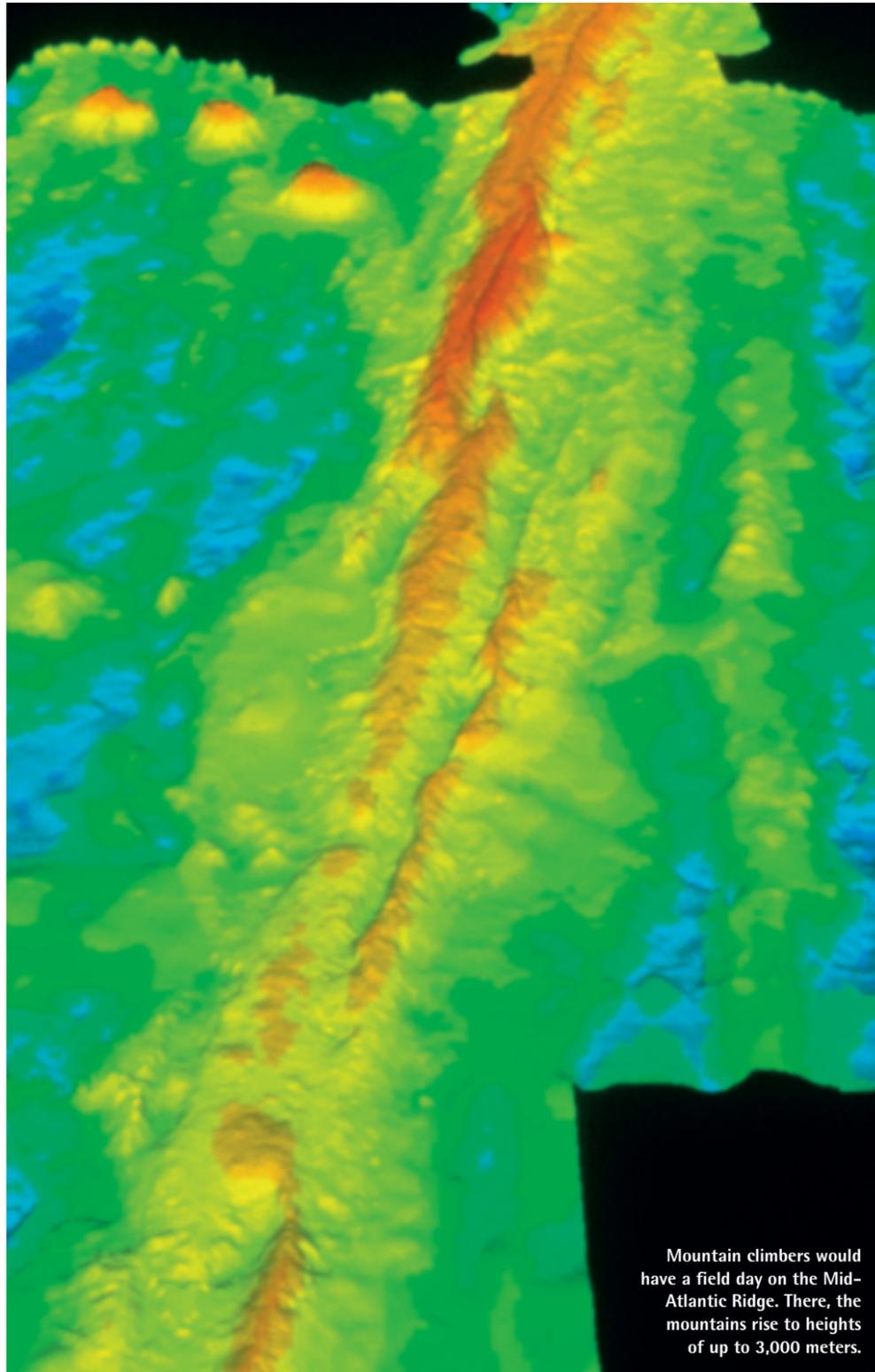


The World in Wax



Mountain climbers would have a field day on the Mid-Atlantic Ridge. There, the mountains rise to heights of up to 3,000 meters.

PHOTO: SCIENCE PHOTO LIBRARY

Scientists often require expensive equipment and precious materials for their work. **EBERHARD BODENSCHATZ** and **WILL BRUNNER** are conducting important research with a lump of wax. At the **MAX PLANCK INSTITUTE FOR DYNAMICS AND SELF-ORGANIZATION**, they use liquid wax to simulate how the continental plates drift apart. In this way, the researchers have already investigated, in the lab, some of the complex phenomena that geologists observe at the seams of the Earth's crust.



PHOTO: CORBIS

The volcanoes of the Mid-Atlantic Ridge raise the sea floor above water in some places – this is also how Iceland appeared.

The activity on the ocean floor resembles that in a witch's cauldron, hissing and bubbling in the night-black depths. Poisonous gases and foul-smelling hydrogen sulfide shoot up from cracks in the floor. Blistering hot magma gushes out of the Earth's belly. Snapping and cracking, the viscous liquid hardens into volcanic rock in the cold water. There is a constant rumbling and groaning in the darkness below the sea where the Earth's surface cracks.

These seething cracks, which extend like gigantic scars thousands of kilometers around the globe, are known as mid-ocean ridges. It is here that the Earth's tectonic plates are drifting apart at a speed of up to 18 centimeters per year. When new fractures occur, magma flows up out of the Earth's interior. Every year, some 3 cubic kilometers of fresh magma spill out of the red-hot cracks around the Earth. This causes the ridges to push higher, sometimes even up to the surface of the water. Iceland, for example, is the visible portion of an underwater mountain range – the Mid-Atlantic Ridge.

The migration of these huge plates is a powerful movement. At the same time, however, it is an extremely slow process. At some cracks, the plates creep at a rate of less than one centimeter per year. Watching the Earth's crust (lithosphere) slide is about as exciting as watching grass grow. The signs of plate tectonics become visible only after millions of years. Mountains rise up. Seas disappear. Geophysicists who research the dynamics of the globe must thus think in terms of very extensive time periods. Making continental drift visible takes sophisticated computer models – and a strong ability to abstract.

A HUNDRED POUNDS OF WAX FOR EARTH'S CRUST

But sometimes it can be done quite easily: To simulate the oceanic plates, Eberhard Bodenschatz from the Max Planck Institute for Dynamics and Self-Organization in Göttingen requires little more than a hundred pounds of wax. The Director of the Fluid Dynamics, Pattern Formation and Nanobiocomplexity Department

normally focuses on fast processes – turbulence in gases and fluids, chaotic states in convection currents and nonlinear systems in general. His wax model is a bit of an exception. In any case, it makes movements visible that, in nature, usually take 100 million years or more.

The simulator is surprisingly simple in design. It is made up of a square steel box the size of a laundry basket and is filled with wax. The bottom of the metal tank is covered with heating coils. These heat the wax, which melts at 72 degrees Celsius, to over 80 degrees. At the same time, a fan blows cool air onto the hot wax perpendicularly from above, causing a firm crust of a few millimeters' thickness to form and float on the liquid wax. With two ruler-sized dipper arms, the wax crust is slowly and evenly pulled apart. While the crust halves glide apart, hot wax from below gushes up through the crack and hardens like magma on the edges of the diverging plates.

What Bodenschatz observed with his experimental setup has startling

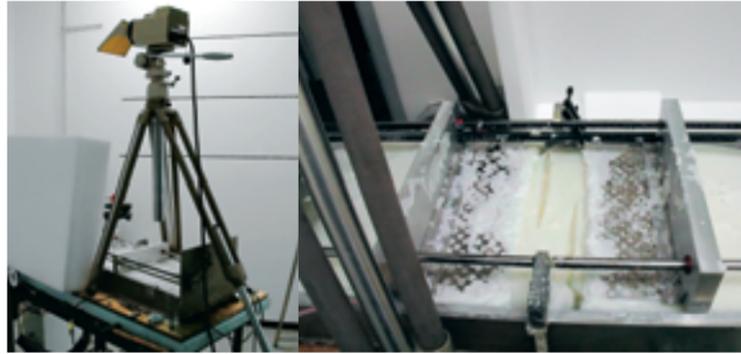


PLATE TECTONICS IN FAST MOTION

With this experimental setup, Eberhard Bodenschatz and Will Brunner simulate, in just a few hours, how the ocean floor spreads over millions of years. A camera (left) films the wax plates, which are pulled apart from both sides. The model can even emulate transform faults (right).



PHOTOS: MPI FOR DYNAMICS AND SELF-ORGANIZATION

similarities to what takes place at the mid-ocean ridges. Although the boundary between the plates of the lithosphere – the ridge – is even like a ribbon, there are occasional off-sets: entire sections of the ridge shift left or right, perpendicularly to the ridge. Even a bit of the crack through which the magma rises gets pushed aside.

These transform faults are typical for all mid-ocean ridges – and they also appear in the wax model. For Bodenschatz, they were a first indication that his model works. “It’s a simplified representation of reality, but it obviously reflects phenomena that occur very similarly in nature,” he says. The advantage is that the wax model shows crust formation in miniature format and, at the same time, in super-fast motion. One hour

of plate migration in the simulator corresponds to 140 million years in reality, and a distance of 1 centimeter corresponds to 250 kilometers.

Bodenschatz has since presented his wax model in several scientific publications, although it really began more as a scientific hobby. For more than 10 years, he has been working on it with students whenever his other research allows.

It all began in the basement of Cornell University in Ithaca, New York, where Bodenschatz worked as a physics professor and head of the Complex Matter Physics Group until he relocated to Göttingen last year. In 1994, Bodenschatz stumbled upon a publication by US physicists Douglas Oldenburg and James Brune. In 1972, the researchers had succeeded in simulating transform faults with a

similar wax model. Bodenschatz was thrilled with the idea of reenacting the invisible dynamics of the Earth. He built his own apparatus and got down to business. However, even though he used the same wax as Oldenburg and Brune, no transform faults formed. When the two wax plates drifted apart, they formed a zigzag pattern.

MATERIAL FROM THE WRONG OIL WELL

Eberhard Bodenschatz was perplexed. He tinkered with the experimental parameters, the feed rate of the two wax dippers, the temperature of the bath – and finally, together with his students, set up the system on campus in the bitter cold. “We hoped that the experiment would work better with the steady winter temperature of minus 15 degrees than with the fan,” says Bodenschatz, smiling, “but it was just the same – no transform faults.”

In the end, the solution to the problem was easier than expected: Bodenschatz phoned Shell, the manufacturer of the wax, and they cleared it up for him. Natural wax is much like wine: its properties depend on where it was produced. With wax, it depends on the oil wells. All oil contains different combinations of hydrocarbon chains. But the wells dry up over time, and that is just what had happened: in the in-

tervening 20 years, the composition of the wax had changed.

Shell sent Bodenschatz a new, synthetic – in other words, oil-well-independent – wax sample that was similar to the wax from the 1970s. Right away, the experiment worked. When the wax drifted apart, transform faults formed – just like they appear on the ocean floor. The researcher has since discovered an array of additional phenomena that Oldenburg and Brune hadn’t previously noticed.

Bodenschatz knows that his experiment can’t be translated to the lithosphere one to one. Due to the enormous mass, the forces in the Earth’s crust are naturally much stronger than in the wax. The densities of wax and magma are, however, quite similar. And their mechanical properties are identical. Bodenschatz is currently measuring these properties in the melting wax and expects that, in the end, it will be possible to scale his model up and translate it to the actual scale. Even if that doesn’t work, he says, the analogies to nature are astounding.

Calculating the processes that take place in the Earth’s crust would require a supercomputer running for months. That would cost millions of euros, and even then, it would be questionable whether the movements could be represented similarly realistically. That is because, in physical terms, both the wax model and Mother Earth pack quite a punch. After all, four physical fields collide here, each of which is already extremely complex. One is fluid dynamics, which describes the movement of fluids – a mathematically challenging discipline. Then elasticity plays a role. This, too, deals with movements: the deformation of a body and the resiling to its original form.

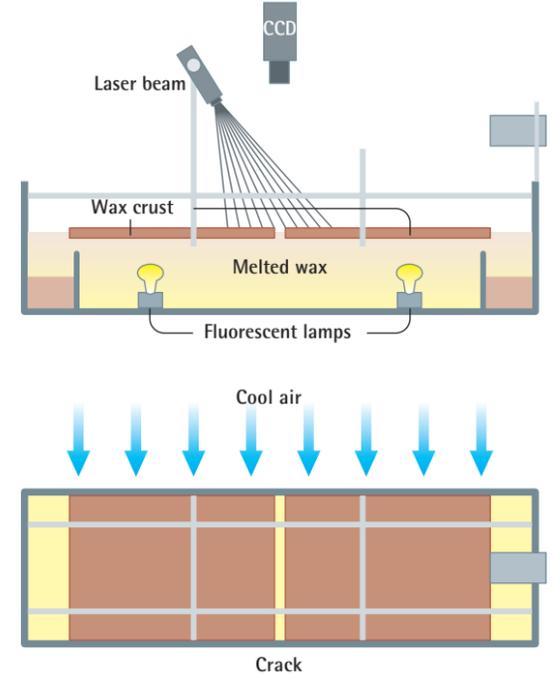
Even calculating a bouncing rubber ball is a real challenge – and all

the more so for the deformation of the Earth’s crust. This is further complicated by the fracture behavior of rock – which is likewise a complex phenomenon. A fracture begins on the microscopic scale, in the molecular lattice, and in mid-ocean ridges, continues on up to the global scale. Finally, the fourth challenge is the solidification of magma, another phenomenon that can hardly be comprehended. “Our solution is relatively elegant,” says Bodenschatz.

A PUZZLE ON THE SEA FLOOR

He is not the only one who thinks so. Birger Lühr, an engineer and geophysicist at Germany’s national research center for geosciences (*Geo-ForschungsZentrum Potsdam, GFZ*) believes the wax model is very helpful in finding new explanations for the processes that take place in the Earth’s crust. “Such a model is by no means trivial,” says Lühr, “because such simplified experiments by our physicist colleagues, who are not geophysically “tainted,” are often precisely what help.”

Many questions still remain unanswered. For example, no one knows exactly how transform faults actually come about. The continental drift theory has only become generally accepted in the last 35 years. Although physicist and meteorologist Alfred Wegener had already postulated continental drift in 1912, he couldn’t explain what forces drive the continents. It wasn’t until the 1960s that researchers recognized that the continents are indeed gliding apart. They discovered that rock on both sides of a mid-ocean ridge is the same age when it lies the same distance from the spreading zone. The magnetic orientation of metallic deposits in the rock on both sides is also identical at equal distances. This is because, when the magma

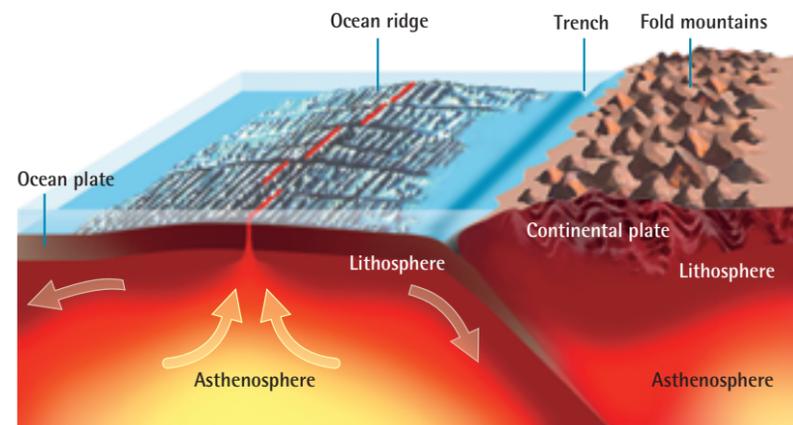


In the tub full of wax, the Göttingen-based researchers study the fundamentals of geophysics. With a camera, they capture how the wax crusts drift apart. In addition, they analyze the processes with laser light and fluorescence experiments (above). A fan blows a cool breeze across the surface of the wax bath, causing it to harden (below).

hardens, the materials orient themselves in line with the current position of the Earth’s magnetic field, whose polarity and intensity vary over time.

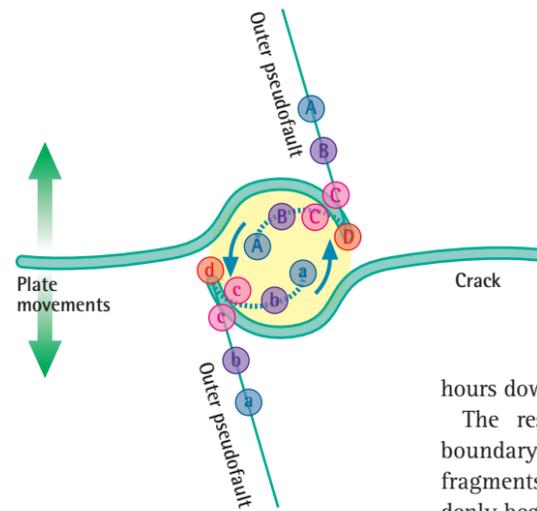
The ocean floor on both sides of the trench is thus mirror symmetric. Since the rock is older the farther away it is from the spreading zone, it was clear that the plates are moving away from each other. This observation is remarkable. After all, the researchers are looking at a world whose movements are practically frozen. As with a perplexing puzzle, structures on the deep-sea floor must be pieced together to form a movement pattern.

The puzzle pieces also include the so-called microplates. These structures on the ocean floor reveal, through accumulated rock that rests at the bottom of the ocean in barely



Everything is in flux: Magma constantly gushes up out of the cracks in the mid-ocean ridge and pushes the tectonic plates apart. At the edge of the ocean, the oceanic crust thrusts itself under the continental plates. That is why New York and Berlin move a few centimeters farther apart each year.

ILLUSTRATION: ROHBERG, BASED ON AN ORIGINAL FROM THE MPI FOR DYNAMICS AND SELF-ORGANIZATION



Overlapping spreading centers create spirals on the ocean floor. Here, the edges of the mid-ocean rift bend to form a hook-like shape. When they drift apart, they push the crust together, forming pseudofaults. At the same time, they form microplates at their rotating center.

perceptible spirals, the pseudofaults. Some 15 microplates are known at present. They are found particularly in the Pacific and have diameters of up to 400 kilometers, which is tiny in geological terms. Geophysicists take them to be fragments of the mid-ocean ridges – rock mass that breaks off into the spreading zone like an ice floe and is set in rotation and, finally, embedded in the plate and transported away from the ridges. It is thus not surprising that most microplates are located in the far reaches of the Pacific sea floor, thousands of kilometers from where they formed.

THE DANCE OF THE MICROPLATES

Of course no human has ever seen a microplate rotate – after all, the geological fragment turns just about 20 degrees in a million years. With his model, however, Bodenschatz has shown for the first time how the microplates could grow, as rotating microplates likewise form in the spread-

ing zone between the wax crusts. Since the wax moves quite slowly, at just a few micrometers per second, the physicist records the scene from above with a video camera and subsequently plays it back in time-lapse mode – cutting 20

hours down to a few seconds.

The result is surprising: at the boundary between the plates, new fragments continually form and suddenly begin to rotate. They grow like snowballs rolling downhill and are abruptly torn away from the spreading zone. Finally, they run aground in the middle of the wax plate – like a frozen strudel. Eberhard Bodenschatz was thrilled. He recalculated the geophysicists' model, compared it with the movements of the wax microplates – and was amazed.

Taking the different scales of the two systems into account, one can see that the spreading rate at the wax fault, the growth rate of the microplates and the shape of the spiral pseudofaults exactly correspond to those of their ocean cousins. The wax model clearly works, although the experiment proceeds about a billion times faster than the growth of the natural microplates. In any case, the wax fragment rotates about its own axis in five seconds.

And a further analogy between the model and the ocean floor astounded the researchers. Geophysicists presume that microplates form at what are known as overlapping spreading centers (OSC). Here, the mid-ocean rift is not smooth, but instead, the opposing edges are bent and interlock like hooks, but in a single plane. No one had previously been able to prove this theory. With the wax model, however, Bodenschatz was able to show that, when drifting apart, hook-shaped edges

do indeed set the freshly hardened material between them in rotation. When the mass begins to rotate, it accumulates more and more wax. Thus, old wax is found in the center of the spiral and young material at the edge – and the real microplates on the sea floor exhibit the same age structure.

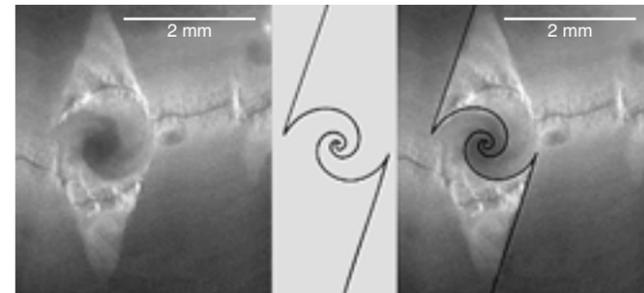
TESTING THE TECTONICS OF OTHER PLANETS

Dutch geophysicist Hans Schouten had already proposed such a growth model for the microplates in the Earth's crust in 1998. Bodenschatz used Schouten's calculations to predict the growth of his wax microplates. Again, it worked: if the scientist selected a certain pulling speed, microplates formed that exactly resembled the predicted spirals in size and shape. Bodenschatz is thus convinced that his wax machine is actually capable of modeling geological processes – not only Schouten's microplate growth, but also other spreading phenomena on the ocean floor: "In the future, we may even be able to use our apparatus to test numerical and mathematical models for the tectonics of the Earth and even other planets," says the Max Planck researcher.

Bodenschatz knows that, to do this, his wax method will have to be further refined. Will Brunner, a young geophysicist who Bodenschatz brought with him from Ithaca, is currently working on this. Brunner wants to study the properties of the wax in greater detail. Solid wax is a peculiar substance that experts describe as mushy – a hybrid of solid and liquid. Fine microcrystals are surrounded by liquid wax. Brunner wants to examine this structure in greater detail to determine the extent to which it really is comparable with the material of the Earth's crust or with magma. Moreover, as with hardening volcanic rock, the viscosi-

ty of the material is interesting, as that is another factor that influences the growth of the lithospheric plates. To do this, Brunner developed a drill-sized tool that he calls Woodpecker. The little machine is equipped with a nodding arm to which a needle-fine plunger is attached. When the plunger hits a lump of wax, the rocker mechanism measures the resistance and thus the viscosity of the sample.

With the help of Brunner and other young researchers, in the coming years, Bodenschatz intends to adjust his wax simulator to even better reflect its reference system, the Earth's crust. "Basically, we are still at the beginning of our work," he says, looking back – and shows more modesty than necessary. Although he is still working on fine-tuning the parameters, he has, just in passing, shed new light on the Earth's dy-



Freestyle plate tectonics: Just like on the ocean floor, spirals can form in the wax model.

namics. In addition, the wax model was able to imitate the different shapes of mid-ocean ridges: depending on the spreading rate, the ocean mountains are flat, steeply towering or trenched. The wax behaves exactly the same way.

Bodenschatz is anxious to see what else his gadget will reveal in the future. While he is in Göttingen setting up a wind tunnel to research turbulence in the atmosphere, or researching chaotic electrical impulses that cause sudden cardiac death, he intends to remain true to his hobby: discovering the world in the wax model.

TIM SCHRÖDER