Marine Geology 380 (2016) 290–314

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Phosphorite deposits on the Namibian shelf

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ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 31 March 2016
Accepted 3 April 2016
Available online 14 April 2016

Keywords:
Phosphogenesis
Upwelling
Paleoceanography
Pleistocene
Climate
Benguela

ABSTRACT

Phosphorite deposits provide a source of fertilizer to feed an increasingly populated world and they provide a record of paleoceanographic changes in upwelling systems linked to climate. The Benguela Upwelling System (BUS) is among the most productive today and is associated with major phosphorite deposits exposed over an area of 24,700 km^2 on the Namibian shelf. Analyses of cores associated with recent offshore mineral exploration provide new insights into the age and origin of these phosphorite deposits. The deposit consists of coarsening upward muddy to gravelly pelletal phosphorite sand, up to several meters thick, on the middle to outer shelf (190 and 350 m water depth) offshore of Lüderitz and Walvis Bay. Less extensive and less continuous deposits occur offshore of Walvis Bay as far north as the Kunene River mouth on the inner to middle shelf (50 and 250 m water depth). Pelletal phosphorite sand (some concentrically banded) and concretionary phosphorite pebbles are the dominant grain types consisting of up to 90 wt.% carbonate fluorapatite (francolite) cement and inclusions of organic matter, pyrite and terrigenous mud. Strontium isotope stratigraphy and foraminiferal biostratigraphy indicate that phosphogenesis was initiated in the latest Miocene but that most phosphorite formed in the Plio/Pleistocene during early burial diagenesis of organic-rich mud as it does today in the Holocene diatomaceous mud belt. The highly-condensed, coarsening-upward succession reflects increasingly high-amplitude Pleistocene sea-level fluctuations. Phosphorite formation correlates to terrestrial aridification as well as to marine proxies of intensified coastal upwelling in the 600 m thick equivalent successions on the upper slope. Repeated phosphorite formation and reworking over Pleistocene glacial to interglacial cycles resulted in the economic concentration of phosphorite, with an estimated total resource of 7800 million tons of phosphate rock at an average grade of 19 wt.% P_2O_5 on the Namibian shelf.

1. Introduction

Phosphorite is a rock type rich in phosphorus (>18 wt.% P_2O_5). Phosphorus (P) in most marine phosphorite deposits occurs as phosphate (PO_4^{3-}) in the carbonate fluorapatite mineral francolite, which commonly contains >1 wt.% fluorine and 3–6 wt.% carbonate substituting for phosphate (Jarvis et al., 1994). Francolite typically occurs as cryptocrystalline, pore-filling or carbonate-replacing cement in phosphorite sand to pebble sized grains, as well as bioskeletal bone and teeth. Phosphorite represents a major long-term sink of biologically active P from the oceans and is important to our understanding of how marine biological productivity has varied in the past and relates to changes in the global carbon and phosphorus cycles, as well as to changes in climate (Föllmi, 1996; Compton et al., 2000; Ruttenberg, 2003). In addition, P is a non-renewable resource in the production of fertilizer. Use of fertilizer to increase agricultural yield has been an important component of the 'Green Revolution' and has contributed to the doubling of human population since 1970 (Amundson et al., 2015). To date most P has been mined from large marine phosphorite deposits exposed on land through tectonic uplift and lowering of sea level (Notholt et al., 1989). Greater demand and higher prices, combined with advances in offshore mining technology, have increased exploration of potentially minable offshore phosphorite deposits.

The western margin of southern Africa is renowned for its phosphorite deposits, first described from dredged samples during the HMS *Challenger* Expedition (Murray and Renard, 1891). The full extent and richness of phosphorite on the margin was only confirmed much later by systematic seafloor sampling. Seafloor mapping was initially carried out by Russian oceanographers during expeditions in the early 1960s (Senin, 1970) and later by the marine geology group at the University of Cape Town and the geological survey (Summerhayes et al., 1973). Samples from these and later surveys formed the basis for early mapping of the sediment distribution of the continental margin of South Africa and Namibia (Birch, 1975; Bremner, 1977; Rogers, 1977; Baturin, 1982). These surveys revealed that the unconsolidated surface sediment included regions of unusually high P content (Fig. 1), particularly on the middle to outer shelf of Namibia where surface sediments contain >25 wt.% phosphorite and have bulk sediment grades of 17 to 24 wt.% P_2O_5 (Summerhayes et al., 1973).

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http://dx.doi.org/10.1016/j.margeo.2016.04.006
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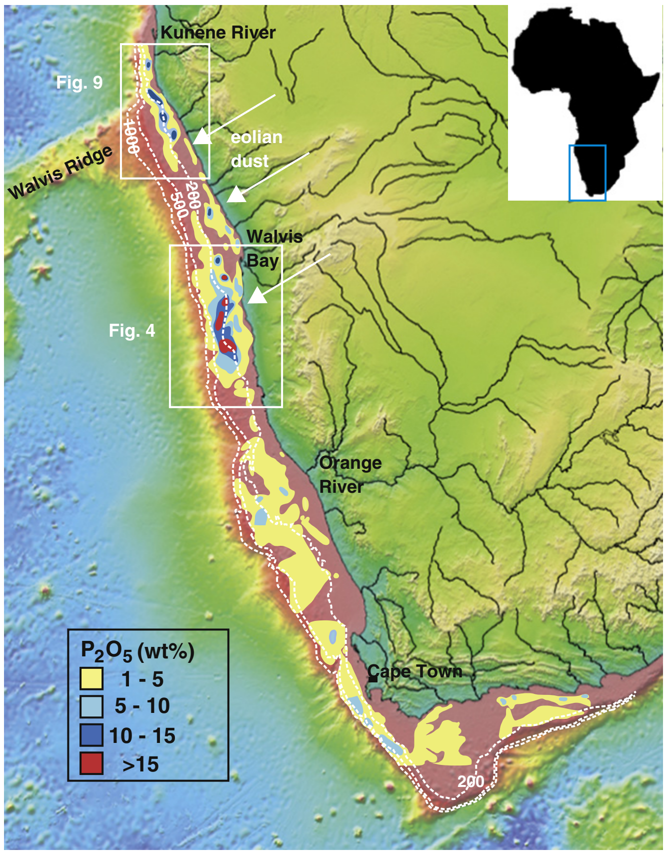

Fig. 1. The continental shelf of southern Africa (pink) and distribution of phosphorite deposits as indicated by bulk sediment P_2O_5 content (Birch, 1975; Bremner, 1977; Rogers, 1977). The richest deposits (>15 wt.% P_2O_5) occur on the Namibian shelf south of Walvis Bay.

There have been a number of studies on the petrography, mineralogy, chemistry and microbiology of phosphorite-rich deposits on the shelf (Baturin, 1969, 1982, 2000; Birch, 1975, 1979a,b,c, 1980, 1990; Bremner, 1977; Bremner and Rogers, 1990; Rogers, 1977; Compton et al., 2002, 2004; Wigley and Compton, 2006, 2007; Schulz and Schulz, 2005) (for a comprehensive review of the literature prior to 1990 refer to Rogers and Bremner (1991)). The phosphorite deposits offshore of South Africa are late Oligocene to Pleistocene in age based on biostratigraphy and strontium isotope stratigraphy (Compton et al., 2002, 2004). Holocene phosphorite from the diatomaceous mud belt is well established on the Namibian inner shelf (Bremner, 1977; Baturin, 1982, 2000), but the age and origin of the far more extensive phosphorite deposits on the Namibian middle to outer shelf are poorly known (Dingle et al., 1996).

Phosphorite and glauconite (potassium-rich, 'green sands') have been recent targets of offshore mineral exploration on the shelf (Coles et al., 2002). Cores recovered from these exploration programs have greatly increased our understanding of the subsurface extent and nature of the shelf phosphorite and glauconite deposits off South Africa (Wigley and Compton, 2006, 2007). This paper integrates unpublished and published studies on the phosphorite deposits on the Namibian shelf to derive a more complete understanding of the extent, age and origin of these deposits. A model is proposed on how these economic phosphorite deposits formed and how their formation is possibly linked to paleoceanographic as well as climatic changes in southern Africa during the Quaternary.

2. Geological and oceanographic setting

The Namibian continental passive margin formed during the Cretaceous breakup of Gondwana. The margin has an unusually broad and deep shelf that extends to 400 m water depth (Fig. 1). The shelf can be divided into an inner, middle and outer shelf (Rogers, 1977). The inner shelf extends to approximately 130 m water depth where it is commonly marked by a wave-cut terrace or notch formed when the inner shelf area of the margin was exposed during sea-level lowstands of glacial periods. The middle shelf is a relatively low gradient area that extends to approximately 200 m water depth. The outer shelf extends from 200 to 400 m water depth and has a steeper gradient than the middle shelf. The shelf break occurs between 400 and 500 m and is marked by the increased gradient of the upper slope.

Precambrian basement rocks are exposed on the rocky shoreline and extend onto the inner shelf, with seaward dipping reflectors further offshore on the shelf interpreted to be Cretaceous to Cenozoic deposits (Rogers, 1977). The Cenozoic succession on the shelf is relatively thin and poorly documented from several dredged samples of Neogene limestone and stiff clay (Bremner, 1977). The seaward dipping beds form an erosional surface which is variably overlain by Pleistocene to Recent (Holocene) sediment. The suspended mud fraction delivered by the Kunene River is transported by bottom water currents (the poleward undercurrent) along the margin to form the Holocene diatomaceous mud belt, a wedge of sediment up to 15 m thick that stretches along the Namibian inner shelf between water depths of 50 m and 140 m (Bremner, 1977). The Namibian mud belt is similar to the Holocene Orange River (Namaqualand) mud belt off South Africa (Herbert and Compton, 2007), but grades into an organic-rich, diatomaceous ooze south of the Kunene River. Surface currents along the western margin are complex and consist of seasonal equatorward drift, coastal filaments and Ekman drift (Shannon and Nelson, 1996).

All other rivers draining into the Atlantic Ocean between the Orange and Kunene rivers are ephemeral and only episodically deliver sediment to the coast during floods. Although mostly dry, these ephemeral river beds and surrounding areas are sources of windblown sediment, particularly in regions north of the Namib Desert. A significant amount of terrigenous sediment is delivered to the shelf by wind, primarily during Berg wind conditions when air descends from the Great Escarpment and transports sediment offshore (Eckardt and Kuring, 2005). Inboard of the mud belt are coastal sands and gravels subject to periodic storms throughout the year having wave heights exceeding 5 m (Rossouw, 1984). The predominant swell direction is from the southwest and net longshore drift of coastal quartz-rich sand is to the north (Rogers, 1977; Bremner, 1977). Rather than accumulating on the shelf, most quartz sand ends up windblown onto land, feeding the Namib Sand Sea and most is ultimately sourced from the Orange River (Vermeesch et al., 2010).

Besides terrigenous sediment offshore of the Kunene River mouth, the middle to outer shelf is dominated by carbonate-rich sediments. Bottom currents and internal waves suspend and transport mud from the middle and outer shelf onto the upper slope (Monteiro et al., 2005; Inthorn et al., 2006; Compton and Wiltshire, 2009). The result is a mix of relict shelly gravel and foraminiferal sand on the middle to outer shelf that transitions into increasingly muddy nannofossil foraminiferal ooze on the upper slope. Highly condensed, relict phosphorite deposits are exposed on the middle shelf region between 130 and 400 m water depth and correspond to Plio/Pleistocene organic-rich, nannofossil and diatomaceous mud successions 400 to 600 m thick on the upper slope (Wefer et al., 1998a).

The Namibian margin occupies a classic eastern boundary setting with significant coastal upwelling associated with the Benguela Upwelling System (BUS) (Shannon and Nelson, 1996). The BUS extends along the western margin of southern Africa from Cape Town to the Kunene River mouth (Fig. 2). The Benguela Coastal and Benguela currents are distinct from the BUS, forming the eastern limb of the South Atlantic gyre and flow equatorward further offshore of the BUS. Seasonally strong, predominantly southerly winds drive the BUS through Ekman transport of surface waters away from the coast as they are replaced by deeper, nutrient-rich waters from below. The upwelling of nutrient-rich waters results in high productivity, with the BUS measured as one of the world's