Geochemistry of the Late Cretaceous Pandan Formation in Cebu Island, Central Philippines: Sediment contributions from the Australian plate margin during the Mesozoic

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Abstract
The Late Cretaceous Pandan Formation in Cebu Island is one of the oldest sedimentary units in the Central Philippines. The inconsistencies in geological descriptions and interpretation of the depositional environment of the Pandan Formation complicated efforts to determine the origin and tectonic history of the basement of Cebu Island. This study therefore looks into the petrological and geochemical characteristics of the Pandan Formation and their implications for the tectonic development of the Philippine Arc during the late Mesozoic. Petrographic analyses indicate significant contribution from mafic sources with additional inputs from felsic rocks, siliciclastics and metamorphic sources. Enrichment of detrital quartz from felsic volcanic and plutonic rocks, as well as from siliciclastic and metamorphic sources, has shifted the SiO₂ composition of the Pandan clastics from a mafic to a more intermediate source. Whole-rock geochemical analyses revealed low SiO₂/Al₂O₃ = 4.21, low K₂O/Na₂O = 1.16, low Th/Sc = 0.13, low Th/U = 2.78, high La/Th = 4.51, significantly low REEs = ca 76.45 ppm and low LaN/YbN = 4.28. A slight negative chondrite-normalized Eu/Eu* (0.91) anomaly and significantly high PAAS-normalized positive Eu/Eu* (1.39) values are consistent with derivation from a young undissected magmatic arc terrane. Tectonic discrimination diagrams suggest formation in an oceanic island arc to active margin/collision zone modelled to be located at the oceanic leading edge of Australia. Rapid uplift and erosion of the magmatic arc and older allochthonous blocks gave way to the rapid deposition of the Pandan Formation in the Late Cretaceous at the subequatorial region.

KEYWORDS
Australian Plate margin, Mesozoic, provenance, whole-rock and trace element geochemistry
1 | INTRODUCTION

Sedimentary geochemistry techniques have proven their reliability in constraining sediment sources, tectonic setting, palaeoclimates and sedimentary processes in ancient terranes for palaeogeographic reconstructions (Bock et al., 1998; Hara et al., 2012; Dimalanta et al., 2017; Amendedjo et al., 2018). Provenance studies of sedimentary rocks can help decipher and determine the geodynamic evolution of the crust (Taylor and McLennan, 1981; Gromet et al., 1984; McLennan, 2001), juxtaposition of different tectonic terranes (Cutten et al., 2006; Gabo et al., 2009), tectonic setting of sedimentary basins (Bhatia, 1985; Bhatia and Crook, 1986; Roser and Korsch, 1986), emergence and unroofing histories of orogenic belts and island arcs (Roser et al., 2002), weathering processes and palaeoclimatic responses in the source region (Nesbitt and Young, 1986), and determine the geodynamic evolution of the crust (Taylor and McLennan, 1981; Gromet et al., 1984; McLennan, 2001), juxtaposition of different tectonic terranes (Cutten et al., 2006; Gabo et al., 2009), tectonic setting of sedimentary basins (Bhatia, 1985; Bhatia and Crook, 1986; Roser and Korsch, 1986), emergence and unroofing histories of orogenic belts and island arcs (Roser et al., 2002), weathering processes and palaeoclimatic responses in the source region (Nesbitt and Young, 1986; Nesbitt et al., 1996) and sediment sorting and recycling (Johnsson, 1993; McLennan et al., 1993) among others.

Provenance studies in the Philippines include those of Suzuki et al. (2000) and Suggate et al. (2013) in Palawan, Gabo et al. (2009) in Panay and Concepcion et al. (2012) in Mindoro (Figure 1). These studies were geared towards establishing the continental nature of the Palawan Microcontinental Block. Geochronological analysis of detrital zircons from the Lasala Formation (Mindoro Island) revealed bimodal U–Pb ages of 2.399 and 48 Ma, coincident with the Palaeoproterozoic and Yanshanian magmatism in mainland Asia. This led Dimalanta et al. (2017) to conclude that the Palawan Microcontinental Block contains Cathaysian tectonic slivers. Likewise, studies conducted within the Philippine Mobile Belt include those of Tam et al. (2005) and Dimalanta et al. (2013) in the Baguio Mineral District in northern Luzon. More recent works emphasized the Cenozoic unroofing histories of the Zambales Ophiolite Complex (Dimalanta et al., 2014) in west Luzon and the Samar Ophiolite in Samar Island (Pacle et al., 2016).

Given these provenance studies of Philippine sedimentary rocks and the valuable information they provide, this research looks into the petrological and geochemical characteristics of the Late Cretaceous Pandan Formation in Central Cebu. The complexity of Central Cebu’s geology, stratigraphy and age remain unresolved, particularly concerning the emplacement and post-emplacement history of the Mesozoic blocks underlying the island. In comparison to other stratigraphic units of the Philippine arc, the Pandan Formation is relatively old, providing crucial information on the early development of the Philippine arc.

1.1 | Regional Geology

The Philippine island arc system is composed of the Philippine Mobile Belt and the Palawan-Mindoro Continental Block (Gervasio, 1966; Holloway, 1982; Rangin et al., 1985; Yumul et al., 2008; Aurelio et al., 2013) (Figure 1). The Palawan-Mindoro Continental Block, which rifted and drifted from mainland Asia during the opening of the South China Sea, started to collide with the Philippine Mobile Belt in the Early Miocene (Hamilton, 1979; Holloway, 1982; Yumul et al., 2005; Aurelio et al., 2013). This collision event affected the geology and tectonic history of the islands in the Central Philippines (McCabe et al., 1982; Yumul et al., 2000). The collision is thought to have resulted in the counterclockwise rotation of the islands of Mindoro and Marinduque, as well as the clockwise rotation of Panay Island and the Western Visayan Block comprised of north-east Negros, Cebu, Bohol and north-west Masbate islands (McCabe et al., 1982).

The eastern portion of the Central Philippines is part of the Philippine Mobile Belt, a region of complex deformation consisting of amalgamated allochthonous blocks of volcanic rocks and their derived sediments, as well as ophiolite and ophiolite complexes and their metamorphosed equivalents (McCabe et al., 1982; Yumul et al., 2005; Dimalanta et al., 2006). This active region is bounded by oppositely dipping subduction zones where the bounding plates, namely the Philippine Sea Plate and Eurasian/Sunda Plate, are being consumed (Rangin et al., 1999; Yumul et al., 2003). Transecting Leyte Island in the Central Philippines is active splay of the north-west trending left-lateral strike-slip Philippine Fault System (Aurelio et al., 1997; Saturay and Tamayo, 2003).

Cebu Island is underlain by a Mesozoic basement consisting of ultramafic, metamorphic and volcanic rocks overlain by sedimentary rocks, as exposed in the northern and central parts of the island (Corby et al., 1951; Santos-Yñigo, 1951; Bureau of Energy Development (BED), 1986a; 1986b; Porth et al., 1989; Rangin et al., 1989; Diegor et al., 1996; Dimalanta et al., 2006; Figure 2A). These units are unconformably overlain by a sequence of Middle Eocene to Late Pleistocene siliciclastic and carbonate sedimentary units.

1.2 | Geology and Stratigraphy of Central Cebu

The oldest unit underlying the central portion of Cebu Island is the Tunlob Schist that is composed of chlorite orthoschists and micaceous parascists belonging to the albite-epidote- amphibolite facies of moderate grade regional metamorphism (Santos-Yñigo, 1951) (Figure 2A). Porth et al. (1989), however, described the Tunlob Schist as a sequence of highly tectonized metavolcanics, greenschists, amphibolite schists and siliceous metasediments. The Bureau of Mines and Geosciences (Bureau of Mines and Geosciences (BMG), 1981) assigned this unit a Jurassic age based on relative dating.

The Early Cretaceous Tuburan Limestone occurs as small, isolated ridge-top remnants in the highland areas of
Central Cebu (Santos-Yñigo, 1951). In several areas, this unit overlies either the Tunlob Schist or the Pandan Formation, while in other places, it is overlain by the Cansi Volcanics. Porth et al. (1989) described the limestone as a pelloidal micrite with fragments of pelecypod, algae, foraminifera and *Orbitolina* sp. The Bureau of Energy Development (BED, 1986a; 1986b) described the Tuburan Limestone exposed in north-western Cebu Island as a probable erosional remnant found in the Cansi Volcanics. Porth et al. (1989) also noted the presence of Tuburan Limestone clasts within outcrops of the Cansi Volcanics, prompting him to conclude an older age for the limestone unit.

The Cansi Volcanics contain interbeds of andesitic flows and breccias, conglomerates and greywackes. A recent study conducted by Deng et al. (2015) revealed that Cebu Island's volcanic rocks (diabases, basalts-basaltic andesites, pyroclastic rocks and porphyritic andesites) exposed in Kansi village in the Municipality of Asturias (Figure 2A) represent Early Cretaceous (ca 126–117 Ma) arc volcanism in the Central Philippines. This age of arc volcanism is much earlier than the intrusion of the Lutopan Diorite dated 105 Ma by Wolfe (1995) and 102–109 Ma by Deng et al. (2015).

The Pandan Formation was first described by Corby et al. (1951) for the exposures along the Pandan River in Naga Cebu. Comprising this formational unit are metamorphosed and highly deformed limestones, shales and conglomerates with occasional coal stringers. Santos-Yñigo (1951), on the other hand, renamed this unit as the Pandan Series due to its heterogeneous sediment character and the presence of interbedded lava flows. Porth et al.
(1989) reported that the Pandan Formation is composed of greenish grey, calcareous, partly siliceous siltstones and light grey, silty, Globotruncana-bearing limestones and assigned a middle to late Late Cretaceous age. A pelagic to partly turbiditic depositional environment is indicated due to the presence of parallel laminations observed in the Pandan Formation in Central Cebu (Porth et al., 1984 in BED, 1986a; 1986b).

Exposures of the Cansi Volcanics and the Pandan Formation are widespread in the central and northern parts of Cebu Island. Balce (1977) lumped the Pandan Formation with the Cansi Volcanics to form the Mananga Group due to difficulties in distinguishing the stratigraphic relationships of the Early Cretaceous Cansi Volcanics and the Late Cretaceous to Paleocene Pandan Formation in the field at many localities in Central Cebu. Balce (1977) assigned a Late Cretaceous to Paleocene age to the Pandan Formation, which he described as a sequence of Late Cretaceous, Globotruncana-bearing clastic rocks, limestones and volcanic rocks including a distinct upper unit of Palaeocene mudstones, sandstones and siltstones.

In this study, exposures of the Pandan Formation at two localities are considered. In its type locality in Barangay Pangdan, Naga City, the formation consists of interbedded and intercalated sequences of greenish sandstone-siltstone, sedimentary breccia-polymictic conglomerates, carbonaceous mudstones intercalated with calcareous sandstone-siltstone and rare occurrences of siliceous mudstone layers (Figure 3A,B). The sedimentary breccia-polymictic conglomerate unit is comprised of sub-angular to sub-rounded, boulder to granule-sized, chlorite–epidote altered volcanic rocks and metamorphosed sedimentary rocks (Figure 3C,D). The exposures in Camp 7, Minglanilla are comprised of interbedded sedimentary breccia-conglomerates overlain by blocks of thinly bedded, graded, alternating green sandstones and red siltstones and limestone boulders (Figure 3E,F).

Recent age dating confirmed the Late Cretaceous age of the formation based on the presence of Orbitoides sp. (late Santonian to Maastrichtian) in the sandstone, and the calcareous nanofossil assemblage comprised of Quadrum gartneri, Micula praemurus, Micula murus and Uniplanarius trifidus in the interbedded limestones in Naga, Cebu. The nanofossil assemblage indicates that the calcareous sandstones-siltstones are within the CC25c–CC26 zones, suggesting a late Maastrichtian age.

Dimalanta et al. (2006) reported that the basement of the Central Philippine islands consists of Early to Late Cretaceous dismembered ophiolitic fragments derived from a subduction-related oceanic basin generated in an intermediate to fast-spreading centre. However, exposures of these dismembered fragments of the oceanic lithosphere in Cebu Island are very limited. These fragments occur as tectonic slivers of serpentinitized peridotites within the Cansi Volcanics/Pandan Formation (Rangin et al., 1989). Diegor et al. (1996), however, considered the chlorite orthoschists and micaceous parascists of the Tunlob Schist to be the metamorphosed mafic cumulates of the ophiolite complex.

Intruding the Cansi Volcanics and Pandan Formation, and exposed at the Atlas-Mining District (Figure 2B), is the Lutopan Diorite which varies from hornblende diorite to quartz diorite. Wolfe (1995) first reported a radiometric age of 59.7 Ma for the Lutopan Diorite. Later radiometric age dating of samples from the Biga and Frank deposits within the Atlas-Mining District using K–Ar and Rb–Sr yielded a 108–101 Ma age (Walther et al., 1981). This radiometric age is close to the zircon U–Pb age of 109 ± 2 Ma obtained by Kernke (1992). Zhang et al. (2019) also reported an age of 108.5 ± 1.6 Ma for the Lutopan quartz diorite porphyry stock determined using zircon U–Pb dating.

The Mesozoic basement rocks in Central Cebu are unconformably overlain by Tertiary to Quaternary clastics and carbonate units (Figure 2B). The Late Oligocene Cebu Formation is composed of the Lower Coal Measures and the Upper Ilag Limestone Member. This unit is conformably overlain by the 500–1,200 m thick Late Oligocene to Early Miocene Malubog Formation, which is comprised of a sequence of interbedded mudstones, shales, limestones, sandstones and conglomerates. Conformable over the Malubog Formation is the Middle Miocene Uling Limestone (Mines and Geosciences Bureau (MGB), 2010). Biocalcarenite and biomicrite containing admixtures of coral head, red algae and benthic foraminifera characterize this unit. The Middle to Late Miocene Bulacao Andesite is composed of porphyritic and brecciated andesite. These older units are overlain by the Talavera Group which is comprised of the Toledo and Maingit Formations introduced by Huth (1963). The Middle Miocene Toledo Formation conformably overlies the Uling Limestone and is composed of interbedded shale, sandstone and conglomeratic limestone (MGB, 2010). The conglomeratic limestone at the base of the Toledo Formation marks the boundary with the Uling Limestone. These units grade into the late Middle to early Late Miocene Maingit Formation (Corby et al., 1951). The Maingit Formation is composed of interbedded limestone, conglomerate, sandstone, mudstone and shale (MGB, 2010). Unconformably capping the older formations is the Late Pliocene to Pleistocene Carcar Limestone (MGB, 2010). This coralline limestone formation is characterized by bedded to massive shallow marine limestone with abundant molluscs, corals, algae and benthic foraminifera.

FIGURE 2 (A) Geological map and stratigraphic column of the study area adopted from MGB (2010). Geological map modified from the Pardo Quadrangle map published by BMG (1983) superimposed on IFSAR DEM. (B) Red points refer to the location of Pandan Formation outcrops investigated by this study in the type locality in Pangdan, Naga City and at Camp 7, Minglanilla in South Central Cebu.
2 | MATERIALS AND METHODS

Seventeen thin sections of medium-grained sandstones and sedimentary breccia/conglomerate from the interbedded and intercalated turbiditic beds of the Pandan Formation were prepared. Samples were collected from the lower to upper sequences of the Pandan clastic rocks characterized by normal grading. The Gazzi-Dickinson method (Ingersoll et al., 1984) was employed in the point counting of 500 mineral grains constituting the samples.

A total of 28 samples covering all of the fine-grained sandstone-siltstone-mudstone sequences were subjected to whole-rock geochemical analyses. Crushing and grinding of the samples was done at the sample preparation laboratory of the Mines and Geosciences Region VII in Cebu. Further sample preparation necessary for the X-ray fluorescence analyses was done at the Economic Geology Laboratory of the Earth Resources Engineering in Kyushu University, Fukuoka, Japan. One gram of each sample was placed in a crucible and heated at 105°C for 1 hr to dry. The samples were then placed in an electric furnace at 1,000°C for 2 hr to determine the loss on ignition. A Rigaku 3100 X-ray fluorescence machine was utilized to determine bulk major and trace element compositions of the samples. Major and minor element oxides (SiO₂, TiO₂, Al₂O₃, MgO, FeO, MnO, CaO, Na₂O, K₂O and P₂O₅) were determined using pressed powdered samples. Samples yielding higher CaO were acid-treated and re-analysed to determine major and minor oxide contents.

For the inductively coupled plasma mass spectrometry (ICP-MS) analyses, trace and rare earth elements were analysed at the ALS Geochemistry Laboratory in Guangzhou, China. A two-day closed beaker digestion using mixtures of HF and HNO₃ acids in Teflon screw-cap bombs was employed. These acid-digested samples were analysed using an Elan DRC-II instrument (Element, Finnigan MAT) to determine concentrations of trace and rare earth elements in the samples including Sc, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pb, Th and U. To ensure accuracy and precision of the analytical determination, analyses of standard samples and replicates were conducted. Standards used for the ICP-MS analysis are GBM908-10 (Certified Geochem Base Metal Reference Material) of the Geostats Pty Ltd., OGGGeo08 (Ore grade multi-element CRM), MRGeo08 (Mid-range multi-element CRM) from ALS Minerals, Vancouver, BC, Canada, and the OREAS-45e, OREAS 120, OREAS-100a of the Ore Research and Exploration (OREAS), Bayswater North, Victoria, Australia. Accuracy is within 1% for major elements and the detection limits for the trace and rare earth elements range from 0.001 to 20 ppm.

3 | RESULTS

3.1 | Petrography

The Pandan sandstones are composed of well-sorted, sub-angular to sub-rounded coarse to medium-grained sand, grading to siltstones and mudstones. Feldspars (24%–82%) and lithic grains (17%–57%) are the most dominant constituents of these sandstones, whereas quartz has relatively low to moderate abundance (1%–21%; Table 1; Figure 4A though F). By means of the Gazzi-Dickinson point-counting method, the Pandan clastic rocks were classified as quartzo-litho-feldspathic, quartzo-feldspatho-lithic, litho-feldspathic and feldspatho-lithic sandstones (Figure 5A).

Sandstones in a mine quarry in Pangdan, Naga City contain significant amounts of monocrystalline quartz (undulose and non-undulose), polycrystalline quartz (undulose, granoblastic and strained), plagioclases and K-feldspars (orthoclase and microcline) (Figure 4A,B). Both sandstone and conglomerate samples in the quarry also contain fine-grained and porphyritic andesite and basalt fragments altered to epidote and chlorite, myrmekitic-textured granitic fragment, quartzose sandstones and lithic metamorphic rocks (epidote altered volcanic rock, mica-schist and quartz-muscovite schist) with a few clinopyroxene grains. The matrix surrounding the plagioclase and quartz grains in the Naga samples was mostly from volcanic sources that were altered to chlorite and epidote or quartz due to diagenesis. The sandstones from Camp 7 in Minglanilla are dominated by volcanic lithic fragments of porphyritic andesite and basalt, plagioclase, clinopyroxene and limestone fragments with a few to rare polycrystalline and monocrystalline quartz grains (Figure 4C,D).

Lithic metamorphic fragments were identified in the Pandan clastic rocks (Figure 4E,F). Samples from Minglanilla contain chlorite-altered volcanic rocks characterized by a greenish yellow to greenish blue colour typical of the Mg-rich and Fe-rich varieties of chlorite. Conversion of groundmass mafic minerals and lithic volcanic phenocrysts to chlorite–epidote suggests low-temperature metamorphism and low-grade metamorphism. In contrast, the Naga samples contain various types of metamorphic fragments including epidote-altered volcanic rocks, quartz-muscovite schist,
### Table 1
Modal composition of the Pandan Formation sandstones in percent abundance

| Sample  | Qm (%) | Qt (%) | F (%) | L (%) | Sandstone type                  |
|---------|--------|--------|-------|-------|---------------------------------|
| MRB28174 | 4.0    | 8.0    | 5.0   | 162.0 | Feldspatho-lithic sandstone     |
| MRB28175 | 1.0    | 5.0    | 8.0   | 260.0 | Litho-feldspathic sandstone     |
| MRB28178 | 4.0    | 2.0    | 4.0   | 341.0 | Litho-feldspathic sandstone     |
| NURB2817P2 | 10.0 | 11.0  | 19.0  | 270.0 | Litho-feldspathic sandstone     |
| NURB2817P3 | 14.0  | 94.0   | 12.0  | 181.0 | Litho-feldspathic sandstone     |
| NACK3017S1 | 57.0  | 69.0   | 74.0  | 203.0 | Quartzo-litho-feldspathic sandstone |
| NACK3017S2 | 19.0  | 30.0   | 67.0  | 191.0 | Litho-feldspathic sandstone     |
| NACK3017S3 | 26.0  | 83.0   | 199.0 | 32.0  | Quartzo-feldspatholithic sandstone |
| NACK3017S4 | 40.0  | 28.0   | 75.0  | 97.0  | Quartzo-feldspatholithic sandstone |
| NACK3017S6 | 40.0  | 26.0   | 58.0  | 128.0 | Quartzo-feldspatholithic sandstone |
| NACK3017S8 | 16.0  | 24.0   | 8.0   | 220.0 | Feldspatho-lithic sandstone     |
| NACK3017S9 | 19.0  | 34.0   | 112.0 | 114.0 | Quartzo-feldspatholithic sandstone |
| NACK3017S10 | 7.0   | 17.0   | 16.0  | 146.0 | Feldspatho-lithic sandstone     |

**Note:** Qt = Qm + Qp, F = K + Pl, L = Lv + Lp + Ls + Lm, Lt = L + Qp, sandstone type based on the classification by Garzanti (2015).

Abbreviations: HM = heavy minerals; Kf = potassium feldspar; Lv = lithic volcanic fragment; Lp = lithic plutonic fragment; Ls = lithic sedimentary fragment; Lm = lithic metamorphic fragment; Pl = plagioclase; Qm = monocrystalline quartz; Qp = polycrystalline quartz.
quartz-mica schist and muscovite schist (Figure 4E,F) derived from metamorphic rocks formed within moderate to deep crustal environments.

The matrix of sandstones from Minglanilla is mostly composed of silt-sized to clay-sized grains from volcanic sources. Comprising the matrix are silt-sized plagioclases, pyroxenes
and clay minerals. Diagenetic alteration is strongly evident wherein matrix materials were converted to chlorite and epidote, giving the sandstones a greenish to bluish green appearance in hand specimen. Minor calcite cement was observed binding the clasts and matrix materials.

3.2 | Geochemistry

Major trace and rare earth element compositions of 28 fine-grained sandstones and siltstones/mudstones of the Pandan Formation are given in Table S1.

The major oxide composition of Pandan clastic rocks exhibits highly variable volatile-free SiO\textsubscript{2} (54.28–65.6 wt%), TiO\textsubscript{2} (0.84–1.57 wt%), Na\textsubscript{2}O (1.00–3.97 wt%), K\textsubscript{2}O (0.98–4.02 wt%), CaO (1.5–5.1 wt%), MgO (3.3–5.1 wt%) and Fe\textsubscript{2}O\textsubscript{3} (6.0–12.1 wt%) also typify these clastic rocks. Four samples showing more than 10 wt% CaO were treated with 1 N HCl to remove excess CaCO\textsubscript{3}. The elevated CaO content is related to the presence of limestone rock fragments, which were observed during the petrographic analyses of the sandstone samples.

Pettijohn et al. (1972) introduced a discrimination diagram using log (Na\textsubscript{2}O/K\textsubscript{2}O) versus log (SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3}) in classifying terrigenous sandstones. Using this diagram, the Pandan samples plot in the greywacke to litharenite fields, suggesting immaturity (Figure 5B). Using the K\textsubscript{2}O versus Na\textsubscript{2}O bivariate diagram after Crook (1974), the Pandan sedimentary rocks reveal intermediate to high quartz enrichment (Figure 5C).

The clastic rocks of the Pandan Formation have average trace element values that are slightly enriched relative to those of the Upper Continental Crust (UCC—Taylor and McLennan, 1985; revised values in McLennan, 2001) and the Post-Archean Average Shale (PAAS—Taylor and McLennan, 1985) such as Sc (17.4–28.2 ppm), V (162–262 ppm) and Cr (20–240 ppm) (Figure 6A,B). These elements, together with Co and Ni, indicate the comparative abundance of ferromagnesian minerals associated with mafic and ultramafic rocks. However, Co (14.5–31.4 ppm) and Ni (14.8–95.1 ppm) in these samples have lower concentrations that are similar to the average values exhibited by the UCC (<30 ppm Co, <100 ppm Ni) implying less contribution from ultramafic sources while having minimal input from continent-derived sediments. Similarly, other trace elements such as Th (0.98–4.02 ppm), La (8.4–27.1 ppm), Zr (100–172 ppm), Hf (2.4–4.6 ppm) and Rb (18.0–83.5 ppm) also show less enrichment compared to upper crustal compositions, reflecting less significant amounts of felsic sediments in the samples. Compared to the UCC, values of the Pandan Formation samples are depleted in incompatible elements like the large ion lithophile (LILE) and high field strength elements (HFSE; Figure 6A). In contrast, the more compatible elements represented by the transition trace elements have slightly higher values suggesting significant amounts of mafic sediments.

The total rare earth element (\textsf{REE}) abundance of the Pandan Formation samples ranges from 58.76 to 112.28 ppm with an average of ca 76.45 ppm, which is significantly lower than that of the PAAS (211.77 ppm). The Pandan clastics registered total light rare earth elements (\textsf{ΣLREE}) of 63.03 ppm and total heavy rare earth elements (\textsf{ΣHREE}) of 13.41 ppm, implying a mafic source as the major sediment contributor. Distinctly shown in the PAAS-normalized spidergram is a depletion of LREE and a flat HREE pattern with a pronounced positive Eu anomaly (Eu/Eu* = 1.39) (Figure 6B). The PAAS-normalized La\textsubscript{N}/Yb\textsubscript{N} = 4.23 suggests slightly fractionated \textsf{REE} values similar to those of the shales and sandstones from the Baguio Mineral District (Tam et al., 2005). These values are consistent with material derived from a less fractionated source typical of mafic rocks.

4 | DISCUSSION

4.1 | Provenance

The dominance of volcanic detritus, zoned plagioclases and pyroxenes in the Pandan clastic rocks implies derivation from a mafic arc source (Dickinson and Suczek, 1979; Marsaglia and Ingersoll, 1992). Likewise, undulose monocrystalline, polycrystalline quartz and quartzose sandstone clasts noted in the medium-grained to coarse-grained sandstones indicate contributions from felsic, metamorphic and siliciclastic sources. The Pandan Formation sandstones containing strained quartz, epidotized and chloritized volcanic rocks and schist fragments suggest subsequent uplift and erosion of a metamorphic basement. The presence of these felsic and metamorphic minerals may have enriched the SiO\textsubscript{2} and K\textsubscript{2}O content of the Pandan Formation samples.

The SiO\textsubscript{2} and K\textsubscript{2}O content of sedimentary rocks proved to be good indicators of sediment maturity. The SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} composition of sedimentary rocks reveals maturity which reflects the abundance of quartz, clay and feldspar minerals (Potter, 1978). Likewise, the Na\textsubscript{2}O + K\textsubscript{2}O concentrations reflect the alkali content of sedimentary rocks related to feldspars in the samples. These ratios could detect contributions from felsic-derived sediments (SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} range of 4.19–6.07) against mafic rock sources (SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} range of 2.91–4.13) (Cullers et al., 1988). The SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} ratio of the Pandan Formation clastic rocks is 3.47–5.24 and the average K\textsubscript{2}O/Na\textsubscript{2}O ratio is ca 1.39, which is intermediate between mafic and felsic source values, indicating derivation from both sources.

The Pandan sedimentary rocks exhibit significantly high K\textsubscript{2}O, TiO\textsubscript{2} and Fe\textsubscript{2}O\textsubscript{3} concentrations. Positive correlation
between Al\textsubscript{2}O\textsubscript{3} with K\textsubscript{2}O ($r = 0.55$), Fe\textsubscript{2}O\textsubscript{3} ($r = 0.52$) and TiO\textsubscript{2} ($r = 0.42$) suggests association of K, Ti, Fe and Al with detrital phases (Amedjoe et al., 2018). The good correlation between Al\textsubscript{2}O\textsubscript{3} and K\textsubscript{2}O can be attributed to illite, muscovite and feldspar minerals. Peinerud (2000) and Nagarajan et al. (2007) considered that Al concentrations in sediments are good measures of detrital influx. Similarly, the Al\textsubscript{2}O\textsubscript{3}/TiO\textsubscript{2} ratio can gauge the composition of the original source material (Concepcion et al., 2012). Accordingly, the Al\textsubscript{2}O\textsubscript{3} ratios for igneous rocks range from 3 to 8 for mafic rocks, 8–21 for intermediate rocks, and 21–70 for felsic rocks. Samples from the Pandan Formation registered an Al\textsubscript{2}O\textsubscript{3}/TiO\textsubscript{2} of 9.18–17.04, reflecting an intermediate source rock composition. However, negative correlation between Al\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2} ($r = -0.66$) indicates detrital influence of quartz on the overall composition of Pandan samples (Amedjoe et al., 2018).

Illustrated in the discriminant function diagram introduced by Roser and Korsch (1988) is the clustering of the Pandan Formation samples within the mafic igneous field (Figure 7A). A few samples also plot within the quartzose sedimentary provenance. A comparison using the major oxide composition of samples from the Baguio Mineral District (Zigzag, Klondyke, Amlang and Cataguintingan Formations) (Tam et al., 2005; Dimalanta et al., 2013) showed that most samples from the Baguio Mineral District consistently plot in the mafic to intermediate igneous provenance. They display similarities with the Pandan Formation which also indicate influence from a magmatic arc source. However, quartz derived from felsic igneous, sedimentary and metamorphic sources identified in thin sections shifted the overall SiO\textsubscript{2} composition of the Pandan clastic rocks compared to those from Baguio.

The TiO\textsubscript{2}, MgO and Fe\textsubscript{2}O\textsubscript{3} contents of the Pandan Formation samples are also significantly abundant. Generally, the abundance of TiO\textsubscript{2} and MgO + Fe\textsubscript{2}O\textsubscript{3} in sedimentary rocks is attributed to a high influx of volcanic detritus (Bhatia, 1983). These concentrations correlate well with the mafic minerals identified in the petrographic analysis.

Trace elements also proved to be valuable indicators of the original composition of the materials supplying detritus to a sedimentary basin. The immobile elements La and Th are correlated with felsic rocks while Sc and Co are associated with mafic sources (Cullers et al., 1988). A significant
increase in the Th/Sc ratio occurs as the source rock composition evolves from a mafic to felsic source (McLennan et al., 1993). Trace element ratios for the Pandan samples show very low La/Sc = 0.57 and low Th/Sc = 0.13 attributable to derivation from mafic source rock compositions (Cullers et al., 1988; Cullers, 1994; 2000; Cullers and Podkovyrov, 2000).

Floyd and Leveridge (1987) introduced a diagram employing the use of La/Th versus Hf in differentiating various arc sources (Figure 7B). Felsic magmatic arcs exhibit low or uniform La/Th values (<5) and Hf values ranging from 3 to 7 ppm. Pandan samples exhibit La/Th ratios of 2.55–11.43 (av = 4.46) and Hf values of 2.4–4.6 ppm, indicating inputs from felsic volcanic sources. Illustrated in the La/Th versus Hf diagram is the dominant clustering of the Pandan samples in the acidic arc field compared to samples from the Baguio Mineral District, which mostly plot in the andesitic arc source. Some Pandan Formation samples also plot in the andesitic arc source consistent with the porphyritic andesite fragments noted in the thin sections.

Overall, the Pandan Formation clastic rocks are dominantly composed of volcanic-derived sediments with contributions from felsic, older sedimentary and metamorphic rock sources. This has been reflected in the bulk geochemical composition of the Pandan Formation clastic rocks indicating intermediate compositions. Addition of quartz from felsic, siliciclastic and metamorphic sources has shifted the originally mafic composition of the Pandan Formation to more intermediate compositions. Trace and rare earth elements, which are known to be conservative indicators of sediment source, also suggested mafic source rock compositions with inputs from felsic volcanic sources beside the main mafic volcanic source.
4.2 | Weathering in the source

The Chemical Index of Alteration, CIA = 100 × [Al₂O₃/(Al₂O₃ + CaO* + Na₂O + K₂O)] (CaO* refers to CaO in silicate minerals) accounts for the mobility of cations such as K⁺, Ca²⁺ and Na⁺, as well as the less mobile cation Al³⁺ (Nesbitt and Young, 1984; Nesbitt et al., 1996). Meanwhile, the Plagioclase Index of Alteration (PIA) is another good measure to calculate the degree of chemical weathering because feldspars exhumed in the UCC alter immediately to form clay minerals, thus increasing the Al₂O₃ concentrations in the sediments (Fedo et al., 1995). Using molecular proportions, the PIA values of sedimentary rocks can be evaluated by this formula:

\[
\text{PIA} = \left[\frac{(\text{Al}_2\text{O}_3 - \text{K}_2\text{O})}{(\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} - \text{K}_2\text{O})}\right] \times 100
\]

The fine-grained sandstone and siltstone-mudstone units of the Pandan Formation are characterized by low to moderately high CIA (50.7–68.0) and PIA values (50.1–72.7). These values suggest weak to moderate weathering in the source area due to probable arid environmental conditions as depicted in the SiO₂ and Al₂O₃ + CaO + Na₂O + K₂O diagram of Suttner and Dutta (1986; Figure 7C). Arid conditions tend to preserve unstable grains due to the reduced effect or absence of chemical weathering. Chemical weathering in tropical climates destroys mafic minerals, plagioclase feldspars and lithic fragments unstable at the low temperature and pressure conditions typical of the surficial environment. The abundance of plagioclase grains in the Pandan sandstones is consistent with the CIA and PIA values.

4.3 | Hydraulic sorting and sediment recycling

Sediment sorting is achieved when minerals are separated during transport according to their stability, shape, size and density. With the increasing textural and compositional maturity of sandstones, quartz grains will become more dominant, feldspars will be susceptible to weathering and there will be a significant decrease in the abundance of clay minerals. Sorting of sediments could also result in the enrichment of certain resistant minerals (e.g. zircon, monazite, magnetite, rutile, etc.).

One indicator of compositional maturity and source rock composition of sediments is the SiO₂/Al₂O₃ ratio. Generally, the average SiO₂/Al₂O₃ ratio for basaltic rocks is 3 and for acidic igneous rocks is 5 (Roser et al., 1996). A higher SiO₂ content indicates enrichment of quartz in the Pandan clastic rocks. The SiO₂/Al₂O₃ ratio of 3.47–5.24 displayed by the Pandan Formation samples indicates weathering of a source rock with an intermediate to acidic composition.

Weaver (1989) suggests that compositional maturity mudrocks have a lower index of compositional variability (ICV) characteristic of cratonic and tectonically inactive settings, Meanwhile, high ICV values are typical of the compositionally immature mudrocks of the first cycle of sediments deposited in active continental margins (ACMs; van de Kamp and Leake, 1995). The Pandan clastic rocks exhibit ICV values ranging from 1.75 to 2.27, denoting a compositionally immature sediment source deposited in an active margin setting. Petrographic analysis determined the abundance of first cycle volcanic-derived sediments, comprising basalt and andesite fragments, as well as plagioclase and augite grains.

The Th and Zr concentrations are also reliable indicators of sediment maturity and recycling (McLennan et al., 1993). These trace elements are abundant in heavy mineral fractions from more evolved and highly fractionated source rocks. The Th/Sc = 0.13, Zr/Sc = 5.73 and Th/U = 2.78 exhibited by the Pandan Formation samples are typical of first cycle mafic source rocks (Figure 7D). Based on these values, a minimal contribution of monazite and a slightly higher contribution from zircon are inferred.

According to Bhatia and Taylor (1981), highly recycled mudrocks are characterized by high Th/U ratios of around 6. Oxidation of U⁴⁺ to U⁶⁺ decreases the U concentration of sediments owing to the formation of a soluble phase (UO₂)²⁻, resulting in an increased Th content, particularly in the highly recycled sedimentary rocks. The low Th/U ratio shown by the Pandan Formation clastic rocks is consistent with sediments derived from volcanic sources. However, addition of zircons from older metamorphic, plutonic and sedimentary rock sources is possible, which is also confirmed by petrographic analyses.

4.4 | Tectonic setting

Bhatia (1983) defined four tectonic settings on the basis of major oxide composition: oceanic island arc, continental island arc, active margin and passive margin (PM) settings. There is a marked decrease in Fe₂O₃ + MgO, TiO₂, Al₂O₃/SiO₂ and increase in K₂O/Na₂O and Al₂O₃/(CaO + Na₂O) as the tectonic setting changes from oceanic island arc to continental island arc to active continental to the PMs. The volatile-free major oxide composition of the Pandan clastics is characterized by very high Fe₂O₃ + MgO (11–20.8 wt%), TiO₂ (0.87–1.67 wt%) and Al₂O₃/SiO₂ (0.19–0.29), sharing similar characteristics with oceanic island arc-derived sediments. However, large variations in K₂O/Na₂O (0.86–2.36) and Al₂O₃/(CaO + Na₂O) (1.92–5.5) values have more in common with ACMs.

Using the major oxide ratios of K₂O/Na₂O versus SiO₂/Al₂O₃ of sand and mud from different tectonic settings, Maynard et al. (1982) discriminated sediments deposited in arcs, evolved arcs, ACMs and PM tectonic settings. Likewise, Roser and Korsch (1986) identified three broad categories of tectonic setting based on SiO₂ and K₂O/Na₂O ratios: PM, ACM and oceanic island arc (ARC).
In the tectonic discrimination diagram of Maynard et al. (1982), the Pandan samples plot consistently within the evolved arc to ACM fields (Figure 8A). A comparison was made using samples from the Baguio Mineral District (Tam et al., 2005; Dimalanta et al., 2013), which are characterized by oceanic island arc and ACM depositional settings. Similar trends were observed in the Roser and Korsch (1986) diagram except for a few Pandan samples that plot within the oceanic island arc field (Figure 8B). The Zigzag Formation samples from the Baguio Mineral District registered an ACM setting and are interpreted to be sourced from the Cordon Syenite Complex and the Palali Formation in the Caraballo Mountain Range (Dimalanta et al., 2013). Furthermore, younger successions such as the Klondyke, Amlang and Cataguintingan Formations were influenced by mafic source rocks derived from the erosion of the Pugo Metavolcanics formed in an oceanic island arc setting. Compared to the Baguio Mineral District, the Pandan clastic rocks show relatively higher concentrations of SiO₂ and K₂O, thus plotting in the ACM field. This indicates a significant contribution from continental sources brought by tectonic collision. Alternatively, it could also be attributed to a subduction system in a continental margin setting causing eventual uplift and erosion of the magmatic arc or an orogenic belt.

Verma and Armstrong-Altrin (2013) distinguished sediments deposited in arcs, continental rifts and collision zone tectonic settings based on the log-ratio transformation of major elements. Applying their equations both in the high-silica and low-silica diagrams, the Pandan Formation samples cluster in the collision zone tectonic setting, although a few samples also revealed an arc tectonic setting (Figure 9A,B).

The tectonic discrimination diagrams using the major oxide composition of the Pandan Formation consistently suggest an ACM/collision zone tectonic setting. The ACM setting described by Roser and Korsch (1986) refers to subduction-related basins formed in continental arcs, continental collision basins or in pull-apart basins associated with strike-slip faults.

Bhatia and Crook (1986) established that La, Th, Zr, Nb, Y, Sc, Co and Ti are the most beneficial trace elements in discriminating greywackes from different tectonic settings. In their trivariate diagrams, the Pandan clastic samples cluster in the oceanic island arc field (Figure 10A,C). Dominance of detritus from magmatic arcs, particularly mafic rocks, influences the trace element abundance that leans towards Sc and Co enrichments.

A distinguishing geochemical property of rare earth elements (REE) relates to their conservative chemistry and their distinct responses to environmental changes through enrichment variations. These marked changes are exhibited as either enrichment or depletion of one REE subgroup or an individual REE.

Oceanic island arc-derived sediments are characterized by a low abundance of REE, low La₉/Yb₉ ratio and a smooth chondrite-normalized pattern with no Eu anomaly (mean Eu/Eu* = 1) (Bhatia, 1985). On the other hand, tholeiitic island arc (TIA) volcanics may exhibit lower REE concentrations, particularly the LREEs. Thus, the TIA is characterized by highly depleted LREE and a positive Eu anomaly on PAAS-normalized plots. Continental island arcs can be distinguished from island arcs by higher LREE and La₉/Yb₉ and a slight negative Eu anomaly. In the chondrite-normalized pattern, samples from the Pandan Formation show a low abundance of REEs (ca 76.45 ppm) and low La₉/Yb₉ = 4.28 and Eu/Eu* = 0.91 ratios (Figure 7B). The PAAS-normalized values of the Pandan samples exhibit significant depletion of LREE, La₉/Yb₉ = 0.47 and a positive Eu/Eu* = 1.39 anomaly. Trace and rare earth element abundances imprinted in the Pandan clastic rocks clearly suggest an oceanic island arc setting inconsistent with the ACM setting exhibited by its major oxide compositions.
In the Eu/Eu* versus La*/YbN diagram after McLennan et al. (1993), the Pandan Formation samples generally plot in the fore-arc region while some samples plot within the trailing edge tectonic setting (Figure 10D). The trailing edge or rifted margin tectonic settings are characterized by quartz-rich sedimentary rocks deposited on a passive, intraplate continental margin facing a spreading centre (Maynard et al., 1982). Thus, the results imply that the Pandan clastic rocks received siliciclastic input from a PM setting consistent with the quartzose sedimentary source depicted in Figure 7A.

These results suggest that the Pandan Formation was formed in the fore-arc basin of a young, undissected magmatic arc with contributions from continental and oceanic crust detritus due to juxtaposition of blocks brought together by tectonic collision. This young, undifferentiated arc corresponds to the Early Cretaceous Cansi Volcanics supplying the bulk of the detritus forming the Pandan Formation in the Late Cretaceous.

4.5 | Tectonic implications

Southeast Asia was formed through the accretion of continental terranes derived from the northern portions of Gondwanaland which drifted during the Palaeozoic and Mesozoic towards the central and northern parts of Asia (Metcalfe, 1996). In the Jurassic to Early Cretaceous, a back-arc basin was created at the northern margin of Australia behind an advancing continental volcanic arc moving towards the north (Monnier et al., 2000). Spreading and rifting led to the fragmentation of the last remaining portions of Gondwanaland (Parker and Gealey, 1985). These tectonic events may be related to the Late Mesozoic Circum-South East Asia Subduction–Accretion Zone formed by the subduction of Mesotethys in the south, and the palaeo-Pacific plate to the east during the Late Jurassic to Early Cretaceous period (Zhou et al., 2018).

Pubellier et al. (2003) postulated that at least two marginal basins were created at the northern margin of Australia.
during the Mesozoic and Cenozoic. Consequently, the Mesozoic basin corresponds to the obducted back-arc basin fragment (New Guinea Ophiolite) now amalgamated and accreted to the Triassic and Jurassic volcanics found in New Guinea, Central Range, Irian Jaya to eastern Papua (Davies, 1971). The Mesozoic basin postulated by Pubellier et al. (2003) could be the proto-Philippine Sea plate, described by Zahirovic et al. (2014) as a back-arc basin formed through the slab roll back of the palaeo-Pacific plate which opened between 155 and 115 Ma. Dimalanta et al. (2019) suggested that the proto-Philippine Sea Plate could have been part of a larger Mesozoic oceanic basin associated with the Mesotethys and the palaeo-Pacific plate that subducted towards the Eurasian-Sundaland continent. Obducted sections of oceanic crusts generated from the proto-Philippine Sea plate could be observed at the central and eastern parts of the Philippine Archipelago (Balmater et al., 2015; Guotana, et al., 2017; Dimalanta et al., 2019).

Recent tectonic reconstructions made by Wu et al. (2016) revealed the existence of oceanic slabs at the lower mantle. These ca 8,000 km × 2,500 km slabs are interpreted to represent the now-vanished East Asian Sea. In tectonic models, these oceanic basins can fill the gap between the Pacific and Indian Oceans at 52 Ma which finally disappeared by 15 Ma due to the convergence of the Pacific, Philippine Sea and Australian plates. The reconstructed East Asian Sea slabs are composed of the East Asian Sea to the north, south and west. The northern East Asian Sea coined by these authors could also refer to the ‘proto-Philippine Sea’ plate. However, in this study, the proto-Philippine Sea plate was located at lower latitudes, specifically a few degrees north of the equator down to 15°S based on recent palaeomagnetic and geochemical
data (Balmater et al., 2015; Guotana, et al., 2017; Dimalanta et al., 2019). The Cenozoic basin of Pubellier et al. (2003) corresponds to the Philippine Sea Plate which developed at the northern margin of Australia (Pubellier et al., 2003).

Zahirovic et al. (2014) suggested that fragments of the proto-Philippine Archipelago (proto-Philippine Arc) were derived from the northeastern margin of Gondwana. These fragments were emplaced during the northward translation of eastern Borneo, Mangkalihat, West Sulawesi and East Java. Likewise, Maruyama et al. (1989) believed that during the Late Cretaceous, the Philippine island arc was located either in the southern Pacific or at the boundary between the Pacific and North New Guinea plates. Other workers (Deschamps and Lallemand, 2002; Queño et al., 2007; Zahirovic et al., 2014; Balmater et al., 2015) also suggest that the Philippine islands were formed at the edge of the proto-Philippine Sea Plate.

The termination of the back-arc spreading of the proto-Philippine Sea Plate at 115 Ma was due to the collision of continental fragments from Sulawesi with an intra-oceanic subduction zone (Zahirovic et al., 2014). This intra-oceanic subduction system corresponds to the recognized Early Cretaceous volcanic flow deposits in Cebu Island (Deng et al., 2015). This event is herein construed as the onset of the collision of the proto-Philippine arc with the East Philippine-Daito arc leading to the Late Mesozoic growth of the Philippine Mobile Belt. The study of Zhang et al. (2019) in the Lutopan quartz diorite porphyry stock in Cebu Island also implied arc development at the leading edge of Australia in the Early Cretaceous. Geochemical data from this porphyry stock suggest partial melting of a young, lower continental crust or interaction between the asthenospheric melts and lower crust melts. Zahirovic et al. (2014) also interpreted the existence of a subduction polarity reversal from a west-dipping to a northeast-dipping subduction system which took place by 85 Ma (Figure 11). This resulted in the subduction of the proto-Molucca and proto-Philippine Sea plates and the transfer of the newly formed fragments of Luzon, eastern Philippine Archipelago and Halmahera onto the Pacific Plate. The northeast-dipping subduction resulted in the formation of the Daito Ridge and Amami Plateau crust, progressing to back-arc opening to produce the crust older than anomaly 24 (53 Ma) in the West Philippine Basin (Zahirovic et al., 2014).

The tectonic setting herein presented for Central Cebu reveals an arc developing at the oceanic leading edge of the Australian Plate (Figure 11). Petrological and geochemical data obtained from the Late Cretaceous (late Santonian to late Maastrichtian) Pandan Formation suggest provenance from an eroded undissected magmatic arc terrane dominated by mafic volcanic rocks with contributions from a metamorphic basement, felsic volcano-plutonic rocks, limestones and quartzose sediments. Discrimination plots show various sources for the Pandan Formation. In particular, basaltic andesitic fragments were likely sourced from the underlying Early Cretaceous Cansi Volcanics, interpreted to have formed at the leading edge of an oceanic island arc setting (Deng et al., 2015).

Subduction of the palaeo-Pacific plate beneath the oceanic leading edge of Australia in the Late Jurassic to Early Cretaceous created the East Philippine-Daito arc and back-arc spreading of the proto-Philippine Sea plate. Being at the oceanic edge of the Australian Plate, contribution from continent-derived sediments was likely. Polarity reversal of the subduction system in the Late Cretaceous, as earlier modelled by Zahirovic et al. (2014), could also have contributed to the scraping of these continent-derived sediments (possibly in the form of an accretionary complex) and eventual metamorphism. The presence of arc, continent and metamorphic rock-derived sediments in the Pandan Formation would be consistent with the model herein envisioned.

The Southeast Bohol Ophiolite and Samar Ophiolite complexes found on adjacent islands in the Central Philippines are also considered fragments of the proto-Philippine Sea Plate (Faustino et al., 2003; Balmater et al., 2015; Guotana et al., 2017; Dimalanta et al., 2019). Thus, future work (e.g. palaeomagnetism) by other authors on these oceanic crustal sections and their overriding sedimentary sequences could provide information to refine or remodel the setting herein presented.

5 | CONCLUSIONS

The Pandan Formation is a Late Cretaceous sedimentary unit consisting of interbedded sequences of sedimentary breccia-conglomerate, clastic and shallow-marine carbonate blocks/boulders, alternating normally graded and ungraded greenish sandstone-siltstone, lenses of sedimentary breccia-conglomerate, calcareous sandstone-siltstone, carbonaceous and siliceous mudstones that were deposited in a submarine slope and canyon environment. The clastic rocks are dominated by mafic volcanic rocks with sediment contributions from felsic, older sedimentary and metamorphic rocks. Bulk geochemical composition of the Pandan clastic rocks registered a moderately high SiO₂ composition displaying a negative correlation with Al₂O₃. This indicates the significant influence of quartz on the overall composition of the Pandan clastic rocks, which were derived from the first cycle mafic rock sources having low Th/Sc, Zr/Sc and Th/U ratios. The low to moderately high CIA and PIA values registered by the samples are due to weak to moderate weathering of the source rock in an arid environment.

Tectonic discrimination diagrams point to ACM and collision zone tectonic settings. Collision of the proto-Philippine arc with the East Philippines-Daito arc in the Late Cretaceous brought blocks of rifted PM Mesozoic sediments to an oceanic island arc at the leading edge of the Australian Margin. Uplift and erosion of the accretionary complex and island arc volcanic rocks led to deposition of the Pandan Formation in the Late Cretaceous onto the adjacent fore-arc basin.
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FIGURE 11  Tectonic model showing the location of the proto-Philippine arc and the East Philippine-Daito arc from Late Jurassic to Late Cretaceous. The fore-arc basin shown on the map corresponds to the depositional basin of the Pandan Formation. Map modified from Deng et al. (2015)
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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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