Balloons in Water

(are as odd as fish out of it.)
A red balloon was inflated to a certain size. The hand provides a scale for how big the balloon was in air. The two pictures are to the same scale – that is, the hand is the same size in both. (It’s also the same hand.)

The balloon was then submerged (by tying it to a really big rock) to a depth of about 10 feet (~3m). If you look carefully you’ll notice three things:

1) the size is smaller,
2) The shape is somewhat modified, and
3) it looks darker red.

For the moment we will focus on the first difference.
If we draw an outline of the balloon in the water and superimpose that on the balloon at the surface we and get a better idea of how much reduction in size has occurred. Remember that the photo scales are the same.

(We can also gauge the shape change better, but we’ll come back to that.)
We can easily quantify the volume difference if we can compare actual volumes rather than just “size”. To do that we need equipment whose function is to measure volume. A **graduated cylinder** is meant to do exactly that.
At the surface of the water the cylinder has air to the 50ml mark – the highest value on this cylinder, as you can see from the photo at right. (What keeps the water level in the cylinder higher than that in the pool?)

At a depth of about 9 feet (2.75m) the air in the cylinder has been compressed to about the 41ml mark – a reduction of 9ml or about 18% of the surface air volume.

What causes this?

This effect is **linear**. For every foot of water depth the reduction is ~2%. The *rate* of compression does not increase with depth, only the amount.

We all “know” that it’s the water pressure that does this because that’s what we’ve been told, but what causes the pressure?
Water pressure (or hydrostatic pressure) comes from the weight of the overlying water – that is, the water overlying the thing to which pressure is being applied. Usually this is expressed as kilograms per square centimeter (kg/cm²) or pounds per square inch (lb/in² or psi). The water above the cylinder weighs enough to compress the air by ~2% for every foot of water depth. (Seawater would compress it ever-so-slightly more. Why?) There is also aerostatic pressure (the weight of the air above you, which is lower in the mountains – dangerously lower in very high mountains, where “Mountain sickness” from lack of oxygen is a risk. There is also lithostatic pressure. What is that?

So if the weight of the water is responsible for hydrostatic pressure why does it push the water upward into the cylinder. Why does it compress the balloon on all sides rather than just flatten it? Why do your ears hurt at the bottom of a pool if your head is upright?

All these pressures are called confining pressures because they operate in every direction by the same amount. (Flattening the balloon would require pressing water sideways out of its way, but where could it go? It would have to push some water upwards somewhere else, right?)
Think back to the first slide. The question was raised about what keeps the water level in the cylinder higher than the level in the pool.

Any ideas?
It’s aerostatic pressure. The atmosphere weighs enough above the pool to keep the water well up into a closed cylinder – much farther than the inch or so you see here.

It will not *push* the water up into the cylinder if you just lower it onto the water surface because then the aerostatic pressure in the cylinder is the same as that outside and there’s no net difference in pressure to do the pushing.

But it will *keep* whatever water you put in the cylinder underwater, even if there’s no air at all in it. Unless you bring the rim out of the water, of course.
Let's return to the shape change because there is an interesting point to make about that.

Notice that the balloon’s shape was not evenly compressed. Ordinarily you expect to see that things are evenly compacted by confining pressures because they are, well, confining.

In this case though the balloon seems to be more compressed at the bottom and less compressed at the top.

Why should that be the case if the pressure is equal in every direction?

There is another force at work and it is working in an interesting way that you don’t ordinarily think of when thinking about this force.

What other force can be at work here?
Think about the implications of the shape change and let’s word our description of that shape change differently: The balloon appears to be stretched upwards as well as compacted, doesn’t it? It is clearly much smaller from the sides when it’s at the bottom, but not much shorter top to bottom. The bottom in particular looks stretched.

What could be pulling the top part of this balloon upward (without changing its shape much) and stretching out the bottom part?

*What force do you know of that operates upward on Earth?*
*There is not one* ... not a single force on the planet that could do this to the balloon in still water in an upward direction *by operating on the balloon*.

But there is one that operates in the opposite direction – downward, and it is pervasive on Earth and everywhere else in the universe. What is it?

Hint. Why did I have to tie a great big rock (bigger than I expected) to the balloon to sink it?

What did the balloon do when I untied it from the rock?

*HOW DID IT DO THAT?*
Think about a small boat. When you step into a boat, how does it react? Why does it do that?

Now, what happens when you step out of it – how does it react? Why?
When you get into a boat it sinks a little bit into the water. You have increased the weight of the boat and so you have also increased the force of gravity operating on the boat. This should be very easy to interpret – the extra weight pushes the boat down into the water farther.

When you step out of it what pulls it back up? Is there a force that pulls it upward? (We’ve already answered this question.)
The boat and its load are only a part of the system that gravity acts upon and that we have to consider. It’s very easy to forget about the rest of the system. What is the rest of the system?

If you’re just waiting for me to tell you then you are approaching this wrong. If you are not trying to figure it out then we are both wasting time here.
When you get into a boat and it sinks into the water, what happens to the water that used to be where the boat is before you got in?

You have pushed it out of the way *sideways* from beneath the boat, displacing it, and making the water ever so slightly deeper in the process. This is obvious in a very small container of water, but not so obvious in a lake or river.

Now, when you step out of the boat, what happens to the water that you are no longer displacing, and what makes it do that?
The reason the balloon looks stretched out is that gravity is trying to pull water underneath it – water I originally displaced by forcing the balloon to the bottom.

At the surface gravity has no control on the shape of the balloon – only the air pressure inside working against the air pressure outside.

But on the bottom gravity *does* affect the shape, not by working on the balloon but by working on the water around the balloon.

The water compresses the bottom more because gravity “wants” it beneath the balloon. This accentuates the general compression resulting from the hydrostatic pressure, making the balloon even narrower than it would be.

This forces a greater proportion of the air into the top of the balloon making it more bulbous there than before and thereby cancelling (in part) the general compression of the top by the hydrostatic pressure.
There is one last point to notice about these pictures. We will come back to explain it later.

These pictures were taken in the same pool on the same sunny day within minutes of each other.

Notice the colors, the reds in particular.

The nice fleshy pink tan of the hand that is obvious at the surface is missing at depth. The hand looks very pale. (In fact, in general almost everything looks more “bleached out” deeper in the water.

Furthermore the balloon is a much darker red at depth than at the surface.

Why?