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Introduction to the Crato Formation

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The Crato Formation takes its name from the university town of Crato, Ceará, situated in a forested cirque in the north central part of the Chapada do Araripe, a large tableland in north-eastern Brazil (Plate 1a). Its outcrop pattern forms a narrow strip along the flanks of the plateau, and is also present as a few isolated outliers to the south of the plateau. As one of the few limestone units in the region, the Crato Formation supports a unique flora of lime-loving species, and even appears to have an endemic bird, the Araripe manakin, *Antilophia bokermanni*, living on the outcrop near Arajara. This bird was only discovered in 1996 (Coelho and Silva, 1998) and apparently has the smallest geographic range of any bird species, only 1 km^2.

The Crato Formation is mined commercially for cement manufacture and paving stones, and is thus of considerable economic importance to the region, providing both raw materials and employment in its extraction (Plate 1b). It is in the quarries where the slabby limestones are extracted for paving stones that an astonishingly high number of rare and beautiful fossils occur. The preservation of the fossils is often exquisite, and many form the centre pieces of museum exhibitions. Although the formation is some 50–60 m thick, and comprises a varied series of rock types, it is only the basal unit, a 0–13-m-thick series of laminated limestones known as the Nova Olinda Member, that yields the spectacular fossils, and earns the formation its status as a Fossil Konservat Lagerstätte. Elsewhere in the succession fossils are extremely rare, or absent altogether.

But it is not just the beauty and quality of preservation of the fossils that makes the Crato Formation a world-class Fossil Lagerstätte. It was deposited when Gondwana was still reasonably intact and in a sedimentary basin located close to the heart of that supercontinent. It also is of an age when angiosperms were beginning to diversify, and the co-evolution of insects as their pollinators was just beginning. It thus forms

one of the best windows into a Cretaceous Gondwanan ecosystem and, perhaps uniquely, allows the co-evolution of the flowering plants and their pollinators to be investigated. Indeed, it may prove to be one of the most diverse assemblages of a Cretaceous terrestrial biota known anywhere, for although it has only been studied palaeontologically since the early 1980s (Brito, 1984), in just a little over 20 years over 200 new species have been discovered and described from this exceptional deposit.

The relationship of the Crato Formation with other sedimentary units in the basin has been covered extensively (da Silva, 1986; Ponte and Appi, 1990; Assine, 1992; Ponte and Ponte Filho, 1996) but there are still problems for intraformational correlation, especially between the sub-basins. There have also been a number of attempts to date the formation using palynomorphs (Lima, 1978, Pons *et al*., 1990), but despite the palaeontological attention that this deposit has attracted (e.g. Grimaldi, 1990; Maisey, 1991; Martill, 1993), there have been few detailed studies on its general geology, and sedimentology.

A number of aspects of the Crato Formation remain problematic. Indeed, the name itself is controversial. Although first designated a formation by Beurlen (1963), he later relegated the unit to a member (Beurlen 1971), and although Martill and Wilby (1993) made a case for reinstating its formation status, some workers have been reluctant to recognize this. The depositional environment of the Nova Olinda Member is also problematic, and has been claimed to have occurred in fresh (Maisey, 1990, 1996), hypersaline (Martill and Wilby, 1993) or brackish water (Bechly, 1998; Neumann *et al*., 2003). Similarly, the water depth has been considered to have been shallow (Maisey, 1990) or relatively deep (Martill and Loveridge, 2006), although few workers have attempted to put figures on the depth. Furthermore, the size of the water body is in some doubt. Those who argue for a freshwater lake environment have indicated that the water body was restricted to the Araripe Basin and contained within its fault bounded margins (Ponte and Appi, 1990), while Beurlen (1971) indicated that it may have had connections with adjacent basins to both the west and north, and possibly the south. In terms of semantics, some call it a lake or palaeolake, while others refer to it as a lagoon (e.g. Martill, 1993). Even the age of the deposit is in some doubt, and is nearly always cited as possibly late Aptian or early Albian (Berthou *et al*., 1990). The unit was mapped as part of Projeto Santana during the 1970s, but 'ground truthing' reveals many inaccuracies. Thus it would seem that there remains ample scope for much interesting research on this important formation.

The Crato Formation has been proposed as a potential World Heritage Site by Viana and Neumann (1999), and there is no doubting its extreme scientific importance. However, most of the fossils that exist in scientific collections are a consequence of commercial activities, including the trading of fossils. Essentially,

the fossils are found by quarry workers who manually extract the Nova Olinda Member limestone, and have a good eye for finding even the smallest of fossils. The fossils that they find are sold at very low prices to a group of 'middle-men' based mainly in Santana do Cariri and Nova Olinda. These gentlemen, who are acutely aware of the worth of the fossils, then sell them on to dealers based in São Paulo and abroad. Without this trade, there would be very few fossils for scientists to study. Although it is possible to undertake scientific excavations, the chances of finding exceptional material are slim, and certainly would be limited by expense of such excavations: thus, scientific palaeontology needs this trade (Martill, 2001). In a few quarries the owners have issued strict instructions for the workers not to collect and sell the fossils. In these quarries potentially valuable fossils are simply thrown on the spoil dumps and carted off to be ground into cement.

It is the aim of this book to summarize the work undertaken so far and to synthesize the present understanding of the geology, sedimentology and palaeoenvironmental setting of this important deposit. It is also an aim to introduce as much of the palaeobiota as is practicably possible within the confines of these pages. Some authors, in reviewing the fossils in their collections, have discovered new species, or have re-evaluated the status of previously described taxa. Thus, this book is hopefully more than just an introduction to the fossil assemblage; it also contains the results of some new and innovative studies published for the very first time.

Many of the chapters in this book refer to specimens in collections indicated by their museum number, with the following abbreviations being used:

AMA-I, Universidad Federal de Ceará, Fortaleza, Brazil; AMNH, American Museum of Natural History, New York, USA; BSPGM, Bayerische Staatssammlung für Paläontologie und Historische Geologie, Munich, Germany; CAMSM, Sedgwick Museum, Cambridge, UK; CJW, Collection Wunderlich, Straubenhardt, Germany; CV, collection Vulcano, Brazil; DNPM, Departamento Nacional Produçao Mineral, Rio de Janeiro, Brazil; GP/It Universidad Guaralhos, São Paulo, Brazil; IMCF, Iwaki Coal and Fossil Museum, Iwaki, Japan; IVPP, Institute for Vertebrate Palaeontology and Palaeoanthropology, Beijing, China; JME, Jura-Museum, Eichstätt, Germany; KMINH, Kitakyushu Museum of Natural History & Human History, Kitakyushu, Japan; LEIUG, Geology Department of the University of Leicester, Leicester, UK; MCSNM, Museo Civico di Storia Naturale, Milano, Italy; MCT, Paleontological Collection of the Setor de Paleontologia do Departamento Nacional de Produção Mineral (DNPM), Rio de Janeiro, Brazil; MNRJ, Museu Nacional, Rio de Janeiro, Brazil; MNB, Museum für Naturkunde, Berlin, Germany; MNHM, Museum National d'Histoire Naturelle, Paris, France; MSF, ms-fossil, Sulzbachtal, Germany; MURJ, collection Masayuki Murata, Kyoto, Japan; MZUSP, Museu de Zoologia da Universidade de São Paulo, São Paulo, Brazil; NHM, Natural History Museum, London, UK; NSMT, National Science Museum/Tokyo University, Tokyo, Japan; RGMN, Martins-Neto Collection, Sociedad Brasileira de Paleoartropodologia de Ribeirão Preto and at MZUSP (see above); PMSC, Palaeontological Museum, Santana do Cariri, Brazil; SMF, Naturmuseum Senckenberg, Frankfurt am Main, Germany; SMNK, Staatliches Museum für Naturkunde,

Karlsruhe, Germany; SMNS, Staatliches Museum für Naturkunde, Stuttgart, Germany; TMM, Texas Memorial Museum, Austin, Texas, USA; UM, Ulster Museum, Belfast, UK; UOP, Department of Earth and Environmental Sciences, University of Portsmouth, Portsmouth, UK.

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