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Article

Mesozoic fossil sustainability: synoptic case studies of resource management

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Abstract: Fossils are a non-renewable natural resource that is not only important to science but also has immense value for education, tourism and commercial trade. Although the importance of sustainably managing exceptionally rich fossil localities is widely acknowledged, it is not universal and irreplaceable scientific information and socioeconomic benefits are being lost. This study provides an overview of the economic, social and environmental factors affecting 10 contrasting fossil localities in Germany, China, Brazil, the United Kingdom, Canada, Australia and France that are significant for preserving the remains of Mesozoic vertebrates; these are amongst the most spectacular extinct animals and readily capture the public imagination. A discussion in the context of sustainable development is carried out. Non-extractive and scientific/educational (e.g. museums, geotourism) usage of fossil deposits are fully sustainable and benefit communities both economically and socially. Conversely, extractive uses (commercial collecting, quarrying) effect resource depletion but can be managed through scientific involvement, regulation and reinvestment of profits. Ultimately, implementation of an integrated approach embracing both profitable development and appropriate protection measures may ensure optimal usage of fossils for the future.

Keywords: Mesozoic vertebrate fossils; palaeontology; geoconservation; geotourism; education; sustainable exploitation.

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Introduction

Fossils are a natural capital (i.e. a naturally occurring resource which can impart welfare; Weighell 2001) that can be converted into social capital as scientific knowledge, educational and recreational opportunities, as well as into economic capital via sale as decorative construction stone or on the commercial collectables market (Webber et al. 2006). However, unlike "non-renewable" fossil *fuels*, which are ultimately renewed in identical form (Van Seters & Price 2001), structural (*body*) fossils and trace (*ichno*-) fossils (e.g. preserved footprints, feeding traces) convey unique knowledge about the past, and are thus irreplaceable in terms of its information content and cultural importance. As with any resource (WCED 1987), sustainable management of fossils must ensure that current usage does not undermine welfare gains by future generations. In the case of fossils, this means not only using the resource at a sustainable rate, but conserving its irreplaceable knowledge value.

A number of authors have discussed the philosophical and economic implications of sustainable fossil usage. *A Future for Fossils* (Bassett et al. 2001) brought together a synthesis of basic principles and management strategies for the conservation of geological sites. Martill (2001) and Besterman (2001) debated the ethics of collection and specimen acquisition by researchers. Dalton (2000, 2004), Du (2004), Fedonkin et al. (2009) and Hecht (2007) reported on the interactions between private collectors and scientists, and Schmidt (2000) and Bloos (2004) addressed the effectiveness of fossil protection legislation. Webber et al. (2006) and Hagan-Braun (2008) investigated the financial costs and benefits of geoconservation. The development of geoconservation is comprehensively summarized in the recent book *The History of Geoconservation* (Burek & Prosser 2008). The development and economics of geotourism and geoparks have been documented by Hose (2008), McKeever & Zouros (2005) and in the volume *PaleoParks* (Lipps & Granier 2009). This study builds on these contributions by undertaking a comparative survey, in the explicit context of sustainable development, of the various usage issues and management solutions affecting 10 different dinosaur and other Mesozoic vertebrate fossil localities. Mesozoic vertebrates provide an important test case because their remains are often spectacular and enjoy a high media profile. This popularity makes them especially sought after for the fossil trade and facilitates geotourism. Possible ways to improve the sustainability of usage of these important fossil resources are discussed.

Overview of resource usage at key Mesozoic fossil localities

Ten case study localities were selected on the basis of their diverse historical (well documented vs. more recently discovered), preservational (body fossil vs. ichnofossil, and *Konservatlagerstätten* vs. *Konzentratlagerstätten*), stratigraphical/geographical (restricted vs. wide ranging) and economic/-social (high income-developed vs. middle income-developing) parameters. Information was obtained from the literature in conjunction with site visits and/or remotely conducted interviews involving staff or individuals directly associated with the activities at each location (see Acknowledgements). These data are summarized in Tables 1–3 and in the extended online supplement.

Konservatlagerstätten in a high-income country (Germany)

Holzmaden. The Lower Jurassic (~175 million years ago [Ma]) black shale deposits around Holzmaden and Ohmden (east of Stuttgart, Baden-Württemberg) are famous for preserving fully articulated ancient marine reptile skeletons (e.g. ichthyosaurs, plesiosaurs, marine crocodiles), some with soft tissue impressions (Etter & Tang 2002: Fig. 1). Commercial usage of these fossils has stemmed from the traditionally important decorative shale (*Fleins*) industry. One local quarry, *Schieferbruch Kromer* (Holzmaden), still operates *Fleins* excavations, but all other former quarries have been backfilled and the land returned to agricultural use. *Schieferbruch Kromer* supplements its income by the sale of fossils that are not subject to compulsory purchase under state legislation (*Schatzregal* law) governing scientifically significant materials (Table 1). Tourists can also pay to collect their own specimens, and a second quarry, *Steinbruch Fischer*, has additionally opened a small museum to attract visitors. The largest museum in Holzmaden is the privately owned *Urweltmuseum Hauff* (Table 2), which enjoys high visitor numbers and maintains interpretive displays, together with a collaborative scientific research programme involving the *Staatliches Museum für Naturkunde* in Stuttgart. *Urweltmuseum Hauff* is funded by a combination of entrance fees and shop/café sales (both of which are dependent upon seasonal tourism), commissioned fossil preparation, and private donations/state support (Table 2). In general, good road access has enhanced the financial viability of quarries and museums in the Holzmaden/Ohmden area (Tables 2 and 3). Economic benefits are limited for other businesses, but some visitors and tour groups utilize nearby food outlets, and contributions to local employment by fossil-related industries have garnered strong community support.

Table 1. Legal constraints governing the excavation, sale and export of fossils in the case study countries and localities.

Jurisdiction	Regulations governing fossils
Germany	European Union requires permit for fossil exports over €50 000. Federal state (*Bundesland*) regulations vary: Baden-Württemberg – "*Schatzregal* law" renders scientifically important specimens state property with financial reimbursement for collectors' expenses; Bavaria – full ownership rights to landowner
China	All fossils are state property with private ownership and commercial sale prohibited; Liaoning provincial exception allows ownership and internal sale of non-tetrapod fossils. Infringement penalties potentially include capital punishment and imprisonment
Brazil	All fossils are state property with private ownership and commercial sale prohibited. Infringement penalties include imprisonment, fines and deportation for foreign nationals caught in breach
United Kingdom	European Union requires permit for fossil exports over €50 000. Full ownership rights to landowner in England and Wales except when designated a *Site of Special Scientific Interest* (meaning land-use changes must not jeopardize scientific importance) or *Nature Reserve*. Scotland designates all important finds state property. Local laws: Dorset – "*West Dorset Fossil Code*" permits responsible collecting enforced by National Trust and Charmouth Council; Isle of Wight – non-enforced collecting code
Canada	All fossils (excluding ammolite and amber) are Crown property with private ownership and commercial sale prohibited. Infringement carries maximum penalty of 1 year incarceration and CAD$50 000 fine
Australia	Full ownership rights to landowner except where site covered by a mineral exploration claim. International exports over AUD$50 000 require permit. State/territory regulations vary: Queensland – excavation of vertebrate fossils requires state government permit, landowner/-leaser permission and acknowledgment of indigenous land custodianship (if applicable)
France	European Union requires permit for fossil exports over €50 000. Within France, full ownership rights to landowner except for protected sites such as *Réserves Naturelles Géologique*

Solnhofen. The Upper Jurassic (~145–155 Ma) limestones around Eichstätt and Solnhofen (north-west of Ingolstadt, Bavaria) are globally renowned for discoveries of the celebrated feathered dinosaur *Archaeopteryx*, and other exceptionally preserved fossils including pterosaurs, non-avian dinosaurs, aquatic reptiles, fishes and invertebrates (Barthel et al. 1990). For centuries, extraction of decorative lithographic limestone has been an important industry for the region, and today still supports many workers, although these are seasonal, being laid-off during quarry closures in the winter. The numerous disused quarry sites have had a positive impact on local biodiversity, with many designated as "*Biotop*" reserves because they support unique colonizer floras. Avoidance of groundwater contamination from quarrying and site remediation is mandatory. There is a well-established commercial trade in fossils, facilitated by unrestricted sale of specimens from private lands (Table 1). Small businesses specializing in fossils (Table 2) cater to the tourist market. Visitors can also pay to collect at the *Besuchersteinbruch* (visitor quarry) *Mühlheim* (Fig. 2); here, valuable finds are retained by the owners with purchase priority given to scientific buyers. Fossils can also be collected for free with equipment rental at *Blumenberg Quarry* (Eichstätt) and at the Hobbysteinbruch (Solnhofen; equipment rental at the *Bürgermeister Müller Museum*). The public/church-funded *Jura Museum* (Eichstätt) and public *Bürgermeister Müller Museum* (Solnhofen) host competent educational displays and important collections. Visitors comprise mainly tourists and school groups. Some scientific research is output from the *Jura Museum* via internal funding and collaborations with other institutions. A small, privately subsidized museum, *Museum Bergér*, is also present in Eichstätt. Despite the importance of geotourism, outdoor pursuits within the *Naturpark Altmühltal* provide the main regional attractions.

Konservatlagerstätten in middle-income countries (China and Brazil)

Liaoning. The Jehol Group deposits of Liaoning crop out in the Heibei, Liaoning and Nei Menggu provinces of north-eastern China. These strata have yielded elements of a complex Lower

Table 2. Sources of income and expenditure items for major fossil-related attractions at the case study localities. See online supplement for further details.

Locality	Attraction	Sources of income	Expenditure items
Holzmaden (Germany)	*Urweltmuseum Hauff*	Entrance fees (35 000 visitors/a); guided tour fees; shop, café and fossil sales; private donors and state grants	Staffing (full-time permanent and part-time); events; exhibition maintenance and upgrade; facilities
	Steinbruch Kromer	Fossil collecting (20 000 visitors/a); decorative shale sales (~50%); fossil sales	Staffing; machinery and maintenance
	Steinbruch Fischer	Entrance fees and tool rental	Staffing; museum and quarry maintenance
Solnhofen (Germany)	*Juramuseum Eichstätt*	State funding – Bavarian State Collection for Natural History (*Staatsammlung für Naturkunde*), Bavarian Ministry of Finance; Bishop's Seminary at Eichstätt (reimbursed); entrance fees (60 000 visitors/a); industry sponsorship (Volkswagen Stiftung)	Staffing (full-time permanent and part-time); exhibition development and maintenance; research costs; facilities
	Museum Bergér	Fossil sales and preparation services; entrance fees; club membership fees; small municipal donations	Staffing (sales); maintenance
	Blumenberg Quarry	Entrance fees; equipment rental; fossil sales; shop sales; European Union grant	Staffing (full-time permanent and part-time); shop and quarry rental and maintenance
	Bürgermeister Müller Museum Solnhofen	Entrance fees (30 000 visitors/a); museum tours and shop sales; large municipal donation	Staffing (full-time permanent and part-time); exhibition maintenance
	Besuchersteinbruch Mühlheim	Entrance fees; fossils sales; excavation groups	Staffing (part-time only); quarry maintenance; consultancies
Jehol (China)	*Beipiao Museum*	State funded	Staffing (full-time guards); construction costs; maintenance
	Chaoyang Fossil Bird Reserve	State funded	Staffing (full-time guards); maintenance
Araripe (Brazil)	*Museu de Paleontologia, Santana do Cariri*	State funded; separate one-off state grant for restoration project	Staffing (full-time and part-time); maintenance; building restoration
Isle of Wight (England)	*Dinosaur Isle Museum*	Grant funded (Millennium Commission); entrance fees; shop sales and tours	Initial building construction and on-going maintenance; staffing (full-time permanent and part-time); media promotions
Dinosaur Provincial Park (Canada)	*Dinosaur Provincial Park Visitors Centre*	State grant funded; campsite and shop sales (~100 000 visitors/a)	Staffing (full-time permanent and seasonal part-time); building and park maintenance
	Royal Tyrrell Museum of Paleontology	State funded (340 000 visitors/a)	Staffing (full-time permanent and part-time); building, exhibitions and facilities maintenance both on-site and at field station; research costs
Jurassic Coast (England)	*Charmouth Heritage Centre*	State (Heritage Lottery Fund) and municipal (West Dorset County Council) funded; shop sales, tours and off-site walks	Staffing (full-time permanent and part-time); building maintenance
	Lyme Regis Museum	Visitor entrance fees; local government subsidy; fossil and heritage walks	Museum maintenance; staffing
	Dinosaurland Fossil Museum	Visitor entrance fees; bank loan to buy and restore building	Building purchase; museum and building upkeep; collection/display expansion; staffing (owner and wife)
Winton (Australia)	*Australian Age of Dinosaurs Museum*	Government and private donations; entrance fees (12 000 visitors/a); shop sales; pay-to-dig geo-tourists. Research programme supported by private sponsorship and federal government grants involving scientists	Staffing (full-time permanent and part-time); building maintenance and fossil preparation; excavations and media promotions
Ardley Quarry (England)	*Oxfordshire Museum*	Local council grants; shop sales and exhibitions space function hire; private and industry (tax credit scheme)	Staffing (permanent full-time and part-time); building, exhibitions and external site maintenance
	Oxford University Museum of Natural History	Central government; university; private grants	Staffing; museum upkeep; exhibitions
Crayssac Plage aux Ptérosaures (France)	*Crayssac Quarry Visitor Centre*	Local government; solar power set-up and maintenance by donation; (Électricité de France in exchange for return electricity); entrance fees; tour fees	Initial site purchase; building; electricity and solar roofing maintenance; staffing (part-time)

Cretaceous (~133–120 Ma) ecosystem, including early modern (therian) mammals (Meng et al. 2006; Hu et al. 2010) and feathered dinosaurs, the latter shedding light on the origin of birds (Zhou et al. 2003). The sale and export of Chinese vertebrate fossils is prohibited by the central government, although non-tetrapod remains are traded in Liaoning and illegal collecting is a major source of income amongst the impoverished local populace (Dalton 2000; Table 1). This is despite heavy penalties including incarceration and even potentially capital punishment (Schmidt 2000). Incentives to collect are amplified by poor law enforcement (Schmidt 2000) and corruption (e.g. bribery or resale of confiscated specimens by the authorities: Dalton 2004). State-funded economic development of the Jehol Group fossils has come in the form of museums (Table 2) including the ~ US$1.2 million *Sihetun Geology Museum* at Beipiao (Dalton 2000), a much smaller

Table 3. Transport and accessibility for major fossil-related attractions at the case study localities.

Locality	Site access
Holzmaden (Germany)	Private car (nearby motorway); public bus to within 1 km, connecting to national rail network; cycling possible from nearby station
Solnhofen (Germany)	Private car to all locations via Eichstätt. Direct rail link to the *Jura Museum* and *Bürgermeister-Müller Museum*. *Bergér/Blumenberg* quarries accessed by foot, bus or bicyle; Mühlheim Quarry only accessible by car or bicycle from Solnhofen
Jehol (China)	Private car or public bus. Rail and long-distance buses connect via Chaoyang (42 km from Beipiao)
Araripe (Brazil)	Private car or public bus/minivan. National buses to Crato (56 km from Santana do Cariri) and Jazeiro do Norte (66 km from Santana do Cariri). Nearest airport at Jazeiro do Norte. Direct access road to *Museu de Paleontologia* at Santana do Cariri under repair as of 2009
Isle of Wight (England)	Private car, public bus (includes ferry) and national rail connection to Sandown; adequate disabled access to *Dinosaur Isle Museum*. Beach entry via car, bicycle or foot
Dinosaur Provincial Park (Canada)	Private car only to park. Air, bus and rail connections to Calgary (240 km from park) or Edmonton (418 km from park), bus to Drumheller (150 km from park)
Jurassic Coast (England)	Private car and public bus to most major sites. National rail, connecting with buses, to Weymouth (45 km from Lyme Regis)
Winton (Australia)	Private car or hotel shuttle/taxi from Winton to site. Long-distance coach from Winton to Brisbane (1,360 km) and Longreach (179 km). Flights to Winton from Longreach, and Longreach to Brisbane
Ardley Quarry (England)	Private car to site. Public bus and car to Woodstock (*Oxfordshire Museum*). Public bus, train and car to Oxford (*Oxford University Museum*)
Crayssac Plage aux Ptérosaures (France)	Private car only. Rail link to Cahors (15 km to site) and bus to Calamane (5 km to site)

facility at Shenyang and the 46 km^2 *Beipiao Fossil Bird Reserve* Geopark near Chaoyang (Fig. 3). Although imposing, the educational content of these displays can be inaccurate and visitor numbers are low despite adequate road access and public transport (Table 3). The (Beijing) Institute of Vertebrate Palaeontology and Palaeoanthropology carries out all formal scientific excavations in the Jehol Group; however, permits must be issued from the regional authorities (Du 2004), and international as well as non-local Chinese researchers frequently encounter bureaucratic difficulties (Dalton 2000). Most of the major discoveries are still derived from non-professional sources (Dalton 2009; Hecht 2007), leading to ambiguous contextual data (Dalton 2000) and environmental damage through the lack of site rehabilitation and subsequent topsoil loss.

Araripe. The Araripe Basin around Ceará in north-western Brazil was listed as a UNESCO Geopark in 2006 at the instigation of local scientists. This was because of its unique record of three-dimensionally preserved fossils, spanning the Crato (~ 115 Ma: producing plants, insects and pterosaurs) and Santana (~ 105 Ma; world recognized for its fish, turtles, crocodiles, rare dinosaurs and diverse pterosaur record: Fig. 4) formations, together with the breathtaking landscape (Chapada do Araripe) of plateaux and escarpments (Martill et al. 2007). Interest in the Araripe fossil material has stemmed from ornamental stone quarrying of the Crato Formation, which still remains a primary industry, but is increasingly supplemented by illegal fossil excavation and trading from the Crato and Santana Formations (Besterman 2001; Table 1). Widespread poverty and cheap labour costs have created a profitable market, with 100–10 000-fold price increases occurring from the point of origin to final export sale (Besterman 2001; Martill 2001). Interception by law enforcement agencies usually occurs at the local dealer stage, and police or customs officials have been implicated in resale of confiscated specimens (Martill 2001). The Araripe fossil trade can be dangerous because local dealers and police carry guns (Martill 2001), and both scientists and collectors/dealers have reportedly been imprisoned or deported for trying to export fossils (Martill & Heads 2007). Government input has led to the establishment of the *Museu de Paleontologia* at Santana do Cariri (Table 2), which boasts a collection valued at upwards of US$30 million (Geopark Araripe 2009; RBS accessed 10/8/2010: http://www.geoparkararipe.org.br/), and provides both laboratory space and accommodation for visiting scientists (Martill & Heads 2007). Other smaller educational displays have also been set up at Jardim and Crato (Martill & Heads 2007). Interpretive signage is being installed (along with better road access; Table 3) at important sites, as well as "Geotope" reserves (specially maintained rock exposures), and viewpoints (Martill & Heads 2007). This has increased regional

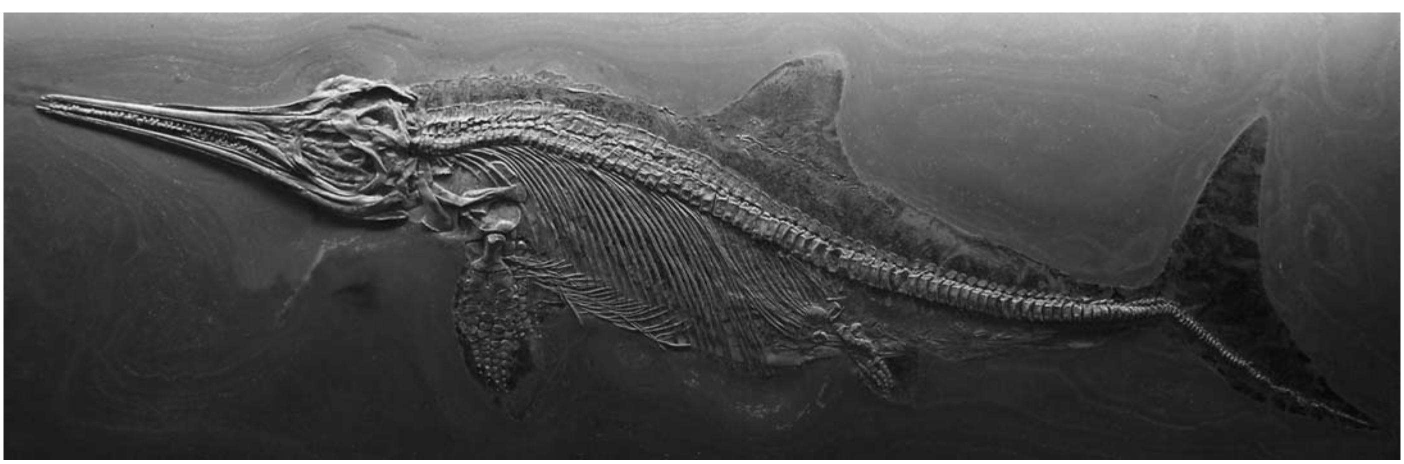

Fig. 1. Articulated skeleton of the ichthyosaur *Stenopterygius quadricissus* preserved with a carbonized body outline, Lower Jurassic of Holzmaden, Germany. Image courtesy Erin Maxwell (Universität Zürich).

Fig. 2. Besuchersteinbruch Mühlheim in southern Germany allows tourists to pay to excavate fossils from the famous Upper Jurassic Solnhofen limestone.

infrastructure development and employment. Scientific excavations in the Araripe Geopark can only be conducted in conjunction with Brazilian researchers and require government permission (Besterman 2001), which is centralized and often difficult to obtain (Martill & Heads 2007). A lack of site management and aridity has also precipitated topsoil loss and

Fig. 3. The on-site interpretive centre at the Beipiao Fossil Bird Reserve Geopark near Chaoyang in north-western China. Image courtesy Thomas Rich (Melbourne Museum).

Fig. 4. Complete skeleton of the Early Cretaceous pachyrhizodont fish *Notelops* (scale bar equals 100 mm) from the Araripe Basin. Image courtesy Matt Friedman (University of Oxford).

pollution of watercourses (Besterman 2001; Martill & Heads 2007).

Konzentratlagerstätten in high-income countries (United Kingdom and Canada)

Isle of Wight. The Isle of Wight off England's south coast is one of Europe's most historically important dinosaur localities, with finds including the iconic *Iguanodon* being described in the literature from as early as 1835 (Martill et al. 2001). The Isle of Wight, preserves a continuous section of Cretaceous strata (~130–65 Ma) and some Palaeogene (~65–23 Ma) outcrops in the northern part of the island (Munt 2001). Tourism has long been a major local industry and is facilitated by both good rail/road access and close proximity to major urban centres (Table 3). Visitors and local collectors frequently find fossils by patrolling the beaches in search of bones and footprint traces eroding from the cliffs. Two shops sell geological items, and in 2001 the public *Dinosaur Isle* museum was established at Sandown (Fig. 5; Table 2). This replaced the somewhat outdated *Museum of Isle of Wight Geology*. A second, privately run museum, *Dinosaur Farm*, opened a display of

Fig. 5. The Dinosaur Isle Museum situated between Sandown and Yaverland on the Isle of Wight, southern England.

Brachiosaurus-like sauropod remains but has recently closed. *Dinosaur Isle* has attractive exhibits including models, an animatronic dinosaur and a working fossil preparation laboratory. The collection incorporates many scientifically significant specimens but there are no permanent researchers, and professional palaeontological work is infrequent. Construction of coastal storm defences and increasing collection by tourists are a concern for some scientists, who perceive both as possible threats to site preservation. There have also been disputes between some amateur collectors and *Dinosaur Isle* staff (Simpson 2001), mainly regarding failures to obtain appropriate permissions for site access from landowners (M. Munt pers. comm. 2010). A fossil collecting code proposed in 2001 has not been widely accepted (Table 1), and nomination of the Isle of Wight as a UNESCO Geopark stalled because of a lack of committed personnel and fears that collecting restrictions would be too stringent.

Dinosaur Provincial Park Dinosaur Provincial Park World Heritage Site, east of Calgary in southern Alberta, Canada, is recognized globally as one of the most productive Upper Cretaceous (~74 Ma) dinosaur localities, with upwards of 40 distinct species having been identified to date (Currie 2005). By law all Canadian fossils are property of the Crown, except those which are treated as gem-grade commodities, e.g. ammolite (gem-like ammonite shell) and amber (Table 1). Strict law enforcement, including regulation of park boundaries and surveillance by both rangers and owners of adjacent properties, has effectively controlled illegal collecting. To further improve surveillance, most scientific work is conducted in remote areas where otherwise surveillance is limited (Landals 2009: see Fig. 1F). Unsupervised tourists are restricted to a small area of the park (Landals 2009). Dinosaur Provincial Park can only be visited by car but road/air infrastructure for nearby towns is well developed (Table 3). On-site facilities for the public are excellent, including a well-maintained interpretive centre (see Fig. 6: this incorporates a fully equipped fossil preparation laboratory) and a campsite with amenities and shops (the latter open during the summer). Both guided tours and self-guided educational trails are offered, with information services provided by seasonally employed staff and/or professional palaeontologists from the nearby *Royal Tyrrell Museum of Paleontology* in Drumheller (Table 2). The *Royal Tyrrell Museum* has world-class educational displays and an enormous collection centred around finds generated from annual digs in the park (Landals 2009). These excavations are conducted exclusively for scientific purposes and require a government permit. Only Canadian institutions actively undertake such work, but this is frequently in cooperation with international institutions. Indeed, joint programmes are common and research access is easily obtainable for specimens held in

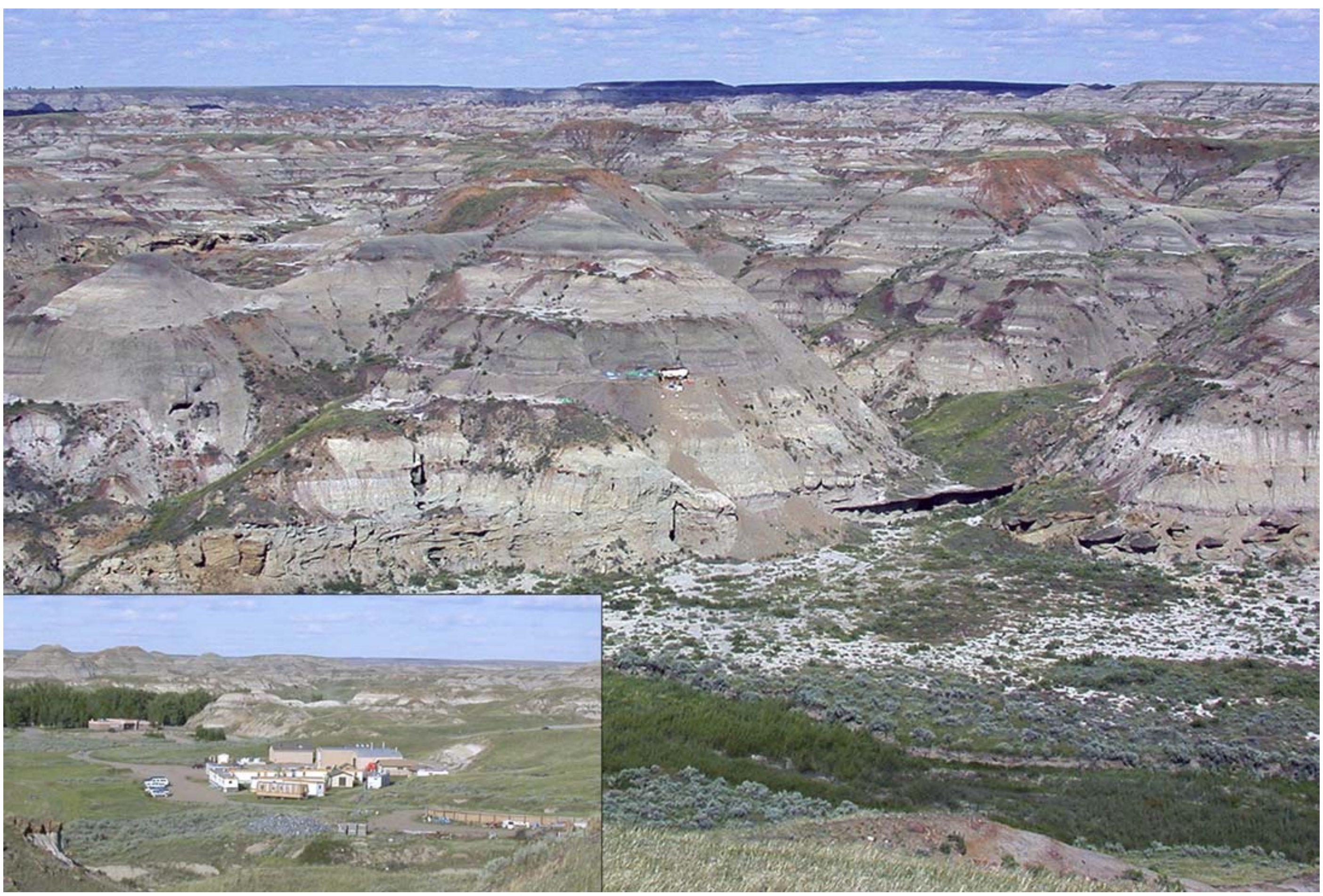

Fig. 6. Excavation of Late Cretaceous dinosaur fossils (distant centre foreground) in a remote area of badlands in Dinosaur Provincial Park, Alberta, Canada; inset (bottom left) shows the on-site interpretive and camping facilities. Images courtesy Robert Jones (Australian Museum).

Fig. 7. The Jurassic coast of southern England (facing westwards); inset (top left) shows the Charmouth Heritage Coast Centre at Charmouth in Dorset. Inset image courtesy Richard Edmonds (Charmouth Heritage Coast Centre).

museum/university collections throughout the country. Outside the park boundaries, developments impacting on bedrock are often required to carry out palaeontological assessment and excavation monitoring (Hyusick & Spivak 2009). This is usually initiated via an electronic database incorporating GIS mapping, which has been created to allow affected companies to determine their targeted site vulnerability and permit requirements (Hyusick & Spivak 2009).

Stratigraphically/geographically wide-ranging localities in high-income countries (United Kingdom and Australia)

Jurassic coast. The Jurassic Coast World Heritage Site spans 155 km of the English south coast between Devon and Dorset, and is renowned for both its section of Triassic–Cretaceous strata (~200–90 Ma; Fig. 7) and well-documented history of fossil discoveries, including the first reports from 1814 to 1821 of ancient marine reptiles such as ichthyosaurs and plesiosaurs (Howe et al. 1981). Given the geographically immense size of the area and wide distribution of the individual fossil localities, no one particular site can be singled out, although the epicentres for much of the geotourism activity are around Charmouth, Lulworth and Lyme Regis in Dorset. These towns are well serviced by transport infrastructure including buses and walking and cycling tracks (Table 3). Lyme Regis is especially famous as the historical home of the renowned fossil collector Mary Anning (Torrens 1995). Geotourism within the Jurassic Coast World Heritage Site generally complements other attractions. Commercial fossil collecting and trading supports substantial employment in Charmouth and Lyme Regis (R. Edmonds pers. comm. 2010). The publicly owned *Charmouth Heritage Coast Centre* (Fig. 7; Table 2) maintains displays and runs fossil identification services as well as guided walks; subsidiary income is also derived from shop sales and tool rental to tourists. The public *Lyme Regis Museum* has displays and runs site tours. The private and profitable *Dinosaurland Fossil Museum* at Lyme Regis displays a large collection of fossils, natural history items, and reconstructions. Professional scientific excavations are infrequent but the Jurassic Coast World Heritage Site does financially support research related to development of the geological resources. A fossil collecting code is enforced by the National Trust and local government in West Dorset (Table 1) forbidding disturbance of *in situ* specimens and stipulating formal recording of any scientifically important finds through a six-month assessment period to be undertaken in a British museum. Despite some prosecutions for breaches of the code, the effectiveness of these guidelines is unclear and some fear that ever-increasing visitor numbers may damage sensitive areas.

Winton. Lower Cretaceous (~100 Ma) rocks of the Winton Formation crop out over vast areas of central-eastern Australia, and have attracted media attention because of recent spectacular dinosaur discoveries (giant sauropods and carnivorous

Fig. 8. Geotourism "dinosaur dig" in the outback near Winton in central Queensland Australia. Image courtesy David Elliott (Australian Age of Dinosaurs Inc.).

theropods: Kear & Hamilton-Bruce 2011). Although widely dispersed, these finds have centred around the town of Winton in central Queensland; this is a result of systematic collecting rather than an unusually large accumulation of fossils. The excavation and popularization of the Winton dinosaurs has been made possible through a productive collaboration between scientists and *Australian Age of Dinosaurs Inc*. This not-for-profit organization was established and continues to be run by local residents for the purpose of developing the region's palaeontological heritage through tourism. Fossils can be freely sold within Australia, although collecting is legislatively restricted in some states and international export of valuable fossils is illegal without a permit. Fossil sites occurring within private pastoral holdings require permission from the property owner/manager to access. Additional legal constraints also govern registered mineral exploration claims, and indigenous or natural heritage reserves (Table 1). Fossil collecting around Winton is uncommon, partly because of remoteness and self-policing by landowners. Nonetheless, some other Australian fossil localities have been notoriously over exploited for trade, and instances of illegal extraction and export from geological reserves/native title lands are known (Long 2002). *Australian Age of Dinosaurs Inc*. runs both a "pay-for-participation" field expedition programme (Fig. 8, that includes laboratory preparation of dinosaur bones, site rehabilitation and subsequent biodiversity monitoring) and a subscription society with an annual magazine. Substantial state government funding, together with private donations, has also been secured for the construction of a regional museum (Table 2). Despite road-only access and limited public transport (Table 3), this attracted 12 000 visitors in its first year (2009 – 2010), thanks in large part to active media promotion. The museum display content is accurate and complemented by education outreach aimed at the public and school groups. Future goals include expansion of the scientific collection and research output via collaborative initiatives with national/international institutions.

Ichnofossil localities in high-income countries (United Kingdom and France)

Ardley Quarry. In 1997, an extensive series of Middle Jurassic (~ 167 Ma) dinosaur footprints of both large herbivores (*Cetiosaurus*) and carnivores (*Megalosaurus*) was found in a disused quarry near the village of Ardley in Oxfordshire, southern England (Day et al. 2004). Although stone quarrying still occurs in the area, this particular locality was economically important as an urban refuse landfill. Once documented by scientists, the *in situ* tracks were covered by protective sheets and reburied with waste. Nevertheless, designation of Ardley Quarry as a Site of Special Scientific Interest in 2010 (Table 1) meant that access to future discoveries in the immediate vicinity would be maintained. There is local support for an on-site visitor centre, but funding is problematic and residents have opposed an alternative incinerator disposal facility because of perceived air and noise pollution (http://www.ardleyagainstincinerator.co.uk). Following their initial discovery, one set of *Megalosaurus* tracks was removed from Ardley Quarry without scientific advice and irreparably damaged by improper conservation. However, a second set recovered later is now housed in a tax-credit funded, outdoor "Dinosaur Garden" (with an awning to shield them from weathering) at the public *Oxfordshire Museum* in Woodstock. This display is accompanied by accurate signage and an imposing life-sized reconstruction of *Megalosaurus* (Fig. 9). The garden's popularity has stimulated construction of a new indoor dinosaur gallery and extensive merchandising (Table 2). Casts of the *Oxfordshire Museum* dinosaur tracks are also exhibited permanently as an inlaid walkway on the lawn facing the *Oxford University Museum of Natural History* in Oxford (see access details in Table 3).

Crayssac Plage aux Ptérosaures ("*Pterosaur Beach*"). Scientifically significant trackways depicting landing and rapid quadrupedal progression of pterosaurs across a Late Jurassic (~ 150 Ma) mudflat (Mazin et al. 2009) have been preserved in a quarry near the village of Crayssac in South West France (Lot *département*). Commercial mining for sand and gravel is still active in the area, but work at the quarry in question was halted and the footprints were preserved because the quarry owner happened to be an amateur palaeontologist and recognized the importance of the find. A series of systematic excavations was subsequently carried out by palaeontologists from 1993 through to 2001, but eventually stopped because of frost damage to the fossils. Local government support allowed procurement of the site in 2002 and establishment of the *Association de Gestion et de Développement du Site Paléontologique de la Plage aux Ptérosaures* (Pterosaur Beach Palaeontological Site Management and Development Association: http://www.agds3p.free.fr), whose mandate was to create a visitor centre and ensure future conservation/development of the site. Construction of a museum building commenced in 2010 (with EU and national/local funding; Fig. 10) when the area was designated a *Réserve Naturelle Géologique* (Geological Nature Reserve), thus protecting it from future commercial exploitation (Table 1).

Fig. 9. Life-sized resonstruction of *Megalosaurus* in the "Dinosaur Garden" at the Oxfordshire Museum in Woodstock, England.

Fig. 10. The partially constructed roof protecting the exposed pterosaur trackway surface at Crayssac in France, as it appeared in 2010; inset (top left) shows the completed interpretive centre in 2011 with its solar panel array for inexpensive, low carbon power supply.

Financial and environmental sustainability have been aided through the installation of solar panels by *Électricité de France* (Fig. 10; Table 2). Scientific work and public outreach events such as conferences and guided tours have increased awareness of the site. Potential difficulties include limited site access (no public transport reaches the site; Table 3) and low financial benefits for the local community; apart from the initial employment of local architects and construction labourers, the site will support only a single full-time staff position.

Discussion: issues affecting sustainable fossil resource management

Although differing in various aspects, the case study examples presented here clearly illustrate the commonality of issues affecting the sustainable exploitation of fossil deposits. One of the primary obstacles is disseminating knowledge beyond the restricted scientific community. Fossils are often popularly perceived as curiosities, of value only as attractions for children or the entertainment industry (see comments in Scott 2010). Fostering greater public education is therefore vital as a first step towards the promotion of fossils as an inherently valuable commodity.

Geotourism can provide a viable means of simultaneously satisfying both pedagogical and financial requirements (Dowling 2010). As shown by the case studies, a common approach is the establishment of on-site museums. These offer a convenient focal point for storing/displaying significant finds and create facilities for teaching, media promotion and employment within the local community. Nonetheless, museums are expensive to construct and maintain, and so if not sustained by governmental or private subsidies, must continuously seek commercial income in the form of entrance fees, revenue from merchandise and food sales, and fees from pay-for-participation guided tours, laboratory work, and/or excavations [see Table 2; Burlando et al. (2010) also described other successful geotourism business models].

Quarrying for stone, commercial fossil collection, and tourists paying to collect fossils, can be economically lucrative and employ large numbers of people. Nevertheless, uncontrolled excavations may damage sensitive sites and precipitate the irreplaceable loss of both contextual information and culturally and scientifically significant material (see Long 2002). Unregulated quarrying and collecting can also cause environmental damage due to erosion, although if properly managed their long-term environmental impact can be minimized. In addition, non-scientific benefits gained from faster-than-erosion extractive uses of any sort are ultimately not sustainable because the primary fossil resource is being depleted. Scientific benefits gained from even faster-than-erosion extraction are sustainable, but only if important information is not lost during extraction. Consequently, judicious management of both in situ and removed fossil stocks (e.g. through sensible site management and reinvestment of capital) is essential to make extractive uses more sustainable.

Legislative regulation of fossil resources is complex and typically controversial. Many governments have enacted stringent laws designed to prevent the export of significant cultural artefacts (Schimdt 2000). However, poverty hand-in-hand with corruption can undermine their effectiveness and generate mistrust or even direct conflict between authorities and those involved in the trade. Shifting the point of enforcement towards the receiving overseas markets has been mooted to alleviate the problem (Brodie et al. 2000; Besterman 2001; Martill 2001). However, the fundamental demand will remain and certainly provides nothing in the way of alternative sources of income for low-income communities. Moreover, strict controls can inhibit scientific usage by limiting access for researchers (Martill 2001). Perhaps a more pragmatic approach is to increase funding (possibly via corporate sponsorship) to allow public institutions to buy important fossils on the market, or to implement compulsory state purchase of finds from collectors. Compulsory purchase occurs in Denmark (Christiansen & Hald 1990) and Italy where compensation matches an agreed market price (Cioppi & Tangocci 2008).

Whether increased police funding is more, or less, economical than maintaining compulsory purchase schemes remains unclear. Certainly though, "intermediate" levels of protection such as compulsory purchases (e.g. Schatzregal regulations in Baden-Württemberg; Table 1) and codes of conduct varying in strictness (e.g. West Dorset Fossil Code enacted within the Jurassic Coast World Heritage Site; Table 1; National Trust Policy for Collecting Geological Materials at http://www.nationaltrust.org.uk; Scottish Fossil Code at http://www.snh.gov.uk) are especially favoured in countries with a tradition of legal fossil sales, and can facilitate cooperation between dealers, scientists, collectors and officials. These nuanced approaches involve prohibiting trade in specific classes of artefacts and grading the vulnerability of significant sites (e.g. exposures being extensive or finite/stable or fragile, see http://www.naturalengland.org.uk for an established set of guidelines).

However strict the protection afforded to fossils, to ensure effective enforcement, emphasis needs to be placed upon law enforcement frequency rather than harshness (*sensu* Stigler 1970), and apprehension for illegal dealing rather than collecting (Leader-Williams & Milner-Gulland 1993). In theory, only a relatively low number of well-publicized arrests relating to the most highly sensitive material would need to be made before the deterrents become effective (see Walker et al. 2007).

Infrastructure and commercial industries situated close to sensitive fossil sites can also negatively impact on their usage. This is because the immediate gains from development often prevail over the largely unpriced benefits of fossils [as in the case of the landfill site at Ardley Quarry; but see Dinis et al. (2010) for an alternative outcome]. Protected and heritage status can alleviate the situation, not least by strengthening the economic case for fossil preservation. However, such status is not usually retroactive, meaning that development already planned cannot be halted. Optimally, developments in and around a designated reserve should be required to undertake regulatory monitoring or mandatory pre-assessment and exploratory excavation by professional palaeontolgists [e.g. with bedrock contacts around Dinosaur Provincial Park, see Hyusick & Spivak (2009)]. This would ensure appropriate documentation of any further discoveries and also strengthen the economic and/or legal arguments against destructive over-development.

Conclusions

What can be clearly seen in this comparison of Mesozoic fossil sites from around the world is that they can provide sustainable sources of welfare, with benefits in terms of income and social cohesion manifesting greatest impact at a local scale, whilst other benefits in terms of knowledge and education are more globally distributed. Nevertheless, many potential benefits are still not properly recognized or accounted for, resulting in difficulty when establishing an economic value for fossils. This issue is akin to the well-publicized debates surrounding the fiscal worth of biodiversity (e.g. Pearce & Moran 1994; Martín-López et al. 2008; Nijkamp et al. 2008), but, as yet, has attracted comparatively little attention. Because the problems of sustainable fossil resource management (e.g. balancing financial, educational, scientific and recreational needs) and its solutions (e.g. education, legislation, geotourism, monitored extraction) are to some extent ubiquitous, a common global strategy towards sustainable fossil usage may someday become feasible as is already seen to some extent for biodiversity (see for example Maczulak (2010). This should not include extreme blanket bans or enforced liberalization, but rather foster mutual assistance between countries to implement and improve existing domestic management schemes. Appreciation of fossils as culturally and scientifically important must also be propagated through public education. The financial and political will to achieve these goals already exists, as demonstrated by the rapid growth of geoconservation organizations (see Henriques et al. 2011). Overall, however, the problems confronting sustainable management of fossil resources parallel the wider issues of sustainable development, in that without adequately accounting for unpriced benefits of natural commodities or fostering greater economic equality, even the best-intentioned management strategies will never fully succeed.

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