The Driving Mechanism

What Can Make a Plate Move?
What to Look For:

- Wegner’s proposed mechanism for driving continental movements was polar-fleeing forces”. It was quickly rejected because (while a real force) it cannot generate the necessary force. Nor can it explain movements away from nor parallel to the equator.
- The ridge-pull hypothesis proposed that the ridge is a ramp down which the adjacent plates slide. There is far too little force to move a huge plate.
- The ridge-push hypothesis proposed that magma injection in the rift zone pushes the plates apart. Because the existence of the magma probably depends upon the pre-existence of the tensional fractures, because there is not enough force generated, and because there is no sign if compressional “pushing” at the ridges (only tension) the hypothesis was rejected.
- Slab-pull proposes that the other end of the system works as a ramp, with the plate sliding under the influence of gravity down the subduction zone. Too little is known about the densities and temperatures of the slab and adjacent asthenosphere to tell if there is enough force to do the moving. The negative gravity anomaly at the trench seems to argue against being able to start the subduction process in this way, and the fact that half or more of the moving plates don’t descend into any trench is a killer. Some people still favor this explanation but it looks like a non-starter to me. (Pun intended again.)
- The generally favored hypothesis is that convection cells in the mantle rift the plates where the rise to the surface of the asthenosphere, raft the overlying plate in the two directions that they subsequently spread, and force subduction where they begin their descent back toward the core. This hypothesis has survive some critical tests. Only better understanding of the thickness and shear strength of the asthenosphere can settle the remaining criticisms leveled at it.
So while we have ample evidence that the plates exist and are capable of moving. In fact, we even know that we can watch them move. We do not have a good explanation for how they move – a driving mechanism.

Before we look a the possibilities we should acknowledge that it is a real and significant problem to say that a thing happens and not be able to say how, at least in science. Other ways of thinking have no problem with it, apparently. However, no scientific theory of anything is complete without the how. Wegner’s detractors, wrong though they were, did have a point …

The continents (and the even thicker slab of brittle mantle they are attached to) are huge and heavy and I hope that it is a marvel to you that they move. The only thing more absurd than the idea that they move is the idea that the world could look and act the way it does with them not moving!

Even today nobody can think of a force to drive this system that is not a consequence of either the rotational momentum of Earth or gravity. Unless we have missed something fundamental in 400 years of clearheaded scientific thinking, there is nothing else “big” enough to work.

Science rightly rejected Wegner’s hypothesis involving the former possibility and, as a by-product, demonstrated clearly that that is not the culprit. (We will look at this first.) This leaves only gravity.

More correctly it leaves the downslope component of gravity. The plates cannot free-fall so if they are moving because of gravity it is more like a rockslide than a rockfall. However, the motions that we infer (and see) are all perfectly parallel to the surface, and therefore perpendicular to the force vector of gravity. There is no obvious slope for the plates to move on. Therefore all the gravitational force affecting the plates proper must be slope-normal “snugging” force (which creates friction) and not slope-parallel “downslope” force (which causes movement)!
Wegner’s Hypothesis

Polarfluchtenkraften
(Polar-Fleeing Forces)
If you drop a marble onto a rotating record it will quickly move to the edge and fly off. If there is a lip on the record to keep it from flying off it will remain parked at the point it first reached the edge. (Actually its inertia and the low coefficient of friction between it and the record may finally make it “go backwards” from the record).

If we plot its path after the fact it will have followed a curved path to the edge. If it flies off into space it does so in a straight line.

In a rotating system like this the objects all have an angular momentum in the direction of rotation. Freely moving objects like the marble go to the place where their momentum is greatest – to the point of largest diameter of their rotational paths.

The curved part results from our old pal the Coriolis effect. Once free of the record’s rotating context the marble continues with its momentum **at that instance** in a straight path.

For our present purposes **only the tendency to move to the farthest rotational point is relevant.**
Remember that Wegner postulated that all the continents were joined into one large supercontinent he named “Pangaea” in the late Paleozoic. This explained the fit of the continental edges and all the observations that suggested former connection of the continents.

Furthermore, he supposed that much of Pangaea was near the South Pole in order to explain the odd paleoclimatic indicators on some of the continents. (He chose the South rather than the North Pole because Antarctica is still there.)

Given this (which, unfortunately, he was not) then the continents must subsequently have moved northward, away from the pole. Wegner then went hunting a force that could make things “flee the poles” or a *polarfluchtkraft*. 
The greatest angular momentum on a rotating sphere, as it is on a record, is the place farthest from the axis of rotation. Objects on Earth’s surface that start at the same longitude (beginnings of arrows) will move greater distances in the same amount of time (lengths of arrows) so some must move faster than others.

Wegner reasoned that, like a marble rolling on a spinning record, an object moving on the spinning planet would go to the point of maximum angular momentum – the Equator.

Why he called this a “polar-fleeing force” and not an “equator-seeking force” is not clear.
Part (arguably most) of the objection to Wegner’s proposed driving mechanism is that the amount of force is not really all that great with respect to what was perceived as 1) the inertia of a thing the size of a planet, and 2) the friction that must exist between it and whatever is below it.

At the time it was assumed that the crust had to move over the mantle (rather than the lithosphere over the asthenosphere). Thought the search for direct evidence of it was just getting started, the consensus was that mountains have “roots” – the crust/mantle boundary is deeper under mountains than under lowlands. This complicated Wegner’s position because his force had not simply to overcome a frictional resistance, it had to deal with the deep heavy “anchors” that the mountain roots must be. (Mohorovicic, among others, later verified this.)

In retrospect, these objections don’t carry the weight they did at the time because we know a lot more about the system. We know, for example, that if there’s any sliding it’s happening at the relatively smooth low-velocity zone and not the irregular crust/mantle boundary.

There are other criticisms of polarfluchtenkraften that are more telling, even in retrospect.
Wegner’s hypothesis predicts that the continents should “flee the poles”, but also that they should stop at the Equator. Asia and North America (and Greenland) have over-run their target if Wegner’s mechanism is correct. In fact, most of the mass of Africa is also too far north.

A polar-fleeing force also cannot possibly explain why the Americas are “fleeing” from the old world. If they are moving as their matching edges suggest then they are moving east-west, getting neither closer to nor farther from a pole.

So, while the postulated force certainly exists, and may contribute in some cases to movement, it cannot be “THE DRIVING MECHANISM” because it cannot explain all the obvious movements.
Post-Seafloor Spreading Hypotheses

1. “Ridge Pull”
The realization of the central role of the ridges in tectonic theory (pun absolutely intended) led to two separate ideas for its control on movements. The first points out that the ridge is like a ramp. The crest is gravitationally higher than the abyssal plains on either side, so there is a downslope component of the gravitational force acting to pull the plates apart, and to pull them off the two sides of the ridge once they have broken.

This is called the \textit{ridge-pull hypothesis}. 
As we have seen in a different context, there is no accurate way to show accurately the size of the ridge in proportion to the job it is supposed to be doing under this hypothesis.

Vertical exaggeration on this diagram is, as in an earlier one, 100x. That is, the ridge looks 100 times higher and steeper than it actually is. If we draw this diagram with no vertical exaggeration then the line is far fatter than the difference in elevation it needs to represent!

This gravitational downslope force does exist, but the “ramp” off which it is supposed to be pulling a huge lithospheric slab doesn’t look very effective, even with a vertical exaggeration of 100x. There is simply too little force to be "THE DRIVING MECHANISM". It is there, and might contribute to movement, but it is just inadequate to be the whole story.
Post-Seafloor Spreading Hypotheses

2. “Ridge Push”
The other hypothetical mechanism by which the ridge drives the movement is by the lateral pressure generated by the intruding magma from its source in the upper mantle.

If all your toothpaste is in the bottom of the tube you squeeze the bottom of the tube to push it toward the top. At it goes into the other end of the tube it pushes outward on the sides. You can tell you have the toothpaste right where you want it when that outward pressure has “inflated” that end of the tube.

Magma being forced into fissures also exerts an outward force on the fissure walls. Part of the problem with this model is that the magma might not be “being forced” into the fissures.

In fact, the best hypothesis for the formation of the magma in the first place is that the fissures are already there. The pressure release that accompanies their openings is what creates the magma, which then simply flows into them with little or no lateral pressure.

As with the other hypotheses we’ve examined, this mechanism (if it exists at all) has a very tiny strength in proportion to what it has to move.

Finally, if the magma is pushing the sides apart then we might expect to find some evidence of compressional stress in the rift. We don’t.

This is called the **Ridge Push Hypothesis**.
Post-Seafloor Spreading Hypotheses

3. “Slab Pull”
There is another candidate for a ramp down which gravity could pull the plate.
The slab of lithospheric material subducting beneath a trench is made of the roughly same thing as the asthenosphere into which it descends (mostly peridotite with a ~5km thin crust of basalt), but it is quite a bit cooler, and therefore denser. Maybe gravity pulls it downward here. This is the **slab-pull hypothesis**.

This is the favored hypothesis of some people, but there are several flaws in it – at least one of which is fatal.

1) The density difference between hot and cold peridotite may not be sufficient to make this work, particularly since the slab doesn’t **stay** cold once it is subducted. Certainly the slab descending into the Peru-Chile Trench a couple thousand km from the East Pacific Rise (EPR) is not any colder than the slab a couple thousand km away on the other side of the EPR, so what made it descend in the first place? If “cold” is the only relevant factor there should be plenty more trenches than there are.

2) The negative gravity anomaly at the trench shows unequivocally that something absolutely different from gravity is holding the plate down in the trench **despite** gravity, which would pull asthenosphere back beneath the trench and push the slab back to the level of the abyssal plains, if this other “something” did not keep it from doing so.

3) The counterargument to #2 is that the entire slab, including the greater part of it **landward** from the trench is what is being pulled, not just the part at the trench. Once again, this ignores the four-dimensional problem of how the subduction originated. Initially there **was no sub-trench part of the slab**, yet it descended anyway. How?

4) The fatal flaw, however, is that there are many obvious plate movements (such as all the plates adjacent to the M.A.R.) that do not descend into a trench. If there is no slab, then slab-pull can’t cause the movement. If you think about it, no more than half the plates can be subducting at any one time because every one that is has to be going beneath one that isn’t.

5) Whether there is or is not sufficient force to cause any movement of any plate by slab-pull is presently unanswerable. We know too little about the deeper parts of the slabs and, more importantly, far too little about the asthenosphere to determine this.
Before we move on we should point out that all the forces we’ve talked about so far actually exist and their strengths can be calculated or estimated, except for slab-pull.

Consequently, the movement of every plate has a force vector associated with each one (except maybe slab-pull). In the case of ridge pull, ridge push, and (maybe) slab-pull the vector is necessarily oriented in the correct direction to be contributing to the movement of the plate, even though they are not the primary moving force.

In the case of polar-fleeing forces the vector sometimes points correctly (Australia moving northward toward the equator) and sometimes incorrectly (Greenland moving northward or the Americas moving eastward).

What is needed is a force that is both adequately strong and consistently oriented correctly that can affect the edges of the plates but not their centers.
If you examine a pot of cooking oatmeal or spaghetti sauce (*careful, don’t stir too much!*), you will notice that the surface of the cooking glop is higher directly above the flames and is depressed along the edge of the pot and near the center.
If you pay attention to what individual grains do you’ll see them rise to the surface above the burners, move laterally across the surface of the glop directly away from the burner, then subside back into the glop at either the edge of the pot or the central depression.
What you are seeing, of course, is just the consequences on the upper surface of a convection system that affects the entire pot. The hot glop right above the fire becomes less dense and rises. At the surface it can rise no higher and so it spreads laterally. By the time it has reached the side or middle of the pot it has cooled sufficiently to dive back toward the bottom, to help replace the hotter glop that has been continuously rising over the burners since it did.
We can illustrate what you see in map view with contour line symbols.

There is a “ridge” of oatmeal above the burners. The glop divides (rifts) here and spreads in both directions.

There is a “trench” of oatmeal along the edge of the pot. The glop sinks (subducts) here and in the center.

I hope this looks familiar to you.
Bubbly, low density rafts of froth form frequently over the burner ridges. Then split along the “rift” beneath themselves. The two halves then ride along on the convecting glop beneath them like rafts on a current.

(Wedge enlarged on the next page)
When the frothy rafts reach the “subduction zones” they are too light to descend with the glop, so they accumulate there. At the edge of the pot the leading edge of a raft is buckled into a thing that looks very much like a fold belt on a continent when it hits the pot edge.

In the center of the pot the “fold belts” form as the rafts collide with rafts that are already there. As more rafts arrive the edges of the new arrivals and the previous inhabitants are both folded by their collision.

I really hope this is looking more and more familiar to you all the time.
One extreme model (shown here) is that the mantle is plastic asthenosphere from the base of the lithosphere all the way to the core.

Thin, **brittle**
LITHOSPHERE – many rock types, mostly peridotite

Remainder of MANTLE -- Peridotite; **plastic** to uncertain depth (ASTHENOSPHERE)

CORE – Iron and other metals, mostly. **Hot** enough to melt, even at extreme pressure.

A plastic substance is capable of slow flow. The great difference in temperature between the inner and outer parts of the asthenosphere sets up a convection system in the asthenosphere to transfer heat from the core to the surface, just as convecting oatmeal transfers heat from the burner to the air above the pot.
Just like in a pot of oatmeal, the asthenosphere above a hot spot in the core will itself be hot, and will rise toward the surface. Where the upper end of this mantle plume reaches the surface it buoys the lithosphere and creates a hump (ridge).

At the surface (just below the lithosphere) the ascent stops and the plastic material spreads laterally, flowing for some distance until it has cooled sufficiently to sink back toward the core, creating a depression (trench).

At both places the bending stress on the lithospheric plate breaks it.
Once the lithosphere is broken at the upper ends of the ascending plumes the laterally spreading asthenosphere beneath the rift exerts lateral forces on the underside of the two pieces rafting them away from the fracture line boats on a stream. Whatever force is exerted by ridge pull and ridge pull (if any) are tiny in comparison to this force. Probably any trench-pull force is tiny as well, if one even exists. The spreading asthenosphere creates tensional stresses on the plates, and therefore a divergent margin.

Spreading of the curved pieces has to occur at different rates so a transform system has to develop to accommodate this.

The broken lithosphere at the descending plumes has stresses operating in exactly the opposite sense. Here the two pieces are being rafted toward the depression. One of them (flip a coin) will necessarily be pulled a little lower and forced to under-ride the other, creating a Benioff zone and potential deep melting of the subducting plate. The converging asthenosphere creates compressional stresses on the plates, and therefore a convergent margin.
Since it was proposed the mantle convection model has, rightly, been subjected to critical testing. Most of the potential objections raised to its operation have ultimately failed to negate it, and the resolution of some have actually made it look more reasonable. (How to get long narrow ridges out of presumably hotspot-like mantle plumes, for example.)

The unresolved criticisms all have to do with the nature of the asthenosphere – how deep does it extend and how much shear strength (not “sheer strength”) does it have.

A very shallow (thin) asthenosphere would create smaller lateral stresses than a deeper (thicker) one, and might not be up to the task of moving the lithosphere. If it is too thin it might not even convect at all.

An overly plastic asthenosphere might not have adequate shear strength to move the plates, but might simply flow beneath them. (This “problem” seems a lot like worrying about whether a stream has the shear strength to move your kayak. Obviously it does, even though a liquid by definition has not shear strength at all. Even the biggest supertankers and cargo ships will drift on an ocean current like feathers.

Since all the other proposed mechanism have fatal flaws, either mantle convection is the driving mechanism or there’s an even better one we haven’t thought of yet. Certainly it is the best game in town. Time and clear-headed thinking about the asthenosphere will eventually decide whether it fails that test.
Take-home Message:

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