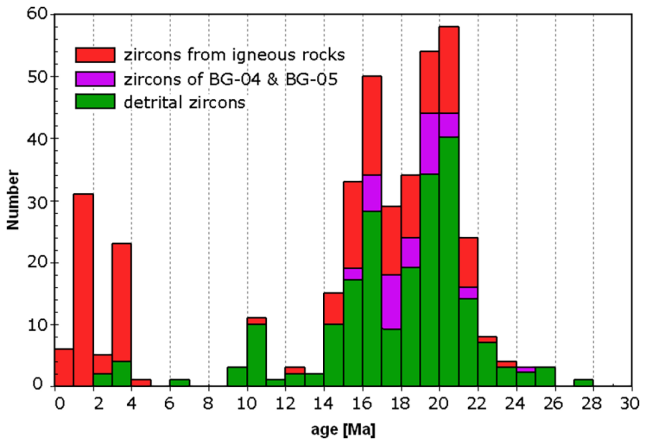

FIGURE 6 | Histogram for all analyzed zircons indicating episodes of igneous activity. BG-04 and BG-05 could also have been plotted igneous zircon. Bars in gray indicated episodes of igneous activity based on Polvé et al. (2007).

Zircons in sample BG-11 of the Baguio Formation have a peak age of about 10 Ma, the YC1σ age is 9.6 ± 0.5 Ma. This agrees well with the Late Miocene to Early Pliocene age assigned to this formation, but is distinctly older than the 3.7 K-Ar age obtained by Maleterre (1989) for an andesitic breccia. This could suggest that BG-11 comes from the bottom of the sequence, whereas Maleterre's sample comes from the top. Besides young zircons that have a bearing on the sedimentation age, the sample also contains a number of zircons dated at 18–23 Ma, that is, the older plutons were eroded at the time of the deposition of the Baguio Formation.

7.2 | Significance of the New Age Data for the Intrusive Units

Samples BG-09 and BG-10 come from the western margin of the CCDC (Figure 2), BG-09 from the Antamok Diorite and BG-10 from the Itogon Quartz Diorite (Shannon 1979). In the map of Yumul et al. (2008) both sampling sites are part of the CCGC but samples are clearly quartz diorites. Zircon ages for BG-09 range from 10.7 ± 0.7 to 19 ± 1 Ma. Excluding the two youngest and the two oldest grains, an average of 15.5 ± 0.5 Ma (MSWD = 1.4) is calculated. This age is identical to the lower intercept age (15.6 ± 0.4 Ma) reported by Liu et al. (2020) for a sample collected slightly east of our sampling site. The presence of two zircons that yielded younger ages of 10.7 and 12.4 Ma may be related to zero-age lead loss as both grains plot on the concordia.

For BG-10, an average of 16.0 ± 0.3 Ma (MSWD = 1.0) is obtained excluding the oldest grains (inclusion of these grains would increase the age only to 16.2 ± 0.4 Ma but would increase the MSWD to 1.7). This age agrees well with a K-Ar age of 15.3 ± 0.8 Ma obtained for the Antamok Diorite from a locality about 1 km west of our sampling site (Polvé et al. 2007). Together with the previously published age data (Bellon and Yumul 2000; Polvé et al. 2007; Liu et al. 2020), the new data indicates that at ca. 15 Ma significant parts of the CCGC of Yumul et al. (2008) were emplaced. More work on this question is required, however, as on the maps of Florendo (1994) and Encarnacion (2004) our sampling sites and the site, for which Encarnacion, Mukasa, and Obille (1993) report an U–Pb age of 26.8 ± 0.4 Ma are part of the same intrusive complex (high-level gabbro and isotropic gabbro, respectively).

BG-14 is a granodiorite that crops out along the Kennon Road. On the map of Pena (1998) the outcrop is not shown but the granodiorite occurrence is considered to be intrusive into the Pugo Formation. On the map of Yumul et al. (2008), the whole area is mapped as part of the CCDC (Figure 2B), whereas on the map of Waters et al. (2011) the sampling site is thought to be underlain by the Mafic Dyke Complex. The 20.3 ± 0.3 Ma age obtained suggests that the granodiorite is a part of the older CCDC. For a gabbro collected southwest of our sampling site, Polvé et al. (2007) report a K-Ar age of 13.7 ± 0.5 Ma and for a second gabbro sample collected south of our sampling site a K-Ar age of 10.8 ± 0.6 Ma. If all these samples were taken

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from the same pluton, this would suggest that the samples analyzed by Polvé et al. (2007) suffered argon loss during later magmatic and hydrothermal activity.

In conjunction with published zircon ages of 32.5 ± 0.7 Ma (Nakajima et al. 2023), 26.8 ± 0.4 Ma (Encarnacion, Mukasa, and Obille 1993), and 15.6 ± 0.4 Ma (Liu et al. 2020), our data suggests that the Central Cordillera Batholith was emplaced over a considerable time span. The oldest units appear to be exposed in the northeastern part of the Bagio area. Antomok and Itogon diorite and quartz-diorite formed at the same time (15–16 Ma) and may be one batholith.

BG-7 comes from the Black Mountain Complex and yielded an age of 3.2 ± 0.1 Ma. This is slightly older than the previously reported K-Ar and $^{40}Ar/^{39}Ar$ ages of 1.7 ± 0.2 Ma for a sample collected north of our sampling site (Polvé et al. 2007) and of 2.81–2.98 Ma (Waters et al. 2011) for samples collected in the mine site, respectively, but lies within the error of the pre-mineralization sample of Waters et al. (2011) (2.98 ± 0.30 Ma).

The age of 1.21 ± 0.11 Ma obtained for sample BG-15 from the Santo Tomas II (Philex) Mine agrees well the ^{40}Ar-^{39}Ar ages of 1.48 ± 0.05 Ma and 1.47 ± 0.05 Ma reported by Waters et al. (2011).

Based on available age determinations, the magmatic activity of the Baguio area was considered to have occurred in several pulses. Polvé et al. (2007), for example, suggested that magmatic gaps occurred between 15.3 and 18.7 Ma and between 3 and 8 Ma, whereas magmatic activity was identified for the periods 21.2–18.7 Ma, 15.3–8 Ma, and 3–1 Ma.

The detrital zircon record shows a different picture (Figure 6). There is an abundance of detrital zircons for the period 15–22 Ma plus a few older zircons (22–28 Ma). The oldest grains confirm the presence of lithologies older than 20 Ma identified by the U–Pb age reported by Encarnacion et al. (1993) for the CCDC northeast of our study area. Zircons in the range 17–19 Ma appear to be less abundant and this period very roughly corresponds to the earlier period of magmatic quiescence suggested by Polvé et al. (2007), but overall, the period apparently was not devoid of magmatic activity. The period 9–14 Ma, a period of major activity according to previous studies, in our study is represented only in the detrital record and here essentially only in our sample of the Baguio Formation plus one grain each in a sample of the Zigzag Formation and the recent Bued River sediment.

7.3 | Evidence for an Ophiolitic or Continental Basement?

It is commonly assumed that the Central Cordillera of North Luzon is underlain by ophiolites. Whether parts of these are exposed or not has been a matter of significant controversy. The oldest unit recognized in the Baguio area is the Pugo Formation, the age of which is commonly given as Cretaceous to Eocene (e.g., Dimalanta et al. 2013; Pena et al. 2009). UNDP (1987) and Mitchell and coworkers (e.g., Mitchell and Balce 1990; Mitchell and Leach 1991) reinterpreted parts of the Pugo Formation and parts of the Agno Batholith as parts of the pre-Eocene ophiolitic basement of the Central Cordillera. However, Encarnacion, Mukasa, and Obille (1993) have shown that the Itogon Quartz-Diorite, thought to be a part of the ophiolite, has an U–Pb zircon age of 26.8 ± 0.4 Ma and thus cannot be part of a pre-Eocene ophiolite. Encarnacion (2004) in a subsequent paper accepted however the interpretation of the units in question as ophiolite and, based on Florendo (1994), considered the ophiolite as product of intra-arc rifting. Fragments of the assumed ophiolitic basement have been found as xenoliths in a dike (Payot et al. 2007). For an amphibole concentrate, a K-Ar age of 115.6 ± 8.3 Ma was reported.

For our samples, we did not find any zircons older than late Oligocene (BG-03-17: 27.3 ± 1.6 Ma), essentially identical with the 26.8 ± 0.4 Ma conventional U–Pb zircon age reported by Encarnacion, Mukasa, and Obille (1993). No detrital zircons match the age of 32.5 ± 0.7 Ma reported by Nakajima et al. (2023). In contrast, Tsai et al. (2019), who studied detrital zircons in river sediments, reported the presence of detrital zircons of Eocene age in all rivers draining the Central Cordillera studied (Abulag, Chico, Abra, Magat, and Agno Rivers). In all rivers sediments, except the Magat River, the Eocene zircons have ages of 33–38 Ma, whereas in the Magat River the record extents to 47 Ma or maybe even to 55 Ma if some analyses with large analytical errors are considered. No pre-Eocene zircons were found.

The absence of pre-Eocene zircons in our samples, which comprise sediments of different age, and in recent river sediments that may contain zircons from all exposed lithologies including those of Tsai et al. (2019), implies that the Baguio District and probably the Central Cordillera is neither underlain by an older (continental) basement nor by older ophiolite complexes. The lack of older zircons likewise suggests that the Pugo Formation is of post-Cretaceous age.

7.4 | Magma Sources

A subset of the dated zircons was analyzed for their Hf isotopic composition. Such data provides information on the nature of the magma sources. As shown in Figure 7, all zircons have positive εHf(T) between 12 and 20 and thus fall into the field typical for magmas derived from the depleted mantle. Sr, Nd, and Pb isotopic compositions reported by Polvé et al. (2007) also plot close to the field of compositions typical for the depleted mantle (exemplified by mid-ocean ridge basalts, MORB). The younger samples contain more radiogenic Sr and Pb and less radiogenic Nd than older samples suggesting successive enrichment of the magma sources by components derived from old crustal material. This enrichment is not seen in the Hf isotopic compositions, suggesting that for the operating enrichment mechanism (fluids/melts) Hf is an immobile element. It thus appears that the magmas erupted in the Baguio area are derived from time-integrated depleted sources with only small additions of subducted crustal components suggesting that Luzon formed within an intra-oceanic environment devoid of older crust. Similar ranges of εHf(T) as the

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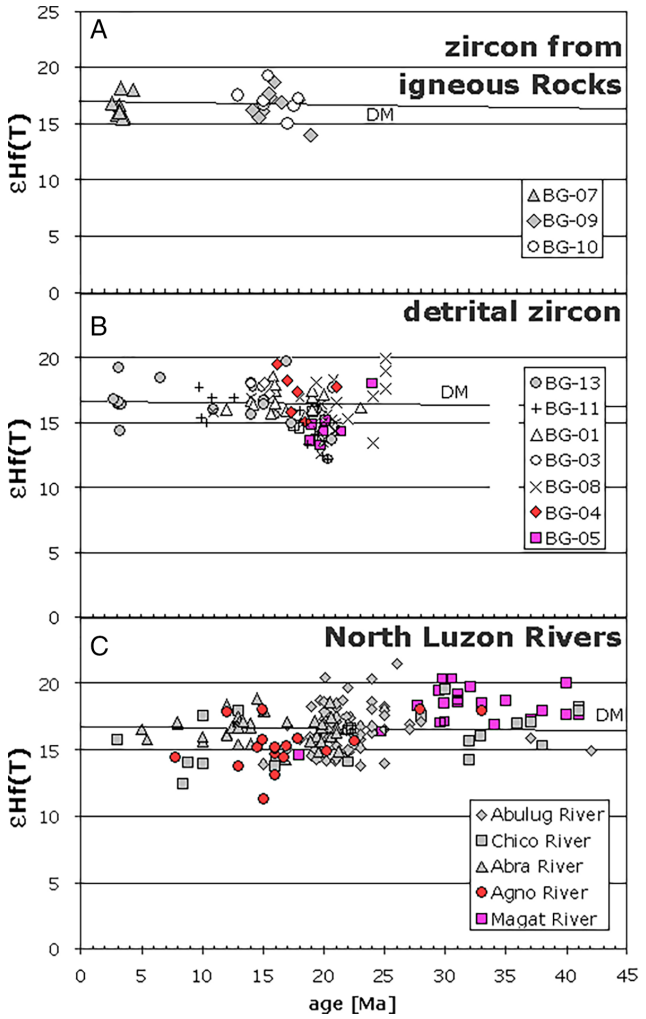

FIGURE 7 | eHf(T) vs. age for zircons from igneous (A) and sedimentary (B) rocks from the Baguio area; data for zircon from rivers in northern Luzon (C) comes from Tsai et al. (2019). Note that BG-04 and BG-05 could also have been plotted in the diagram for igneous rocks (see text) and that the Agno River and the Magat River (colour symbols) drain parts of the Baguio area.

zircons found in this study were reported by Tsai et al. (2019) for detrital zircon from recent river sediments derived from the Central Cordillera (Agno River, Magat River; Figure 7C) and by Lai et al. (2018) for zircon in Miocene to subrecent volcanics of the Coastal range of Taiwan. This suggests that the PMB is a site of new continental crust formation that incorporates minor continental crust derived components only since the collision with the PCT and the subduction of the South China Sea crust.

8 | Conclusions

Dating single zircon from intrusive rocks and detrital zircon from sediments and from a river draining the study area reveals several periods of igneous activity in the Baguio Mineral District at ca. 1, 3, 16, and 20 Ma. This roughly agrees with previous results based on K-Ar data.

Acknowledgments

We acknowledge the help for the Hf isotope analyses of Hao-Yang Lee. We thank Jon Encarnacion and two anonymous reviewers for comments that substantially improved the manuscript. We also thank Mike Ausejo and Americus Perez for help in retrieving literature that is difficult to access.

Conflicts of Interest

The authors declare no conflicts of interest.

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