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Anomalous Occurrence of Cretaceous Placer Deposits: A Review

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Abstract

During the Cretaceous, the CO_2 content of the global atmosphere drastically increased in response to volcanism associated with the disintegration of the former continents. This increase in the global atmospheric CO_2 level subsequently led to a considerable rise in global temperatures. The interaction among the high levels of atmospheric CO_2, extreme global warmth, and humidity witnessed in the Cretaceous implies extreme environmental conditions, which involved a possibly more acidic and chemically destructive atmosphere than at present; these conditions are believed to have favoured widespread deep weathering at that time. Economically important minerals were reworked from their primary sources during these Cretaceous weathering events. The extreme global warmth witnessed in the Cretaceous also caused the melting of most of the polar ice caps, resulting in the expansion of the volume of Cretaceous seawaters, which subsequently led to a significant rise in the global sea level. Extensive palaeo-seaways played a vital role in transporting and depositing the huge volume of sediments generated during the Cretaceous weathering events, which included economically important minerals (e.g., gold, diamond, and platinum). These mineral deposits are now preserved in Cretaceous sands as placer deposits. Three categories of Cretaceous placer deposits can be distinguished: those occurring in Cretaceous sands resting unconformably on the Precambrian basement, those occurring in Cretaceous sands resting unconformably on the Palaeozoic rocks, and those occurring in Cretaceous sands that unconformably overlay Mesozoic strata.

1. Introduction

Palaeogeographic studies e.g., [1, 2, 3] show that before the Jurassic period, all the continents of the Earth were sutured together into one supergiant continent, Pangea. The disintegration of this supergiant continent started in the early Jurassic and subsequently resulted in two giant continents: Laurasia and Gondwana. The disintegration of Laurasia opened up what eventually became the Gulf of Mexico and the Atlantic Ocean. Closely associated with Pangea's breakup and the subsequent disintegration of continents is volcanic activity that emitted large volumes of CO_2 into the atmosphere [4]. It is estimated that during the Cretaceous, the global atmospheric level of CO_2 was significantly higher than that at present [5, 6, 7, 8, 9, 10, 11, 12, 13]. As the Earth's surface temperature is significantly influenced by greenhouse gases (mainly CO_2), the enhanced tectonic activity during the Cretaceous, which emitted large quantities of CO_2 into the atmosphere, resulted in a corresponding rise in global temperatures, leading to a greenhouse climatic condition.

Weathering rates are controlled by many factors including climate, tectonics, and lithology. Studies on tropical deep weathering e.g., [14, 15, 16] have suggested that climate is a particularly important. The degree of mineral dissolution during weathering increases with the increase in temperature. Temperature controls mineral solubility, moisture availability, precipitation, evapotranspiration, and run off, all of which have direct effects on deep weathering [17, 18]. Chemical weathering proceeds faster under warm and wet climatic conditions [19, 20, 21]. Interplay between the high levels of atmospheric CO_2 and extreme global warmth suggest that the Cretaceous period was also a period of intense and widespread deep weathering [16].

The formation of placer deposits is essentially the result of weathering, mechanical liberation, and chemical dissolution of a pre-existing deposit. The placers are then redistributed and concentrated primarily by alluvial and chemical processes. During transport in the fluvial environment, the original crystalline deposit is deformed, abraded, and carried on the streambed through saltation. A prerequisite for the formation of placer deposits is that the mineral grains should withstand erosion, weathering, and transport. Only minerals that go into the realm of sediment transport in considerable quantities will probably form deposits of economic significance. In conditions best for placer development, there should be some reasonable level of connectivity between the mineral sources and deposition areas [22]. Some degree of continual reworking of sediment results in concentrating the heavy minerals, forming comparatively minor lenses in larger bodies of less-dense host sediments (e.g., Fig. 1).

Figure 1. *Example of a sandstone (the Neoproterozoic Torridon group) containing beds of heavy minerals (dark magnetite) from Mellon Udrigle, NW Scotland. Note the convolute structure in the rock, which developed at deposition or shortly after deposition as a result of sediment instability.*

2. Materials and Methods

Records of variation in the atmospheric level of CO_2, palaeo-temperature, and global sea level from the Jurassic to recent years were taken from the relevant published literature e.g., [23, 24, 25, 26]. The relative extents of marine transgression that occurred in the Jurassic, Cretaceous, and Cenozoic were compared to emphasize that significant marine transgression occurred during the Cretaceous. The records of Cretaceous placer gold, diamond, and platinum were compiled from the relevant geological literature. The estimated locations of these Cretaceous placer deposits were then plotted on a reconstructed Mid-Cretaceous World palaeogeographic map in order to relate their occurrence to the Cretaceous palaeogeographic history and highlight the role played by Cretaceous palaeo seaways in transporting and depositing the Cretaceous placer deposits. The estimated locations of cratons and kimberlites were also plotted on the Mid-Cretaceous World palaeogeographic map to establish the relationship between the kimberlites (primary sources of diamond) and Cretaceous placer diamonds.

3. Cretaceous Marine Transgression

Global temperature covaried with atmospheric CO_2 during the Phanerozoic [27; 28, 29; Fig. 2]. The extreme global warmth experienced during the Cretaceous was a direct consequence of the high level of atmospheric CO_2 that prevailed globally at that time [30, 31]. Variations in the sea level are an important consequence of the variation in climate. When global temperatures increase, the volume of seawater increases and polar ice caps melt, both of which cause the global sea level to rise. Conversely, when global temperatures decrease, polar ice caps grow and the volume of seawater decreases, causing the global sea level to fall. An increase in the rate of sea-floor spreading during continental break-up decreases the volume of ocean basins because hot rising magma causes the lithosphere to be lifted along the mid-ocean ridges, thereby reducing the volume of ocean basins. This results in a sea-level rise as the continental margins become flooded by the oceans [32].

Palaeotemperature estimates e.g., [33, 34) from a range of geochemical proxies show that the Cretaceous is a classic example of a greenhouse Earth [30]. During this 80-million-year period, temperature varied over a considerable range, and the carbon-dioxide content drastically changed in both marine and atmospheric reservoirs (Figs. 2 A and B). The interaction among the high levels of atmospheric CO_2, extreme global warmth, and high humidity witnessed in the Cretaceous implies extreme environmental conditions, which included a possibly more acidic and chemically destructive atmosphere than at present; these conditions are believed to have favoured widespread deep-weathering events at that time. U–Pb zircon provenance data e.g., [35, 36, 37, 38], demonstrate that rock fragments occurring in Cretaceous transgressive strata include the weathered products of very much older rocks, including Archaean basement gneisses and Proterozoic granites and gneisses.

The extreme global warmth of the Cretaceous caused most of the polar ice caps to melt, which resulted in the expansion of the volume of seawater. Cretaceous sea levels varied with measures of tens of metres [39] and flooded some of the continental region, creating widespread seaways [40, 24]. The global sea level rose (with fluctuations) in the Mesozoic to reach a maximum in the Late Cretaceous. The relative extent of the Cretaceous marine transgression is approximately 55% greater than that of the Cenozoic and approximately 42% greater than that of the Jurassic (Fig. 2C).

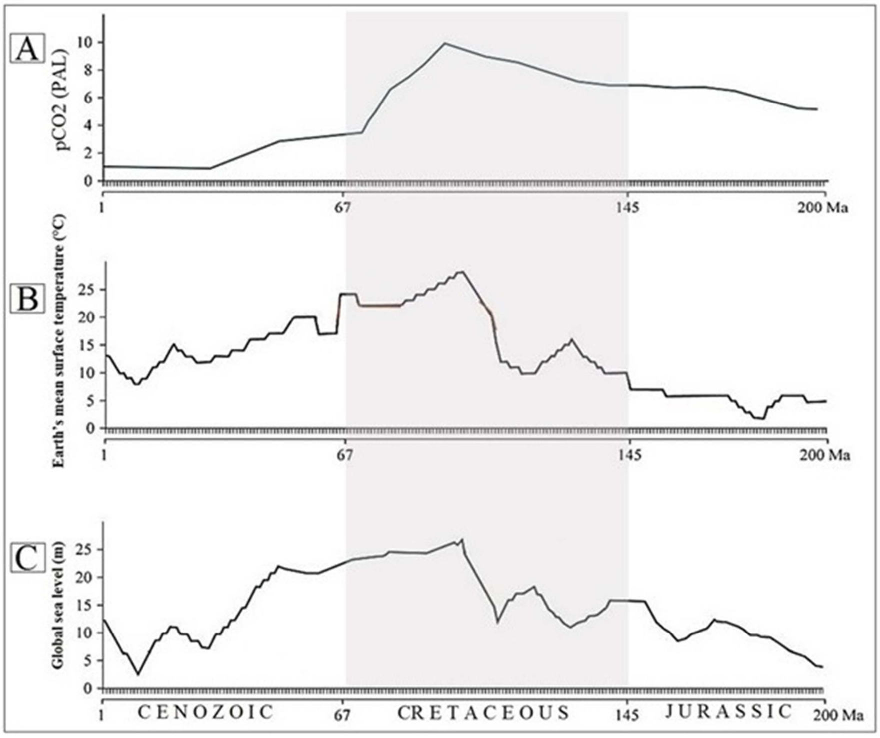

Figure 2. *(A) Variations in the atmospheric level of CO_2 from the Jurassic to the present day (modified from [26]). Note the high atmospheric levels of CO_2 during the Cretaceous. Here, pCO_2 is the partial pressure of atmospheric CO_2 in pre-industrial atmospheric levels (PALs). (B) Variations in the global mean surface temperature (modified from [23]). (C) Variations in the global sea level from the Jurassic to the present day [25]. Note that the relative amount of marine transgression that occurred in the Cenozoic is 55% less than that in the Cretaceous. The relative amount of marine transgression that occurred in Jurassic is 42% less than that in the Cretaceous.*

4. Cretaceous Placer Gold

Most Cretaceous sedimentary basins were developed in foreland settings. Foreland basins are known to collect huge volumes of sediment on the hinterland [41]. The largest placer gold deposit in the world, the Archaean Witwatersrand placer gold, was formed in a foreland basin setting [42; 43], which implies that processes linked with foreland basin development have the ability to concentrate placer gold deposits, provided suitable primary gold sources exist. In the Cretaceous, these processes were related to the global greenhouse climatic condition at that time, which resulted in widespread intense weathering. Records of examples of Cretaceous placer gold are presented in Table 1 and Figure 3.

Table 1. *Records of Cretaceous placer gold.*

S/No	Country	Locality	Name of Host Rock	Age of Cretaceous Strata	References
1	Egypt	Mersa Alam	Nubian Formation	Cenomanian	[44]
2	Canada	Western Canada Basin	McMurray Formation	Barremian	[41]
3	France	Cévennes	Parkstein Fan Complex	Upper Cretaceous	[45]
4	Switzerland	Gotthard Massif	Parkstein Fan Complex	Upper Cretaceous	[45]
5	Germany	Bohemian Massif	Parkstein Fan Complex	Upper Cretaceous	[45]
6	Malaysia	Southeastern Kalimantan Borneo	Manuggul Formation	Turonian–Senonian	[46]
7	Mongolia	Gobi Basin	Iren Dabasu	Upper Cretaceous	[47]
8	New Zealand	Southern New Zealand	Blue Spur Conglomerate	Albian	[48]
9	Nigeria	Mid-Niger Valley	Nupe Sandstone	Upper Cretaceous	[49]
10	Russia	West Siberia	Kiya Formation	Lower Cretaceous	[50]
11	Indonesia	South-eastern Kalimantan	Manunggul Formation	Late Cretaceous	[46]
12	Russia	Tambov District Area, SE Russia	Tsentral'noe	Upper Cretaceous	[51, 52]
13	Canada	Yukon	India River Formation	Albian	[53]
14	USA	Wyoming	Harebell Formation, Pinyon Formation	Upper Cretaceous	[54]
15	USA	Colville Basin Alaska	Colville and Nanushuk Group	Upper Cretaceous	[55]

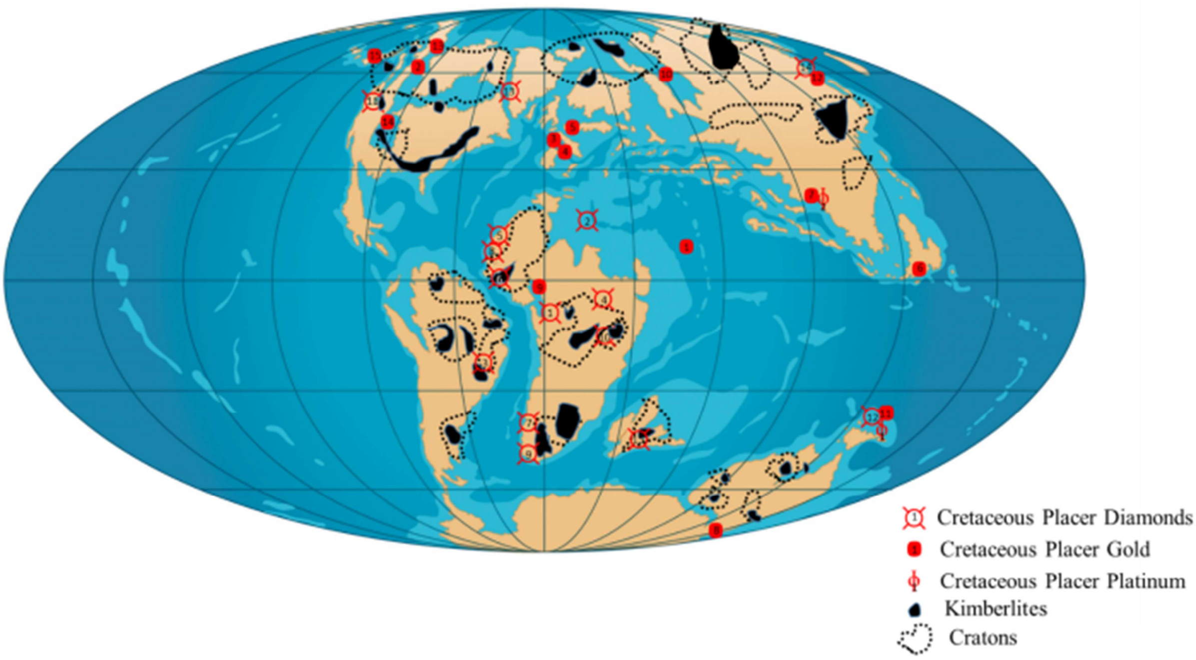

Figure 3. *Mid-Cretaceous world palaeogeographic map showing estimated locations of Cretaceous placer deposits. The details of locations are presented in Tables 1, 2, and 3. Note the good connection of most Cretaceous placer deposits with Cretaceous palaeo seaways (light blue on map). Also note the estimated locations of cratons and kimberlites. Most Cretaceous placer diamonds have been transported from the kimberlites, which are their primary source.*

An example of Cretaceous placer gold deposits in North America is the placer gold associated with the McMurray Formation in the Western Canadian Basin (Fig. 4A). The crystalline basement occurring in the Alberta region of the Western Canada Sedimentary Basin is covered with Palaeozoic to Cretaceous sedimentary sequence. The Western Canada sedimentary foreland basin east of the Canadian Rocky Mountains runs southwards in the Cordillera and strikes the structurally comparable Sevier belt of western USA. These mountains have extensive fold structures with faulted crystalline basement cores, which formed the Laramide orogeny [41]. Gold-bearing veins occur within the ranges of the Canadian Rockies [56, 57, 58].

Because of the Cretaceous greenhouse climatic condition that favoured intense weathering, gold from these Canadian Rockies was shed towards the Western Canada sedimentary foreland basin at different times during the Late Cretaceous [59]. Placer gold sourced from these metamorphic rocks occurs in sandstones near the eastern mountain front and is believed to have travelled for approximately 250 km [59].

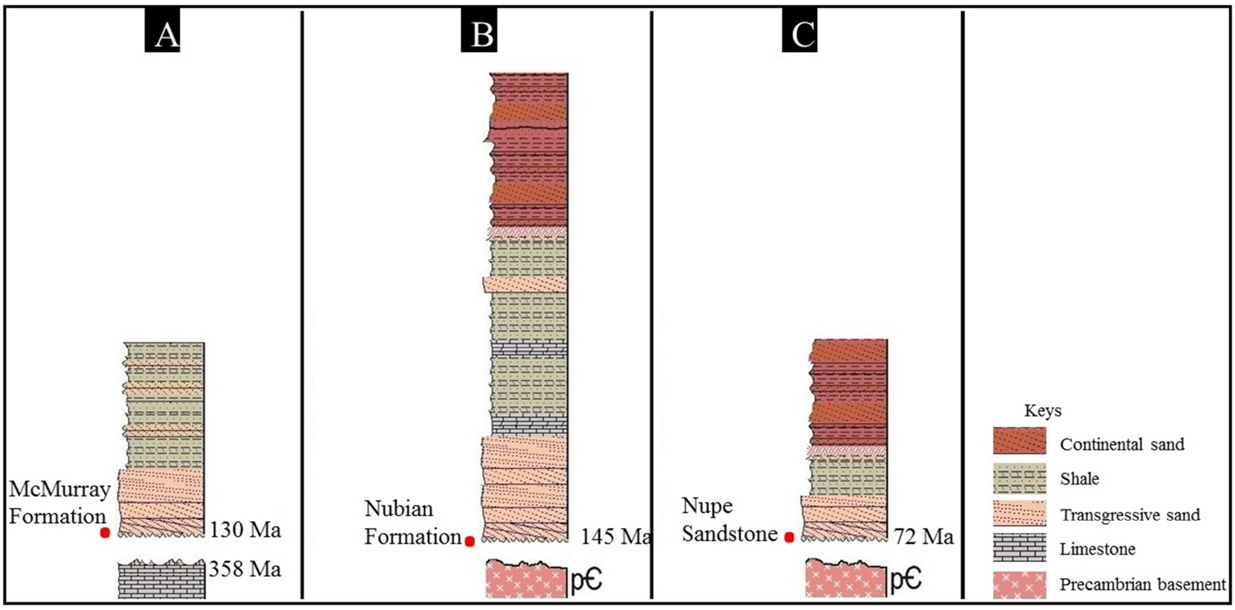

Figure 4. *Stratigraphic positions of some Cretaceous strata containing placer gold deposits. (A) McMurray Formation in the Western Canadian basin. (B) Nubian Formation of the Mersa Alam region in Egypt. (C) Nupe Sandstone in the mid-Niger valley in Nigeria. Note the gap in age (unconformity) between the Cretaceous strata containing placer gold and the underlying basement/strata. Red dots show positions of the Cretaceous transgressive sands above plane of unconformity.*

Examples of Cretaceous placer gold deposits in Africa are associated with the Nubian Formation of the Mersa Alam region in Egypt and the Nupe Sandstone in the Mid-Niger Valley in Nigeria (Table 1; Fig. 4). Lithified Cretaceous placer gold occurs at the base of the Upper Cretaceous Nubian Formation that overlies the somewhat peneplained surface of the Precambrian basement rocks [44]; Fig. 4B. These Cretaceous placer gold deposits occurring around the Mersa Alam region are mostly associated closely with auriferous quartz veins, which have been a main objective for gold prospecting since ancient times. The arid and warm climate that typifies the Egyptian deserts, especially during the Cretaceous, must have resulted in the weathering of the auriferous quartz veins and dispersion of the placer gold into the palaeo drainage basins.

Placer gold associated with the Cretaceous Nupe Sandstone in the Mid-Niger Valley is sourced from primary gold mineralization in the Nigerian basement rocks occurring around Ilesha-Egbe, Minna, Birnin-Gwari, Sokoto, and Yelwa [49]. Each of these goldfields covers several thousand square kilometres. The placer gold deposits occurring in these goldfields are found not only in the present river channels but also in older buried placers (e.g., Cretaceous Nupe Sandstone, Fig. 4C) occurring in several locations fringing the mid-Niger Valley and acting as the source of most modern placers in the region.

In Europe, Cretaceous placer gold deposits occur in the Cévennes region of France, St Gotthard Massif in Switzerland, and the western edge of the Bohemian Massif in Germany (Table 1; Fig. 3). The bedrock geology of these provinces is marked by siliciclastic rocks altered in the course of low-to-high-grade regional metamorphism and by the ensuing emplacement of acidic igneous rocks in the late Variscan. Detritus produced as a result of the Cretaceous weathering events and erosion of the uplifted basement rocks in these regions along with Mesozoic sediments containing placer gold was delivered into a newly formed drainage system, the trunk river of which runs somewhat parallel to the Franconian Line boundary fault [45].

Traces of Cretaceous placer gold are associated with placer deposits bearing diamond and PGMs in the river terraces and alluvial river gravels of south-eastern Borneo (Table 1; Fig. 3). The geology of the south-eastern Kalimantan in Borneo is characterized by the presence of an Early to mid-Cretaceous accretionary complex, unconformably covered with Late Cretaceous sedimentary and mafic volcanic rocks of the Manunggul Formation Gold with the other placer deposits in the Cretaceous Manunggul Formation is believed to have been liberated from the Early to mid-Cretaceous accretionary complex [46].

Cretaceous placer gold associated with platinum occurs in the Gobi Desert of Mongolia (Table 1; Fig. 3). These Cretaceous placer deposits occurring in the red thick angular conglomeratic fans are believed to have been derived from the Devonian Altan Uul metamorphosed cherts, basic lavas, and altered gabbros in the region, possibly during the general Cretaceous weathering events [47]. Elsewhere in the Gobi Desert, Cretaceous palaeoplacers are found associated with remains of dinosaurs, and it has been suggested that dinosaurs probably walked around on gold and platinum dust in the Cretaceous [47].

Cretaceous placer gold associated with fluvial quartz pebble occurs in the Late Cretaceous and younger sedimentary sequence of southern New Zealand (Table 1; Fig. 3). Southern New Zealand is underlain by Palaeozoic–Mesozoic greywacke and argillite, as well as schist metamorphosed from those rocks [48]. The placer gold deposits occurring in southern New Zealand are associated with Late Cretaceous–recent alluvial sediments deposited during basin formation and inversion and are believed to have been derived from the Otago Schist in the region, which is also cut by numerous fault-hosted, gold-bearing, mesothermal vein systems [48].

Cretaceous placer gold also occurs in West Siberia (Table 1; Fig. 4). These placer gold deposits in the Cretaceous Kiya Formation in Southern West Siberia are believed to have accumulated during the fluvial transport of an auriferous terrigenous material derived from the weathering of rocks on the northern face of Kuznetsk Alatau and Salair region during the Cretaceous [50]. In general, Cretaceous placer gold deposits are usually associated with texturally immature Cretaceous sediments. The extreme environmental conditions witnessed in the Cretaceous, uplifted and eroded volcanic/metamorphic sequences with traces of primary gold. The predominance of foreland basins with erosional sedimentary processes combined with the above to cause sorting and detrital gold concentration from significant and seemingly insignificant gold sources in the Cretaceous hinterlands.

5. Cretaceous Placer Diamonds

Diamond-bearing kimberlites are mostly associated with Archaean cratons or adjacent mobile belts more than 2.4 Ga old [60, 61, 62, 63], while diamondiferous lamproites are usually linked with younger mobile belts flanking Archaean cratons [62]. Once they are transported to the surface, these kimberlites and lamproites are exposed to erosional processes, leading to the dispersal of diamonds into the sedimentary environment. [64] demonstrated that the placer diamonds found today around the Ghoumel River near Constantine in Algeria could have been sourced from kimberlite or lamproite deposits 1500 km south-west of the Ghoumel River. The rounded shape of the Constantine placer diamonds also suggests long sediment transport, as inferred for many Sahara diamonds [65]. [66] used detrital zircon ages and palaeocurrent trends to demonstrate that the Numidian sandstones were sourced from the Saharan craton and/or its Early Cretaceous cover, which could have also served as sources for the Saharan diamondiferous formations and the Ghoumel fluvial sediments.

Placer diamonds occur in the Cretaceous Calonda conglomerate at Lunda Angola (Table 2; Figs. 3 and 5A), where they are believed to have been derived from the Lulo kimberlite province located within the Angola-Kasai Archaean Craton [67]. The Lunda region has experienced at least three major crustal uplifts since the emplacements of kimberlites. These crustal uplift events associated with weathering and erosional events (especially during the Cretaceous) controlled the complex multi-cyclical alluvial diamond distribution in the Lunda region of Angola.

Cretaceous placer diamonds occur in the Upper Cretaceous Mouka–Ouadda Sandstone in the eastern part of the Central African Republic [68]; Table 2; Fig. 3. The underlying geology of the Central African Republic is mostly comprised of Archean and Proterozoic basement rocks. These basement rocks are divided into two main geologic groups: a granitic–gneissic complex and a schist–quartzitic complex. Overlying the Archean basement rocks is the schist–quartzitic complex, which is believed to be of Neoproterozoic age and is composed of quartzitic and schistose rocks that are only weakly metamorphosed and generally folded. Both of these complexes are intruded throughout the country by basic Neoproterozoic rocks. Overlying these older rocks is a sequence of Palaeozoic rocks of glacial origin, which are unconformably covered by Cretaceous sandstones [69]. The Mouka-Ouadda Sandstone, which is the host to the Cretaceous placer diamonds in the Central African Republic, covers an area of approximately 40,000 km² and forms a plateau generally less than 500 m thick. It is composed of layers of sandstone and conglomerate. The Mouka-Ouadda Sandstone is thought to have been derived from detrital material from the fluvial-glacial Kombélé Formation and from the Precambrian schist and quartzite complex, and it was deposited on a peneplained Precambrian granitic–gneissic basement [70, 68].

The primary source of the Cretaceous placer diamonds in the Central African Republic has been a subject of controversy because there are no known records of kimberlites, lamproites, or other primary geologic sources rich with diamonds in the Central African Republic. [71] suggested that the diamonds could have eroded from some undiscovered kimberlites in the northern part of the Democratic Republic of Congo. There is no direct evidence for this claim, although tectonic, mineralogical, and crystallographic evidence support the interpretation. Other authors such as [72] suggest that the primary source of the Cretaceous placer diamonds in the Central Africa Republic could be the kimberlitic intrusions in the Central African region that occurred during the Mesoproterozoic (Kibarian) and the Early Cretaceous. Some kimberlite pipes in the Mitzic region of Gabon, are the nearest pipes to the Central African Republic. It is therefore possible that the Cretaceous placer diamonds in the Central African Republic were derived from the kimberlite pipe located in Mitzic, Gabon, but this also implies that the Cretaceous placer diamonds occurring in the Central African Republic may have been deposited and reworked twice or thrice [73].

The Cretaceous placer diamonds associated with the Maastrichtian Loia Group in the Mbuji-Mayi/Tshikapa provinces of the Democratic Republic of Congo are believed to have been derived from diamondiferous kimberlites in the Bakwanga–Mbuji-Mayi area of the Democratic Republic of Congo (Table 2; Fig. 3). Kimberlite pipes in the Mbuji-Mayi region are mostly aligned east–west and emplaced through an Archean basement and Neoproterozoic siliciclastic/carbonate sediments belonging to the Mbuji-Mayi supergroup, which are covered with Cretaceous sediments. Thin feeder pipes have intruded through the hard limestones and expanded dramatically into the overlying and unconsolidated sediments. Kimberlite facies in the Mbuji-Mayi region include volcaniclastic, resedimented volcaniclastic, and coherent magmatic crater-facies with dolerite and sills overlying Mesozoic siliciclastic sediments in the region [74].

The Cretaceous placer diamonds occurring along the Orange and Vaal Rivers originating in South Africa (Table 2; Figs. 3 and 5B) are believed to have originated from Kimberley, where five kimberlite pipe mines are located within a circle 8 km in diameter [67]. Similarly, Cretaceous placer deposits in Namibia are suspected to have originated from the Archaean Kalahari craton (more than 700 km to the east of Namibia), which is a region having more than 1000 kimberlites with emplacement ages ranging from ~80 to ~1200 Ma [75]. Some authors suggested that the Cretaceous placer deposits occurring around the Namibian coast resulted from the erosion of distal Cretaceous and Jurassic kimberlites with diamonds transported to the coast by the Cretaceous palaeo-Orange river [76, 77].

Cretaceous placer diamonds occur in the West African countries of Guinea, Liberia, and Sierra Leone (Table 2; Fig. 3). These West African placer diamonds can be traced to Mesozoic kimberlite pipes and lamproite dykes in West Africa. Several episodes of kimberlite emplacement have been recognised, but the Mesozoic kimberlites are the most extensive with several fields occurring in Guinea, Sierra Leone, Liberia, and Mali on the West African Craton [78]. Locations of the Cretaceous diamond placers in West Africa are consistent with the drainage path of the palaeo-Tethys Sea, suggesting that the palaeo-Tethys Sea, which controlled the deposition of most of the basal Cretaceous sediments in the region, also played a very important role in dispersing the placer diamonds liberated from the kimberlites and lamproites on the West African Shield.

In Brazil, the occurrence of Cretaceous placer diamonds is associated with the Upper Cretaceous Bauru Group at Minas Gerais (Table 2; Figs. 3 and 5C). The primary sources of diamonds in the Minas Gerais region are still debated. [79] suggest that the placer diamonds occurring in the Minas Gerais were brought through glacial transport from primary sources located in the São Francisco Craton. Others [80, 81, 82] believe that the kimberlite-bearing rocks in the region could be the primary source of the placer diamonds. The significant concentration of placer diamonds in the Minas Gerais region and the presence of kimberlite indicators in Romaria, support the arguments for the primary sources of diamonds in the region. Some part of the Sao Luis Craton, where Minas Gerais is located was linked to the massive

West African Craton within Gondwana during the Cretaceous [83]. Cretaceous placer diamonds as well as kimberlites occur in Liberia, Sierra Leone, Guinea, Ghana, and Mali, which were all part of Western Gondwana together with Brazil in the early Cretaceous.

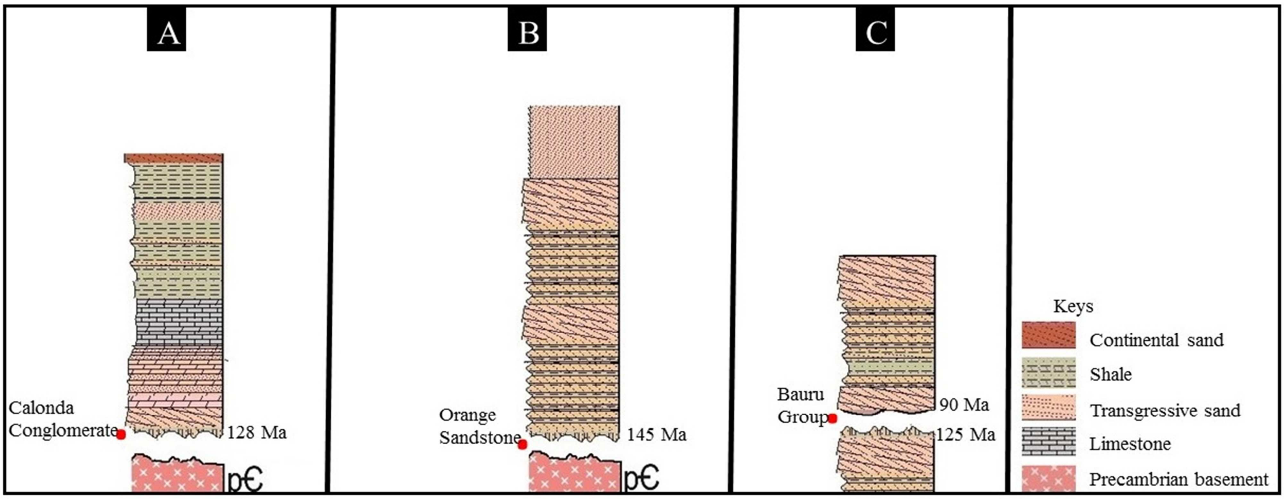

Figure 5. *Stratigraphic positions of some Cretaceous strata containing placer diamond deposits. (A) Calonda conglomerate, Lunda, Angola. (B) Orange sandstone, Vaal River, South Africa. (C) Bauru Group, Minas Gerais, Brazil. Note the gap in age (unconformity) between the Cretaceous strata containing placer diamonds and the underlying basement/strata. Red dots show positions of the Cretaceous transgressive sands above plane of unconformity.*

Cretaceous placer diamonds associated with the Mannvile Formation occurs in Saskatchewan, Canada (Table 2; Fig. 3). These Cretaceous placer diamonds are believed to have been sourced from the Cretaceous Fort à la Corne (FALC) and emplaced near the margin of the Western Canadian Interior Seaway during cycles of marine transgression and regression in the Cretaceous [84, 85]. The FALC kimberlite region is close to the north-eastern rim of the Interior Platform of North America. Drilling in the FALC province has shown that the FALC kimberlites have diameters up to 2000 m with vertical thicknesses up to 200 m. These kimberlites formed near the eastern margin of the Western Canadian Interior Seaway during the Cretaceous, which was also a time of continual marine transgression and regression in the Saskatchewan. The kimberlites are roofed by about 100 m of glacial overburden [85].

Table 2. *Records of Cretaceous placer diamond.*

S/No	Country	Locality	Name of Host Rock	Age of Cretaceous Strata	References
1	Angola	Lunda	Calonda conglomerate	Mid-Cretaceous	[67]
2	Algeria	Ghoumel River, near Constantine	Nubian Sandstone	Early Cretaceous	[64]
3	Brazil	Minas Gerais	Bauru Group	Upper Cretaceous	[83]
4	Central African Republic	Eastern Central African Republic	Mouka-Ouadda Sandstone	Upper Cretaceous	[68]
5	Guinea	Banankoro			[67]
6	Liberia	Mano/Lofa R.			[67]
7	Namibia	CDM / Guano Isles/ Elizabeth's Bay	Orange Sandstone	Mid-Cretaceous	[67]
8	Sierra Leone	Yengema/ Tongo			[67]
9	South Africa	Namaqualand coast, south of the Orange river mouth and Vaal River	Orange Sandstone	Mid-Cretaceous	[67]
10	Zaire (Democratic Republic of the Congo)	Mbuji mayi/ Tshikapa	Loia Group	Maastrichtian	[67, 74]
11	Canada	Saskatchewan	Mannvile Formation	Mid-Cretaceous	[84, 86, 85]
12	Indonesia	South-eastern Kalimantan	Manunggul Formation	Late Cretaceous	[46]
13	Greenland	Disco Island West Greenland	Actane Formation		[87]
14	Russia	Tambov District Area, SE Russia	Tsentral'noe	Upper Cretaceous	[51, 52]
15	India	Krishna-Godavari Delta Region	Gollapalli Sandstone	Upper Cretaceous	[88]

The Cretaceous sediments adjacent to the kimberlite bodies correlates with the regional stratigraphy of the Western Canada Sedimentary Basin, implying that the Cretaceous sediments were *in situ* and undisturbed at the time of kimberlite emplacement [84]. The age of the FALC kimberlite body has been determined using U–Pb analyses as 99.8±2.4 and 99.5±1.8 Ma [85]. The ages imply that the kimberlites were emplaced relatively soon after the deposition of the country rocks. The age of the kimberlite emplacement may be correlated with a period of relative local regression in the region, which is consistent with the interpretation of the main infill of the FALC bodies as subaerial pyroclastic material [85]. [86] explained that the subaqueous air-fall deposits and the FALC kimberlite body have been reworked by wave processes, which is evident in their extremely altered nature and sorting that are consistent with subaqueous deposition and reworking. The gradational contact observed between the kimberlite and overlying sediments are consistent with the assertion that the kimberlites were covered by the Cretaceous interior sea at the time of the Cretaceous marine transgression.

6. Cretaceous Placer Platinum

Platinum-group minerals (PGMs) have been used as geochemical indicators to study various igneous processes on Earth, such as magmatic fractionation, mantle melting, and melt–rock exchanges, and to apprehend the nature and evolution of the source mantle [89, 90, 91]. PGMs are also useful tools in lithogeochemical exploration for Ni–Cu-sulphide deposits [92]. The largest known platinum-group deposits in the world occur in the Bushveld Complex and Great Dyke of Southern Africa and the Stillwater Complex of the USA, which are all located within cratons rather than craton margins [93]. Smaller platinum-group deposits also occur on craton margins. Examples are the Palaeo-Proterozoic Pana deposit in the Kola Peninsula [94] and the Partimo-Pennikat-Suharko deposit in northern Finland [95]. Placers of platinum-group minerals (PGMs) have been reported from many locations around the world. Examples are in the former USSR, Colombia, and Canada, which were the principal sources of PGMs in the early 20th century, when primary deposits were discovered in South Africa and Siberia [96, 97, 98].

Cretaceous placers of PGMs associated with placer diamonds and gold have been reported in the south-eastern Kalimantan of Indonesia [46]. These widely dispersed diamond–Au–PGM deposits occurring around the south-eastern Kalimantan of Indonesia are multi-cycle placers spatially linked to, and reworked from, conglomerates in the Cretaceous Manunggul Formation. The Cretaceous placers are believed to have been derived from medium-grade metamorphic rocks (schists and gneiss), andesitic volcanic rocks, metasedimentary rocks, dioritic to tonalitic plutons, and ultramafic rocks in the Riam Pinang area of the region. The geological settings for the inferred sources of the Cretaceous placers in Kalimantan are characterized by Phanerozoic sedimentation, magmatism, and tectonic activity, in contrast to most other diamond provinces in the world, which consist of much older terranes.

Table 3. *Records of Cretaceous placer platinum.*

Country	Locality	Name of Host Rock	Age of Cretaceous Strata	References
Indonesia	South-eastern Kalimantan	Manunggul Formation	Late Cretaceous	[46]
Mongolia	Gobi Basin	Iren Dabasu	Upper Cretaceous	[47]

7. Discussion

Evidence in the geological record demonstrates that during the Cretaceous, the CO_2 level of the global atmosphere rose significantly in response to volcanism associated with the disintegration of the former continents during the Cretaceous. Earth's surface temperature is known to be controlled by greenhouse gases (mainly CO_2). There is good correlation between the global temperature and the level of atmospheric CO_2 during the Phanerozoic (Figs. 2A and B). The increase in the global atmospheric CO_2 level witnessed in the Cretaceous led to a considerable rise in the global temperatures, resulting in a greenhouse climatic condition at that time [99, 12]. Temperature is known to control mineral solubility, moisture availability, precipitation, evapotranspiration, and run off directly. All of these, in turn, have direct consequences on chemical weathering [18]. The interaction among the high levels of atmospheric CO_2, extreme global warmth, and humidity experienced in the Cretaceous resulted in the widespread weathering of the Archaean basement gneisses, Proterozoic basement/strata, and Mesozoic strata [16].

Typical present-day weathering profiles in the equatorial regions (where warm climatic conditions prevail) is approximately 200 m [100]. Such expected weathering layers would have been much thicker under the hyper-tropical climate witnessed in the Cretaceous than at present. It is therefore plausible that the thickness of the Cretaceous weathering profile could have been up to 4–5 times the present value. This implies that large amounts of sediment were produced during the Cretaceous weathering events [16]. Some economically important mineral deposits (e.g., gold, diamond, and platinum) were also removed from their primary sources and shed into the realm of sediment transport during the Cretaceous.

U–Pb zircon provenance data of some Cretaceous sands e.g., [35, 36, 37, 38] have demonstrated that the Cretaceous sands contain some rock fragments that are weathered products of very much older rocks. Most of the Cretaceous sands that host the Cretaceous placer deposits considered in this study occur unconformably above much older rocks (e.g., Figs. 4 and 5). Three types of Cretaceous sandstones hosting Cretaceous placer deposits can be distinguished in the data set presented in this study: Cretaceous sands occurring directly above Precambrian basement rocks (e.g., the Nubian Formation of the Mersa Alam region in Egypt, the Nupe Sandstone in the Mid-Niger Valley in Nigeria, the Calonda conglomerate occurring in the Lunda region of Angola, and the Orange sandstone occurring around the Vaal River region of South Africa), Cretaceous sands occurring directly above Proterozoic rocks (e.g., McMurray Formation occurring in the Western Canadian Basin), and Cretaceous sands occurring unconformably above Mesozoic strata (e.g., Bauru group occurring in the Minas Gerais region of Brazil).

These Cretaceous sequences commonly begin with continental siliciclastic units overlying the plane of unconformity, and the sediments grade up into marine sediments, indicating seaward clastic influx that is consistent with marine transgression [101].

Most of the former continents were flooded during the Cretaceous as demonstrated in Figure 3. The relative extent of marine transgression that occurred in the Cretaceous is significantly higher than that in the Jurassic or Cenozoic (Fig. 2C). Extensive palaeo seaways that existed during the Cretaceous played an important role of transporting and depositing the huge volume of sediments generated during the Cretaceous weathering events, which included the economically important mineral deposits considered in this study.

Primary gold deposits occur globally in different geologic settings. The main primary gold deposits occur in Precambrian shields, Palaeozoic fold belts, and Mesozoic or Quaternary volcanic arcs [102]. When primary gold lode deposits associated with bedrocks are exposed to weathering conditions, they produce surficial placer deposits that usually disperse into the realm of sediment transport. Numerous giant placer gold deposits occur in Mesozoic–recent foreland basins surrounding the Pacific Rim. Examples include placer gold deposits occurring in New Zealand, California, and Alaska, which are products of weathering and erosion of Palaeozoic–Mesozoic orogenic gold deposits [103, 104]. Apart from the Archean Witwatersrand placer gold in South Africa, placer gold older than the Tertiary are rare in nature [93]. The widespread occurrence of Cretaceous placer gold (Table 1; Fig. 3) therefore suggests the widespread processing favourable to the release of placer gold from primary gold deposits during the Cretaceous. Such geologic processes were favoured by the greenhouse climatic condition witnessed in the Cretaceous.

Primary sources of diamonds (diamondiferous kimberlites) are known to be associated with Archean crustal blocks. Such crustal blocks are characterized by low geothermal gradients and relatively thick crust, which allow for high pressure at comparatively low temperatures, resulting in the generation of diamonds within stable fields in the mid-lower portions of the cratonic lithosphere [60, 77]. Furthermore, diamond-bearing kimberlites and lamproites also occur in Proterozoic belts such as Western Australia and the Buffalo Hills in Alberta, Canada [105]. These Proterozoic kimberlites and lamproites are believed to be underlain by older cratons. Diamonds, which originate from the sub-continental mantle (approximately 150-km deep), are conveyed to the Earth's surface by deep-seated alkaline volcanics such as kimberlites or, less frequently, lamproites. Diamond placers are expected to occur on continents richly endowed with Archean blocks; however, because diamonds are extremely robust, they can withstand prolonged surface transport and subsequently accumulate in placer deposits far removed from their native kimberlite/lamproite source (s). There are several global examples of diamond placer deposits that have no clear connections to known primary kimberlite or lamproite sources [106]. Most of the Cretaceous placer diamonds presented in this study occur in localities further away from their inferred primary sources (Fig. 3). This again highlights the important role played by the Cretaceous palaeo seaways in transporting and depositing these Cretaceous placer deposits. Platinum-group elements (PGMs) originate from layered mafic intrusions brought to the surface, where they weather and disperse into the sedimentary environments as placer deposits [107, 108].

8. Summary and Conclusions

Evidence for the widespread occurrence of Cretaceous placer deposits is presented in this study. Specifically, this study demonstrated the following:

i) During the 80-million-year Cretaceous period, the CO_2 content of the global atmosphere drastically increased in response to volcanism associated with the disintegration of the former continents. This caused both atmospheric and oceanic temperatures to rise and vary over a wide range.
ii) The interaction among the high levels of atmospheric CO_2, extreme global warmth, and humidity witnessed in the Cretaceous resulted in the widespread weathering of the Archaean basement gneisses, Proterozoic basement/strata, and Mesozoic strata. Consequently, some economically important mineral deposits (e.g., gold, diamond, and platinum) were removed from their primary sources in some of these older rocks and shed into the realm of sediment transport. These economically important metals are now preserved as placer deposits in some Cretaceous transgressive sands.
iii) The extreme global warmth of the Cretaceous caused most of the polar ice caps to melt, which resulted in the expansion of the volume of seawater. This further resulted in a significant rise in the global sea level at that time. The Cretaceous sea-level rise resulted in the landward movement of coastlines at that time.
iv) Extensive palaeo seaways existed during the Cretaceous. These Cretaceous palaeo seaways played an important role of transporting and depositing the huge volume of sediments generated during the Cretaceous weathering events, which included the economically important mineral deposits considered in this study.
v) Three categories of Cretaceous placer deposits can be distinguished: those occurring in Cretaceous sands resting unconformably on the Precambrian basement, those occurring in Cretaceous sands resting unconformably on the Palaeozoic rocks, and those occurring in Cretaceous sands that unconformably overlay Mesozoic strata.

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