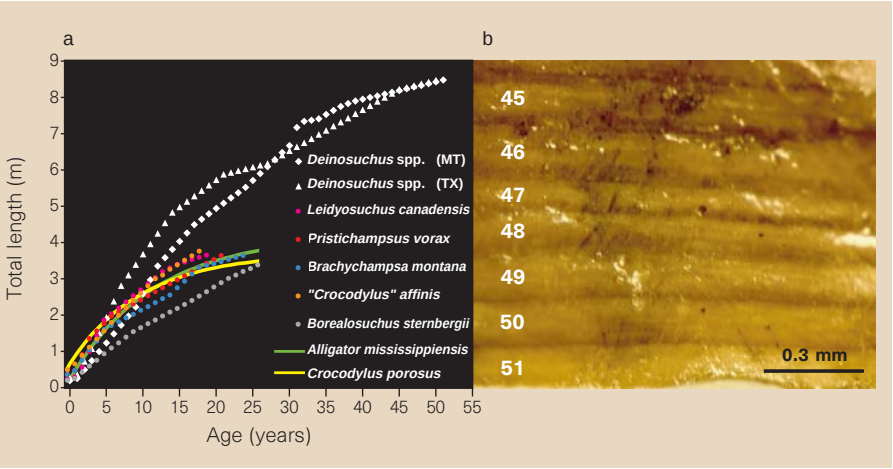

Figure 2 Growth rates of crocodylians and osteoderm growth rings. a, Total length against age in non-gavialoid crocodylians. The data for individuals from extinct clades (symbols; specimen numbers are available from the authors on request) are based on growth line counts in dorsal osteoderms extrapolated to total body length. The idealized growth curves for large extant crocodylians (lines) are from capture–recapture analyses from hundreds of individuals[10,11]. The similar patterns between the two data sets for specimens of comparable sizes indicate that the methods used provide reasonable estimates of crocodylian growth. The *Deinosuchus* growth curves show a continuation of ancestral juvenile growth rates past 10 years of age and presumably greater longevity. b, Lamellar bone growth rings from the ventral surface of an osteoderm representing the final seven years of growth (years 45 to 51) in a specimen of *Deinosuchus* from the Aguja Formation of Texas.

the total length for the *Deinosuchus* specimens to be 8.43 to 9.10 metres. Plots of length against age for *Deinosuchus* outgroups show that the primitive character state for growth in non-gavialoid crocodylians was characterized by rapid linear increases early in development, with rates typically declining by the first decade after hatching (Fig. 2). *Deinosuchus* showed similar rates (about 0.3 metres per year) to other crocodylians from the phylogenetic bracket during the first five to ten years of life, but maintained these juvenile growth rates for several decades (Fig. 2).

The primary histological structure of *Deinosuchus* skeletal elements supports the interpretation that primitive developmental growth rates were retained. Bones from the giant crocodylian showed slowly deposited lamellar–zonal bone tissue typical of non-gigantine crocodylians (the ancestral pattern in reptiles). Because patterns of bone fibre packing correlate with osseous deposition rates[1], it seems that bone formation was not accelerated appreciably. This is in contrast to the skeletons of dinosaurs, which show evidence of derived, accelerated rates in the form of rapidly deposited fibro-lamellar bone[1].

The evolution of increased metabolic rates in dinosaurs is believed to have facilitated the evolution of gigantism by enabling them to build their skeletons swiftly using fibro-lamellar bone[1]. *Deinosuchus* achieved the same outcome, but it took much longer. Dinosaurs of similar size to *Deinosuchus*, such as hadrosaurs ('duck-billed dinosaurs'), reached adult size in only seven to eight years[9], whereas the giant crocodylian required more than 35 years. We believe that the retention of an ectothermal physiology constrained *Deinosuchus* to the deposition of slow-forming somatic tissues (such as lamellar bone) throughout development, necessitating a greater developmental time to reach dinosaurian proportions.

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Localization or classical diffusion of light?

Wiersma *et al.*[1] have reported near-infrared optical transmission and coherent backscattering data from strongly scattering slabs of micrometre-sized semiconductor particles. Their optical transmission was much weaker, and the angular shape of their coherent backscattering more rounded, than would be expected for classical diffusive light propagation without absorption. The authors interpret this as evidence for the onset of strong localization of light, but we find that their data can be explained by classical diffusion combined with reasonable amounts of absorption. Moreover, the turbidities of their samples are much lower than those given in ref. 1 and are comparable to samples with classical transport properties. We therefore question whether their samples are in fact close to the proposed localization transition.

In diffusive transport through disordered non-absorbing media in which $\lambda \ll l^* \ll L$, we have $T \propto l^*/L$, where $\lambda = 2\pi/k$ is the wavelength, l^* is the transport mean free path, T is the optical transmission, and L is the slab thickness. For $kl^* \to 1$, the scaling theory of localization predicts that $T \propto L^{-2}$, whereas inside the regime of strong localization ($kl^* \leqslant 1$), $T \propto \exp[-L/l_{loc}]$, where l_{loc} is the localization length. In classical diffusion ($kl^* \gg 1$) with absorption, T crosses over from $T \propto L^{-1}$ at small L to $T \propto \exp[-L/L_a]$, where L_a is the absorption length, at large L. Thus, it is difficult to distinguish localized light from absorbed light solely on the basis of measured average light intensities.

Wiersma *et al.*[1] used powders of gallium arsenide produced by grinding. No significant distortion of the bandgap was seen, but this does not exclude absorption for wavelengths inside the gap, because contributions from surface states, dangling bonds, defects, internal stress or impurities, for example, are likely to increase upon grinding. For the 1-μm particles, the coherent-backscattering cones were found to be substantially flatter close to backscattering than for non-absorbing samples, but were not much wider at larger angles (Fig. 1a). Figure 1a compares data from ref. 1 with data from a dense powder of non-absorbing TiO_2 particles[2]. Because the cone width scales with kl^* and the TiO_2 sample has $kl^* \approx 5.8$ (ref. 2), the comparable widths suggest that $kl^* \approx 5.0 \pm 1$ ($l^* \approx 0.8$ μm) for this GaAs sample, in contrast to $kl^* \approx 1.5$, as given in ref. 1. The latter value was obtained by fitting the low-angle ($\leqslant 10$ mrad) slope in the region of strong rounding. This provides unphysically

small l^* values (also seen from the dashed line in Fig. 4b of ref. 1), making $T(L)$ much lower than the data, whereas the classical T values must always lie above any data from a localizing — or absorbing — sample. For more quantitative comparison, we slightly rescaled the angular axis of the GaAs cone (Fig. 1a). The agreement becomes striking if we introduce an absorption length $L_a = \sqrt{(l^* l_a/3)} \approx 8$ μm, or $l_a \approx 300$ μm for TiO_2 using classical diffusion theory. Note that identical results are obtained from numerical simulations. We conclude that kl^* is 5 ± 1 rather than 1.5, and that the shape of the GaAs cone can be explained by classical diffusion including absorption.

Next we analysed the transmission of the same sample[1]. As $l^* \geq 0.5$ μm, the classical transmission without absorption lies above the experimental values for all cases. Figure 1b shows that the T data can be described by diffusion theory with absorption over the whole L range; l^* and l_a found by fitting are very close to values obtained from coherent-backscattering cones, emphasizing the consistency of our analysis. Finally, for the smallest particle size (~0.3 μm), an exponential decay with decay length of ~4.3 μm was reported[1]. This is a reasonable L_a value, given the expected stronger absorption and smaller l^* of this sample.

In conclusion, we believe that the results of Wiersma *et al.* cannot be considered as unambiguous evidence for the existence of the critical regime, or Anderson localization, of light. Further investigation is needed to quantify the role of absorption.

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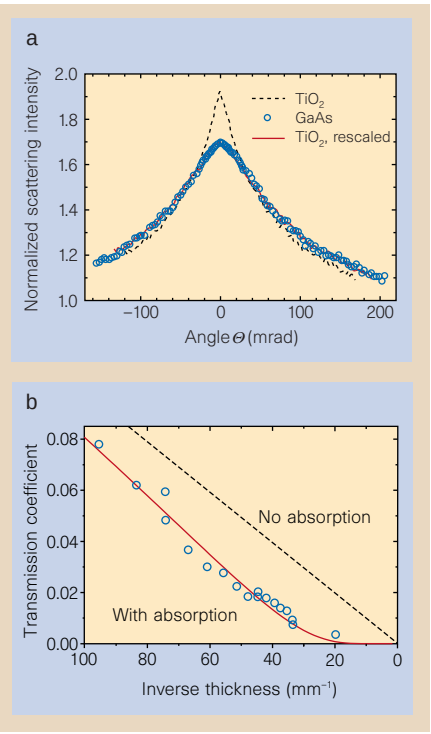

Figure 1 Optical properties of very turbid powders. **a**, Comparison of coherent backscattering cones for GaAs powder (Fig. 3b of ref. 1) and for pure TiO_2 (ref. 2). The red line represents data for TiO_2 that include absorption transformed according to $\Theta^2 \rightarrow \Theta^2 - \Theta_a^2$, where $\Theta_a = 1/(kL_a) = 21$ mrad, and rescaled by $\Theta \rightarrow 1.13 \times \Theta$. **b**, Plot of transmission T of GaAs powder (circles) of average particle size 1 μm against inverse sample thickness L^{-1} (Figs 4b and 5b of ref. 1). The red line is derived from diffusion theory with absorption $T(L) = (L_a/\gamma l^*)\ \sinh^2(\gamma l^*/L_a)/\sinh(L/L_a)$, $\gamma \approx 5/3$, $l^* = 0.59$ μm, $L_a = 8.9$ μm. For the dotted line, $L_a \rightarrow \infty$.

Wiersma et al. *reply* — Scheffold *et al.* have compared different data sets from our group and suggest that our evidence for localization is not conclusive and that the role of absorption should be characterized further. We believe that their analysis is misleading, and that our conclusions about localization are still valid.

Scheffold *et al.* compared our data on coherent backscattering from GaAs powders[1] with our previously published data[2] on coherent backscattering from TiO_2. From a comparison of the widths of the cones, they estimate the inverse of the scattering strength, kl^*, of our GaAs samples, where k is the wavevector of the light and l^* is the mean free path. However, the GaAs data were recorded using linearly polarized light, whereas the TiO_2 data were recorded with circularly polarized light[2]. This difference is fundamental, as linearly polarized light inherently gives a smaller enhancement factor (the top of the cone is lower) than circularly polarized light. To overlay our two data sets, Scheffold *et al.* scaled the y-axis of one of the data sets and shifted the zero of its y-axis. The results are misleading, however, because shifting the zero also changes the full width at half maximum of the cone, and so gives the wrong value of kl^*, because the width is inversely proportional to kl^*.

To illustrate the inconsistency of this approach, we repeated the procedure used by Scheffold *et al.*, but keeping the TiO_2 instead of the GaAs data fixed, and scaling and shifting the y-axis of the GaAs data. The result indicated that the backscattering cone from GaAs is three times wider than that from TiO_2, which corresponds to a scattering strength of the GaAs samples of $kl^* = 1.7$, instead of 5.0. This shows that manipulating the y-axis leads to strongly varying and thereby inconsistent conclusions about the same experiment.

A strong argument against absorption, for example from surface states, is that the shape of the bandgap does not change upon grinding (see the temperature measurements in Fig.1 in ref. 1). Additional evidence that excludes absorption is the observation that the top of the backscattering cone remains triangular while the surrounding region becomes round. This is exactly the behaviour expected at the localization transition, whereas in the case of absorption, the top of the cone would never be triangular. However, Scheffold *et al.* have replotted our data in Fig. 1a in such a way that this triangular shape is obscured by the use of larger symbols.

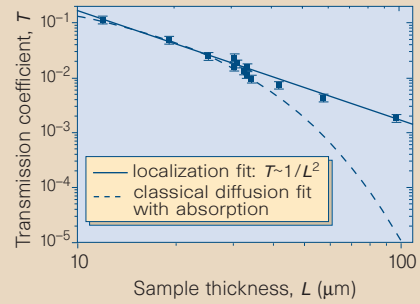

Figure 2 Comparison of scaling theory and classical diffusion using transmission coefficients of a GaAs sample. Scaling theory, solid line; classical diffusion with absorption, broken line. Average particle diameter is 1 μm, mean free path l^* is 0.59 μm, and absorption length L_a is 9.6 μm. Data show the L^{-2} behaviour characteristic of the localization transition, and cannot be fitted as classical diffusion with absorption.

Scheffold *et al.* use classical diffusion theory with absorption to fit our transmission data (Fig. 1b). An absorption fit yields a χ^2 of 0.033, whereas our fit with scaling theory (that is, with the desired L^{-2} behaviour instead of exponential decay) yields a better value of 0.0053. Our independent, new transmission measurements using GaAs powders (Fig. 2) show L^{-2} behaviour over two orders of magnitude, confirming again the scaling behaviour at the localization transition and the absence of absorption.

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editorial note: This exchange has been subject to unusual delays during the editorial process: the comment by Scheffold *et al.* was submitted on 22 April 1998 and the reply from Wiersma *et al.* on 7 December 1998.