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History of the Benguela Upwelling System since the Oligocene inferred from phosphorite deposits on the western margin of southern Africa

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The Benguela Upwelling System is one of the World's oceans most productive eastern boundary currents with upwelling cells uniquely centred over the continental shelf. Holocene organic-rich sediment deposition results from these high-productivity surface waters and is the site of marine authigenesis that includes glauconite, pyrite, dolomite and phosphorite formation. The history of upwelling on the margin, however, is not well understood because of poor sediment preservation and difficulties in resolving the age of reworked deposits. Here we report on an integrated study of the Sr isotope stratigraphy, biostratigraphy and lithostratigraphy to elucidate the complex diagenetic history of the margin and its relation to global palaeoceanographic events including other late Cenozoic phosphorite deposits. The Sr isotope composition of phosphorite (carbonate fluorapatite) cemented grains (PCG), phosphate cemented limestone (PCL), skeletal phosphorite grains (SPG) and biogenic calcite (mollusc shell, benthic foraminifera and echinoid spines) from sediments of the western continental shelf of South Africa ranges from 0.707981 to 0.709167 and corresponds to an age range of late early Oligocene to late Pleistocene. Most biogenic carbonate Sr ages agree with biostratigraphic ages, but some samples contain significantly older and reworked robust ($>$250 μm) benthic foraminifera. Although the Sr ages of biogenic and phosphorite grains indicate that sedimentation was fairly continuous, most sediment is reworked with only lower Miocene, upper Pliocene and upper Pleistocene successions generally preserved. The initial phosphogenic episode from the latest Oligocene to early early Miocene (21-26 Ma) was the largest, with additional phosphogenic episodes in the late early Miocene (16-19 Ma) and middle Miocene (10-15 Ma). Most phosphorite occurs as PCG that formed during marine transgres-

sions and highstands from the late Oligocene warming event until the mid-Miocene climatic optimum, a period of episodic Antarctic glaciation and several positive marine δ^{13}C excursions. Upper Oligocene to lower Miocene PCG are extensively reworked and associated with major erosional unconformities. PCG vary from peloidal sands to gravel mollusc moulds and contain variable amounts of quartz, glauconite and pyrite inclusions. PCL formed from 9 to 17 Ma by cementation and replacement of older calcareous sediment during the middle to late Miocene marine regression. Phosphorite, as well as associated glauconite and pyrite, indicate that periods of rapid accumulation of organic-rich, terrigenous mud derived from the focusing of the suspended load of rivers and organic matter produced in areas of coastal upwelling have occurred episodically on the margin since the late Oligocene. The relative paucity of phosphorite younger than the middle Miocene may result from frequent erosional events as documented by pronounced unconformities on the shelf that reflect lowered eustatic sea level, tectonic uplift and high-frequency, high-amplitude Quaternary sea-level fluctuations. Phosphogenesis on the South African margin largely overlaps with, but is initiated up to a million years before, the large phosphorite deposits on the Florida Platform.