BIOMECHANICS

Boxed up and ready to go

Flow-tank experiments and fluid-dynamics simulations refute the idea that water movements over the body of boxfishes are a stabilizing influence, instead showing that the fish's shape amplifies destabilizing forces to improve manoeuvrability.

STACY C. FARINA & ADAM P. SUMMERS

A curious denizen of reefs, the boxfish flits among the corals, turning this way and that as it feeds on small invertebrates. The fish has been used as the biomimetic model for a low-drag concept car, the Mercedes-Benz Bionic, but it does not seem to be hydrodynamically gifted, because its swimming is neither swift nor effortless. Writing in the *Journal of the Royal Society Interface*, Van Wassenbergh *et al.*[1] measured the hydrodynamic properties of the boxfish shape by using three-dimensional (3D) printed models and computer simulations of fluid flow. They found that, contrary to previous research, the shape of the boxfish's body creates high drag and passively lends itself to destabilizing flow.

The boxfish would be an ideal costume for a fancy-dress party, because it can be modelled with a painted cardboard container with holes for the head, arms and legs. Its stiff carapace is an external skeleton made of plate-like, fused scales with large keels, like the edges of a box, that run along the length of the body (Fig. 1). Most other fishes power their swimming by moving their muscular bodies and tail from side to side, whereas the inflexible boxfish waggles its pectoral and pelvic fins, aided by occasional steering from the tail. Its progress through the water is largely determined by the shape of its wrap-around armour.

For swimming and flying animals, stability and manoeuvrability are opposing needs, with a gain in stability usually meaning a loss of manoeuvrability. Observations of swimming boxfishes have shown that they are highly stable during straightforward swimming, only infrequently being pushed off course by ambient flows and their own body movements[2,3]. Data from models of boxfishes suggest drag coefficients less than one-fifth of that of a cube moving through the water. These observations led to the boxfish being touted as a model for a low-drag, high-stability shape for a high-volume structure[3]. However, boxfishes are also extremely manoeuvrable, able to make 180° turns in the length of their body[4]. This presents a paradox — how can the carapace of a boxfish provide stability without inhibiting manoeuvrability?

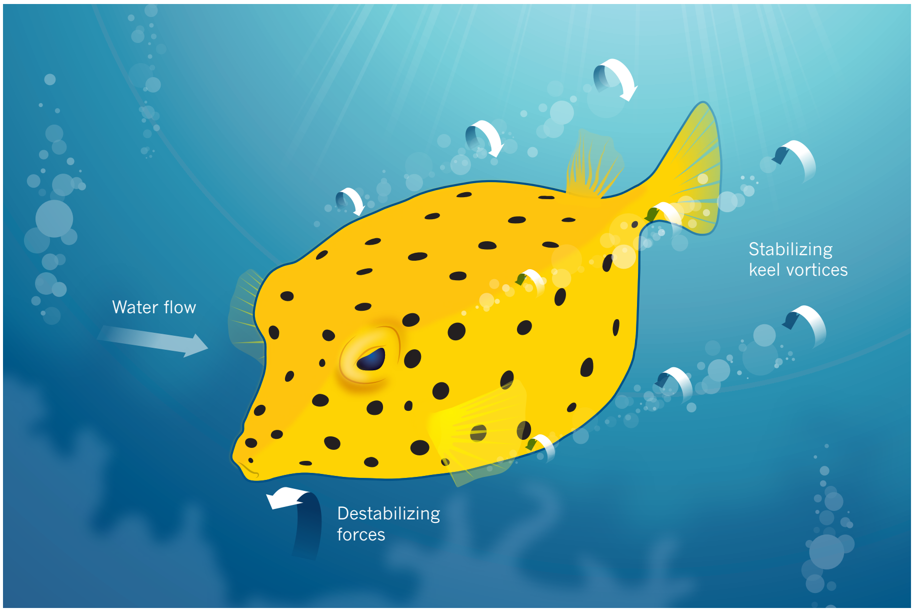

Figure 1 | Boxfish instability. The external skeleton of boxfishes — the carapace — is made up of rigid, fused scales. The edges of this carapace are called keels. Previous research[5–7] had suggested that water flow leads to vortices forming around the keels that stabilize the boxfishes' movements. However, Van Wassenbergh *et al.*[1] now show that the effect of these stabilizing vortices is outweighed by the destabilizing forces generated by the boxy front of the boxfish carapace, and this overall instability is what gives the boxfish its remarkable manoeuvrability.

A series of previous studies had suggested that the boxfish carapace is self-stabilizing[5–7]. The authors of these studies proposed that, when the fish is thrown off course by turbulence, vortices form around the keels, pushing the fish back into a forward-facing position, so the keels act like the stabilizing flights of a dart. This passive process would require no energy or neural input from the fish, allowing instantaneous and inexpensive stabilization. Using 3D models of carapaces in a flow tank, the researchers visualized the vortices responsible for this self-stabilization and consistently found vortices occurring in positions that would provide stabilizing forces.

However, in the latest study, Van Wassenbergh and colleagues quantified flow around the entire carapace, not just around the keels, and found that the overall shape of the boxfish is actually destabilizing. The authors scanned the surface of the carapaces of two boxfish species to create 3D models, then used computational fluid dynamics to analyse the flows around each digitized shape. Drag measurements are fraught with pitfalls, but these physical and computational models put the boxfish drag coefficient at twice the previous values, which seems more likely. But the really interesting results addressed the paradox of a stabilized yet manoeuvrable fish.

On the basis of the shape of the carapace alone, a boxfish thrown off course by the current, or by its own fin movements, would tend to continue turning in the direction in which it had been pushed. Van Wassenbergh and colleagues visualized vortices trailing from the keels of the carapace and also observed that these vortices produce stabilizing forces — just as the previous studies had shown. However, these forces were not nearly strong enough to overcome the larger destabilizing forces at the front of the carapace (Fig. 1). These destabilizing forces lead to great manoeuvrability, so the boxfish gains passive amplification of its movements from its shape. The authors corroborated this finding by printing their 3D models and measuring the forces acting on them in a flow tank under a variety of flow conditions. They again found that the shape of the carapace amplified the movements of the boxfishes, rather than stabilizing them.

So it seems that, far from being darts gliding across the reef in a stable manner, boxfishes are tumblers, able to exploit small asymmetrical force inputs at the front of the carapace to generate large changes in direction. This raises an entirely different possibility for biomimetic applications, because the most manoeuvrable, low-radar-signature fighter jets, such as the F-117 Nighthawk, are also dynamically unstable[8].

If the boxfish carapace has high drag and is unstable, how was Mercedes-Benz able to model a low-drag car inspired by its shape? The answer lies in the nose of the car, which is rounded and so does not reflect the boxy front of the boxfishes. The front of the carapace amplifies the upsetting force, whereas the boxfishes' keels are stabilizing. By retaining the keels but omitting the boxy head, the car combines stability with low drag. ■

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EARTH SCIENCE

Mixing it up in the mantle

Analysis reveals that the uranium isotopic composition of oceanic crust that is being subducted into Earth's interior is distinctive, allowing the development of chemical heterogeneity in the mantle to be tracked. SEE LETTER P.356

JON WOODHEAD

It is now more than three decades since researchers first proposed[1] the radical hypothesis that oceanic crust, returned to the mantle (or subducted) during collisions between tectonic plates, could strongly influence the chemistry of Earth's interior, and furthermore, that the tell-tale signatures of this process could be seen in the volcanic products of mantle melting. In particular, the chemical traces of such 'crustal recycling' (Fig. 1) phenomena could be discerned in rocks termed ocean island basalts (OIBs) that are associated with volcanic 'hotspots' such as Hawaii. Variations on this simple yet provocative idea have provided a focal point for studies of mantle geochemistry and planetary evolution ever since. However, despite a substantial research effort and considerable advances in our understanding, definitive estimates of the timing of crustal-material transport into the mantle have remained elusive. In this issue, Andersen *et al.*[2] (page 356) report on how a relatively new approach, using isotope ratios of the element uranium, provides some long-awaited temporal constraints on these crustal-recycling processes.

It is generally accepted that recycled materials have a key role in the generation of compositional heterogeneity in Earth's mantle[3], and indeed, evidence to this effect continues to appear[4]. By contrast, the question of when the mantle became modified in this way has proved remarkably intractable. For example, the abundances of the isotopes of lead (Pb) — derived from slow decay of long-lived uranium (U) and thorium (Th) parent nuclei — in OIBs form linear correlations that suggest a broad, model-dependent age range (about 2.5 billion to 1 billion years) for the establishment of isotopic heterogeneity in their mantle source[5]. Another temporal constraint is provided by the unusually low abundance ratios of thorium to uranium (Th/U) observed in basaltic lavas erupted at Earth's ocean ridges, known as mid-ocean-ridge basalts (MORBs). These ratios are lower than those estimated for the bulk Earth and have been explained[6] as resulting from uranium recycling into the mantle at subduction zones, perhaps starting about 2.4 billion years ago, coincident with the rise of atmospheric oxygen (and hence the availability of water-soluble hexavalent uranium, U(VI)). Beyond these few, rather imprecise estimates, we have scant information on the timescales of crustal-recycling phenomena.

Isotope geochemistry has always been an instrument-intensive discipline, quick to embrace new opportunities provided by technological advances. The introduction of mass spectrometers known as multiple-collector inductively coupled plasma mass spectrometers (MCICPMS) over the past 20 years has allowed detailed investigations of isotopic systems previously beyond our analytical capability, resulting in many breakthroughs.

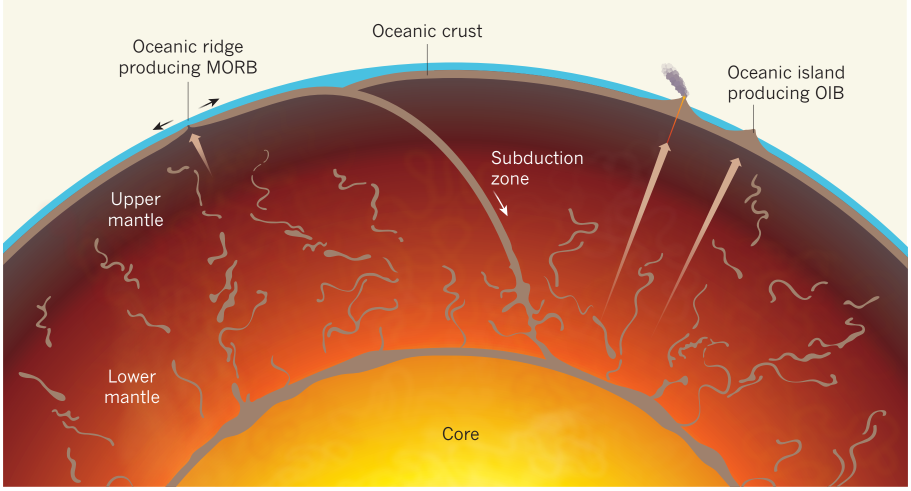

Figure 1 | Crustal recycling. Oceanic crust (brown) is 'recycled' into Earth's mantle at convergent plate boundaries (subduction zones). Over time, this crustal-recycling process has formed a chemically heterogeneous mantle mixture. Andersen and colleagues' results[2] place constraints on the timing of these events. They suggest that the upper-mantle source producing mid-ocean-ridge basalts (MORBs; short brown arrow) was contaminated in this way over the past 0.6 billion years, whereas heterogeneity in the deeper-mantle source producing ocean island basalts (OIBs; long brown arrows) probably resulted from a much older period of contamination between 0.6 billion and 2.5 billion years ago.