[SQUEAKING]

[RUSTLING]

[CLICKING]

JOHN SOUTHARD: This is where we ended last time. Vito Vanoni, a senior colleague of mine at Caltech, did this interesting experiment. He had a flume running. And he had a microscopic, down-looking view of an area on the bed, right about at critical conditions.

He used two sediments. I don't know whether you can read this-- glass beads, about 0.4 millimeters, and quartz, about a tenth of a millimeter. And he counted the number of grain movements per unit time. And he thought that this would be negligible transport way down-- this is the Shields curve way down below here, small transport, what he thought was critical transport, and then general.

So this shows you how well-- arbitrary, guess you'd say, it is to try to pin it down. There he is, Vito Vanoni, one of all-time greats in sedimentation engineering, really nice person. He'd already retired. He was the head of the hydraulic lab at Caltech.

Now, the sediment load-- what I mean by the load is all the sediment particles being transported at a given time-- is called the sediment load. And now I'm going to do some of my thought experiments here.

Did I tell you about thought experiments? They're really important. You figure out in your mind how things are going to work in some system or experiment. And then you do it. And if it's the same as what you thought, you say, I've learned something. That's nice. And if it's something totally different, you say, oh, shit, I need to go back and think about it.

So it's nice to have thought experiments. So you can think about instantaneously freeze a block, take it out, melt it. And that sediment's the load. That's one way you can think about the sediment load.

Now, you probably know there's bed load and suspended load. And I'll tell you a little bit about it. They integrate. It's not a sharp division. But all the particles moving on or near the bed-- and by near, I mean pretty close to the bed relative to the overlying turbulent flow-- is called bedload. And then suspended load is everything moving well above the bed.

Now, remember, we had the little thought experiment in which you magically shrink yourself to micro size. And you're down there among the grains. Well, if you were down here among some of the bed grains and you're watching what was happening, you could imagine things landing and about to take off, just landed, sitting there, and part of the bed. You've got to make sure that you're not getting flattened between some grain hitting another grain. But this gives you a picture of what's happening with the grains moving near the bed.

This is important. Most particles travel more slowly in the flow, or they can get up to speed of the flow. But they tend to lag behind the flow.

Now, you've probably heard of saltation. Saltation is the big thing in aeolian environments. But a lot of people think that there's a saltation layer of particles taking off, moving fairly close to the bed, and landing again. And it's controversial. And I've never thought much about it. It doesn't seem to make that much sense to me. But a lot of people think that there is saltation near the bed.

Wash load is the part of the suspended load that gets washed through the reach of a channel or a flow or a river or a tidal current. And it's not represented in the bed. Bed material load is stuff that's in the bed. And it can go into suspension. But it's not washed right through. Grains can be put up into suspension. They travel some distance. And they come down to the bed at some distance downstream.

And this may help you. I don't know. Wash load is part of the suspended load. But bed material load can also be in the suspended load. And of course, the bedload is clearly bed material load. So-- in case that helps you a little bit.

By transport stages, I mean, how is it working? Once you get past the initiation, the Shields curve, where there's no movement, first you have rolling. And then the person who-- I copied this from somebody-- thinks that saltation is important-- so that's saltation and rolling. And then when you get up to a certain criterion, it goes into suspension. And you have suspension, saltation, unrolling, all at the same time. If you want to know more about transport modes, there's a thing in the notes you can look at.

Now, this is a big deal in engineering practice, sediment transport rates. How much sediment is going to go through the system? You think of the-- a unit sediment transport rate in any given slice, or the whole flow could be a total sediment transport rate. And many formulas have been developed to try to predict sediment load for that-- sediment transport rates because of its importance in hydraulic engineering.

There's no analytical solution. So you have to work semi-empirically and have-- make some assumptions and then work from there. And I'm not going to do anything with it here. But you should recognize that sediment transport rate is an important consideration in sedimentation.

And here's how you could conceptualize it. There's my magic screen stretching right across the flow. And you somehow magically pick out all the particles that are going past into that screen or through that screen at-- per unit time. And that's the sediment transport rate.

Here's another way of doing it. Here's my magic vacuum suction trap. There's no such thing. But it's nice to think about. And so it catches everything that's going by, coming along in the flow. And all the sediment transport and that pile of sediment, if you normalize per unit time, is the sediment transport rate. So now you know something about the sediment transport rate.

How do you measure the sediment being transported? And that's a tricky business. Suspended load is not too difficult to do. You can have an array of little flip-top bottles that you can remotely flip. You take a sample here, a sample here, a sample here. And then you integrate it, and you get a suspended load transport rate.

Bedload is tougher. Various bedload traps have been devised. You put it on the bed. And you somehow let the sediment get into the trap. It's almost like catching an animal in a trap. And you close the trap and bring it up. And they work sort of well, but not really that great. So you just keep in mind that it's not easy to measure sediment transport rate.

So that's my pitch on sediment transport in water. So now let's think about the wind. That's an important consideration as well. Why is it so great? Here's a mistake. I have discovered a few serious mistakes, thoughtless mistakes, in my notes. And I'm making an addendum before the next presentation to show them to you.

This should be rho s over rho. How did I do that? So the density ratio, sediment density over fluid density, is far greater in wind than in water. And that has implications for the independence of movement of sediment particles. If the density difference isn't great, they can do their inertial thing more or less unaffected by the turbulent flow that they're in, the wind flow.

Ralph Alger Bagnold, the biggest figure in aeolian sand transport that's ever lived-- I almost had a chance to meet him because he was visiting MIT here in the late '50s, when I was an undergrad. And my advisor had him over for dinner one night. But of course, I wasn't invited. So I never got a chance to meet Bagnold.

He did his work in the years before the First World War and the Second World War in the Libyan desert. And he went out on expeditions and did all kinds of things. This book-- you can look at it because I parked-- I bought a copy. And I parked it in Kristin's lab.

It's a classic. And it's worth looking through. So I figured I'd like to get one. So I went to AbeBooks, which is a-- I don't know what you know about AbeBooks. But you can buy books, used books, from hundreds and hundreds of booksellers all around the world.

I typed this in. And I copied-- $5, a good copy. And I bought it. And I got it. It's one of these Dover reprints. It was brand new. The next most expensive cost $50. So fortunately, I was able to get this thing for $5.

So how do you study sediment moved by the wind? Well, you build a wind tunnel. And we've built two wind tunnels, one small and one pretty big. The one we built, the person would have been like this tall, not that tall. That's the extent of my artistic ability, stick figure. I never got beyond stick figures.

So you have a flared entrance, a rectangular duct with a sand bed, and a collector that keeps the sand in. And the air is sucked out by a fan. And it's very effective. But if you want to really see the grains moving, here's the channel, the side view of the channel of the duct. You have a strobe light-- blink, blink, blink-- and a collimator and a slit.

So you can look from the side and watch the saltating particles-- bloop, bloop, bloop, bloop, bloop. It's really a nice way of seeing-- or you go out into the wind and look at a sand bed on a windy day. That's a lot of fun.

Grotzinger and I and a couple other people were out on the White Sands in New Mexico, gypsum sands. It was a windy day, really windy day. It was a hot day. And we were sweaty. And we ended up looking like snowmen at the end of the day. It stuck to us. It was hilarious.

[LAUGHING]

So saltation is a big deal in aeolian transport. Saltation trajectories-- they take a pretty steep angle up into the wind flow. And then they arch over and splash down later on. It's very, very characteristic. And that's what you can see if you did your strobe experiment that I just mentioned.

And the amazing thing is that the spin rates are fantastically high. And I've never really understood why. I must-- must be theories about it. But I haven't managed to get into it. But they're spinning at hundreds of revolutions per second, which seems incredible. But it's true.

And one more point I want to make-- there's an aerodynamic threshold. You have a flat, planar sediment surface in the wind tunnel. Crank up the wind velocity till some particles finally starts to move. And that's called the aerodynamic threshold.

But suppose you already have a saltating system and you gradually decrease the velocity. Because of the effect of the saltating grains hitting other grains when they land, you have to go to a much lower velocity of wind velocity before the saltation stops. There's a-- I don't know what you call it-- a hysteresis effect. You can call it that.

What causes the particle to be launched at the high angle? That's always been a somewhat controversial issue. And it has to be some combination of lift forces. Remember I told you about lift forces on an airfoil? It's because of the pressure differences in the bottom and the top.

Well, clearly, there are lift forces on these particles. And of course, the splashing down particles can kick up more particles and make them vulnerable to high angles of launching. And we're talking about a saltation carpet about this high. It's down around your legs and up to your waistline. And seldom in-- even in the very strongest winds, it wouldn't be more than about 2 meters.

So you hear about sandstorms. You often read about big sandstorms. You're choking and the-- because you can't see anything. Those are dust storms. They're not sandstorms. They're dust storms. Keep in mind they're sandstorms.

Now, I don't know whether any of you are planetary people. But you can think about the threshold, shear stress needed to get saltation going. Mars is much greater than Earth. And Earth is much greater than Venus. And it mainly has to do with differences in the air density, the atmospheric density. Is anybody in planetary stuff here? There you go.

I just have to mention this. We're dealing with stuff on Earth. And now they're doing great things on Mars. But there are zillions-- not literally, but figuratively-- zillions of planets out-- Earth-like planets with saltation going on. And I don't think we're ever going to know anything about them. But there they are.

I figure that there are probably 10 to the 20 something stars in the observable universe. And some non-negligible percentage of them would have Earth-like planets. Now, it might be 10 to the 17th, 10 to the 18th. And so there are these people like us out there watching this stuff. And we're never going to know about it. That's what I think, anyway.

All right. So even on Earth-- I made this up once. And we looked at the density ratios. This time, I did it right, rho s over rho. And you start at 1. And anything on the left is just floating sediment. But when the sediments are denser than the water-- here's sand and water.

Golden water-- gold is very dense. We did some experiments once with tungsten particles. Tungsten is almost as dense as gold. And we had some interesting-- the ripples are much smaller. Snow in air-- and I have a surprise slide for you later about that-- sand in air, and sand on Mars would be way over there, 10 to the fifth.

This is a big topic for us, for sedimentary geologists. And I've been dealing with it for decades and decades. So there's a strong coupling. Flow makes the sediment move. And the sediment movement develops a geometrical bed configuration. But there's an inverse effect here because the bed configuration, once it's formed, greatly influences the sediment transport, and also the flow. So there's a forward problem and an inverse problem here you have to deal with.

This is just a terminological thing. A bed configuration for me-- it's a distinctive pattern of geometrical features on the bed caused by a flow. And a bedform is any one of those individual things that are in the configuration.

Now, most people nowadays lump these together and call it bedform, one word. I'm fighting a losing battle on this. Well, I'm not even in the fight anymore. And I think of a bed state as a kind of existence field for some kind of bed configuration. And we'll be dealing with that considerably pretty soon here.

Why are we doing this? Well, there's a great variety of bed configurations that can be produced by flows, given the flow velocity and the sediment size. And so we have a lot of sedimentary structures, current-generated sedimentary structures, that we would like to be able to interpret.

So if there's only one kind of bed configuration, it would be a dull world for sedimentologists because there wouldn't be this great variety of structures to see. But yet we have an enormous variety of structures-- is possible. Some we understand. Some we don't understand. And I'll get to that, also.

So we'll start with unidirectional flows. There's my flume. And it's about the right scale, given the person standing there. It can be small or it can be even larger. But what you do is have a channel that you can tilt by means of a screw jack. And there's a pump of various kinds that circulate the water in the sediment.

So the flow starts at the head box, flows down, moves the sediment. The water and sediment go into the tail box and is pumped out. So it's a closed-circuit recirculating flume. You're recirculating both the sediment and the water.

There's another kind, similar, but not quite the same. You can have a freefall into the tail box. The sediment collects. The water gets recirculated. And you have to keep adding sediment at the upstream end. They both work. They're useful for different purposes. But that's basically what-- this was my living, basically, for decades.

So in a very general way, this is what you would see. This is the first cut. With increasing flow velocity, we finally get to the point where sediments move. Ripples develop. This is the right medium-- fine to medium sand. And then eventually they disappear and dunes form, larger features.

Then it all washes out to a plain bed. And eventually, if the water is shallow enough and the velocity is high enough, you get antidunes. You may have heard of these terms. I don't know. But we'll deal with them.

And I want to introduce the concept of flow regimes. This is something that developed mainly among hydraulic engineers. There's a lower flow regime and an upper flow regime. The lower flow regime are examples of a rugged bed, a rugged bed of ripples and dunes. And they wash out to have a plain bed. And that's called the upper flow regime. Just it's a terminological matter. You should know about it.

So ripples-- it's pretty clear, I guess. I do have a pointer here. That's the crest, trough, trough, et cetera. This is called the stoss surface. And this is called the lee surface. It's just terminology. But we'll be using that.

And typically, what happens you'll see in a moment. Sediment comes up to the crest, gets dumped, slides down in little miniature gravity flows, grain flows, to cause the slip face to advance.

That's very cartoonish. But now this tells you a little bit more about what's going-- and this is sort of complicated. The flow is from left to right. There's a ripple profile. These little arrows going up the stoss side are bedload transport, basically.

This can be stuff in suspension as well. And for reasons I'll tell you in a minute, a lot of sediment-- some sediment can get suspended in the trough and continues on as suspended load. The grains reach the crest, flow down. So that helps. But this is going to be better to understand.

Here's a crest, a trough. The flow is this way. So the flow separates. I told you about that in the last one. They separate. The flow separates as the turbulent shear layer develops a wake, an expanding wake, which, incidentally, has to go far, far down the flow-- I may have mentioned it-- before it comes back to invisibility.

And you get a rotating vortex in there, which tends to carry sediment up onto at least the lower part of the slip face. And keep that in mind. And then the wake reattaches at this point. And then it's-- flow up the stoss side of the next ripple. That's typically how ripples work.

But ripples are very changeable. They're fickle things. They move along and sometimes disappear. A new ripple forms. Ripples can divide into two, or they can merge together. And so we did this once.

This is a cartoon. But we did this once, stationed a whole lot of students down along the flume. And each one of them keeps track of a ripple as a function of time, along with a scale along the-- and then we plot it all up.

And these are the-- what do you want to call them-- the trajectories of ripples. And you can see how they come and go. They divide. They merge. They disappear. They reappear. So they're very changeable things.

This is just a non-climbing ripple. There's a train of ripples along a surface. But if the sediment is not much available, if not enough sediment is available to maintain the ripples, you get what's called starved ripples. And I'll show you a nice slide of starved ripples.

But if the bed is aggrading while the ripples are moving, then we build up the bed in the form of what are called climbing ripples. Each ripple climbs up the back of the last one. This is a little fakey because they don't throw right up on top, typically. But they can shear off the top of the ripple and be deposited on that. I'll get to that very soon.

I'm going to show you some photos of how ripples develop from a planar bed. It's an interesting problem. You're going to see that they-- first, they're two-dimensional. And then they're three-dimensional.

Now, this is tricky. This is a hydraulics term. Two-dimensional features are those that have straight crests. And so they look the same at every flow-parallel cross-section. Three-dimensional features, that I'm going to talk, but every section is going to look different. So there's 2D bedforms, and there's 3D bedforms. That can confuse people if they don't-- if they're thinking in a different way.

And this is sort of like what I said about saltation and wind. The flow velocity needed for-- to keep pre-existing ripples going is a lot less than the need for initiation of plane bed. And again, because the sediment is already in motion-- has already created these features. And so they keep operating until finally, the current gets so low that the ripples shut off. And you get a static bed configuration. And you may have sediment coming along, draping it. There's a lot of draping involved, sometimes.

This would be a not quite starved ripple. There's a nice ripple moving from left to right. And you can see that the trough is almost bare of sediment. And the next ripple over here, which isn't in the picture, looks a lot like the one you were just looking at-- so almost starved, but not quite. It's from northern Maine.

This is from my flume. It's about a meter wide flow from top to bottom. That's a foot rule there. And you can see that the ripples have very irregular shapes. But they're dominantly flow transverse. And I want to especially point out that there are deep troughs. Here's a trough with water in it. Here's a trough with water. And it's reflecting a light. And that's going to figure importantly when we talk about sedimentary structures produced by movement of ripples during aggradation, during bed aggradation-- nice picture of ripples.

Here's a side view of the ripples. And you can see this is in very fine sand. And it had some fine organic matter in it. And so that accentuates the foreset. Those are foreset laminae. The foreset is toward the flow. And the backset is on the back of the ripple. And they're dominantly flow transverse. But you can see they're rather irregular-- classic ripple picture. I have some pictures from the ancient.

Sometimes, you see bedding surfaces that are rippled, which are nice to see. I wish I'd put a scale in this. It's a closeup of ripples. And you can see the sharp crests, the irregular shapes, planform shapes, the deep troughs here and there. That gives you the essence of these ripples.

There's another bedding plane from the Dakota sandstone. A closeup-- I can't remember where I took that. But it's a nice closeup of a curved crest of a ripple and a trough.

Sometimes, you see an interesting thing called linguoid ripples. I've seen this very seldom. I saw this once in Utah, near the Green River. They're shaped convex downstream. But they come together and be just-- the crest is just downstream of the next trough upstream.

So they have a very regular pattern. I don't understand it at all. But it's not very common. There's something going on that I don't understand. And I don't think anybody else understands, either.

Spacing ripples is almost always in the range of 10 to 15 centimeters. It depends on the grain size. The spacing is a weakly increasing function of the sediment size within the range of flow for which ripples are formed. But they're very stable in this size range. So if you see something much bigger, you know it's not a ripple. Now, on other planets, this may be different. And I'll make a brief mention of that later.

All right. So we did this experiment. This was, I think, the second paper I ever published with one of my graduate students. A guy did a master's thesis. And we're looking down on a planar sediment bed in the flume and make a little indentation.

And that indentation produces erosion deposition to produce an incipient ripple. And that one triggers two others. And you can see that it keeps on going. And eventually, it fills the whole channel. And I'll show you that in a minute. Bob?

AUDIENCE: So that sort of looks like your linguoid ripples that you showed before.

JOHN SOUTHARD: Well, sort of like, yes. But this gallops off into total irregularity. Why it stays regular in that pattern when the ripples are fully established, I don't know. I think it's an interesting question.

So my colleague, Venditti, and Mike Church, his advisor, did an interesting study in which they did the same kind of thing. They triggered it. And it expanded somewhat differently from what I showed you.

The initial ripples are almost two-dimensional, although there are some irregularly developing down here. But you could see if you went far enough down, it would develop into three-dimensionality.

Here's another. Here's a closeup-- we did this ourselves-- in which you can see that the ripples are just-- flow from right to-- from left to right. Ripples are just forming each other. And at first, as they're growing, they're two-dimensional. They're already getting three-dimensional. The ones that are older are already getting three-dimensional. Yeah, so we--

AUDIENCE: --might be a naive question, but--

JOHN SOUTHARD: I'm sorry?

AUDIENCE: This might be a naive question.

JOHN SOUTHARD: There are no naive questions.

AUDIENCE: How do you tell the flow direction from the configuration of the bed? And can you always tell what the--

JOHN SOUTHARD: Yes, always. Remember, go back to the cross-section of a typical ripple. So the upstream, stoss side is always fairly gentle. The downstream side typically is at or near the angle of repose, although it can be smoothed out a little bit. So that's a good word for it, the definitive parallel current indicator. I'm glad you pointed that out.

Here's another example in which the ripples down here-- they're already forming. And they're two-dimensional, gradually passing into pretty-- three-dimensional. It's pretty typical.

I love this photo. I took this photo on a tidal sandbar at low tide up there at Plum Island. And you can see this is a lens cap. And those are bird tracks. And the same kind of thing was happening on this planar surface. As the tide changed and it came across the bar and increased in velocity, it produced these growing patterns of ripples, which eventually would have merged and become a total three-dimensional field.

What was always-- mystified me is, why did we have a nice totally planar bed surface in the first place? Somehow, during the falling tide, it went from high-velocity flow plane bed to being exposed without developing ripples during that time.

It happened. But I'm not sure how it happened. But once we had the plane bed, once the plane bed was there and the tide came in and velocity increased again, it produced new ripples just like that. It looks like dinosaur tracks, doesn't it?

[LAUGHING]

Now, here's a mystery slide for you. This is a parting surface in a sandstone. You can see the parting lineation, which I'll mention later, gives you the flow direction-- or the flow orientation.

And here are these depressions with little ridge marks that are-- if this is a ripple trough that just was starting to form, you can see the curvature is such that the flow is in that direction. I think I'm right about that. And I've never seen anything like that before. Just this one time I've seen this. It gives you an idea what could be happening when the ripples are just getting going.

There's a really good paper in 2014 by my close colleague, Mauricio Perillo, on genesis of ripples, both unidirectional flow, oscillatory flow, and combined flow. It's a really nice paper.

Now let's talk about barchan dunes. It looks like I'm changing the subject, but not entirely. You probably know what a barchan dune is. In the desert, you find these masses of sediment with horns tailing off downstream.

That's just a diagram. You've seen that before. We made them in a flume in very coarse silt underwater. Now, this channel is only 17 centimeters wide. So these are very small dunes. And my feeling is we had a sand surface.

It was actually coarse silt. It was even finer than sand size. And it was just about a threshold. And some grains started to move. But most grains weren't moving. And I think that the origin of the barchans is there's some place where there's enough irregularity in the bed to catch some of the moving grains. And the moving grains then build a structure with a stoss slope and a lee slope downstream. And I think the horns are there because the flow starts to diverge and carries sand around both sides to make the horns.

And I'd have to go back and read Bagnold's book to make sure of that. But I think that's how it works. And these are very small. It's like this size. This is what I just told you about how they might form. But that's my picture of it, anyway.

This is my favorite current ripple. I love this ripple. We made it in a flume. And I took a nice photo of it. These are centimeters down here. So here are all the features that I was telling you about. We have a stoss surface, a lee surface. The sand is transported as bedload up to the crest. It moves down by way of little miniature grain flows out into the trough.

But you can see that there is some sediment being carried back up onto the lee side by the reverse flow in the wake that I told you about. And you can see how if you follow laminae down, they tail out and get planar. And you can see that-- the dark material being worked up onto the lee slope.

But there are other things I can talk about. Earlier on, the ripple had a stoss side which was erosional. And in total equilibrium, the stoss side would always be erosional. But things happen upstream somewhere. Ripples change. The supply of-- local supply of sediment coming along to feed this ripple can be great enough so that now we have a stoss surface with aggradation. Those would be called foreset stratifications. And it goes down on that way.

The other thing is this ripple is riding over another one. There was an earlier ripple. This one came along. And its trough eroded down into the earlier ripple, but left some of the ripple foreset from the previous ripple. You get a lot out of this picture, I think.

Now let's talk about dunes. Too bad. At flow velocity-- no, dunes are much larger than ripples. And I'll get to that. Low flow velocities are two-dimensional and-- at higher velocities are three-dimensional. I have some pictures for you.

Here are 2D dunes in that same channel that I showed you, medium sand. They're not perfectly two-dimensional. They're somewhat sinuous. But they're close to being regular, whereas at a higher flow velocity in that same sand, in the same channel, you can see they get highly three-dimensional. And what I think is important is to see these deep scour pits here and there. And they're going to figure prominently in the stratification that develops when these ripples are moving on the bed.

This is actually a big, big dune because, first of all, it's big. And second, we built this enormous duct. And we ran 80-degree seawater through it. Now, I didn't tell you about scale modeling. And if you want to know, I can tell you about scale modeling. And using the lower viscosity water gives you a scale ratio of about 2 and 1/2.

So what's going on in here is 2 and 1/2 times as big as it would be if we didn't have the water. This is about 4 or 5 meters along that distance. It's a big dune. And you can see the same way the Dune at first was-- it had a lot of curvature, it finally built up to a good, strong stoss surface.

And you can see the sediment being moved in bedload or low temporary suspension. And when it gets to the separation point, the sediment which was being carried along to the crest is raining out onto that surface. So it's not just a matter of grain flows going on the surface. That stuff can be settling out onto the surface at the same time.

That's not the same dune. But it's the same duct. In this case, the ripple was building upward. So if you picked the crest point where the-- changes from this to this, you can see it moving upward as the ripple is growing. And you get the same-- you have same view. I love the way this is falling out in little sheets of sand.

Same duct-- this is an even bigger dune. This is all one big dune. But there are dunes, smaller dunes, on the big ones, superimposed upon the big ones. And so whenever you have a stretch of surface, whether it's a planar bed or the back of a very large dune, smaller dunes can develop if they have enough distance to develop. In this case, you have superimposed dunes.

So 2D dunes-- I don't remember where I took that. It may be up in the North Shore of Massachusetts. But I don't remember for sure. This is the Arkansas River near Tulsa, nice two-dimensional dunes, not very big. There's no scale here. But you can imagine from the trees what it looked like, with lots of superimposed ripples.

Now, that leads to a question. Were those ripples in equilibrium with the dunes as the river stage fell and became exposed subaerially, or were they produced when the flow decreased to the point where it couldn't maintain the dunes, but could make ripples? And I don't know how you tell the difference.

I know from our experiments in the lab that you can have ripples superimposed on dunes. You can even have ripples superimposed upon dunes, which themselves are superimposed on even larger dunes. I don't think you can go farther than that. But you can do that. I've seen it happen.

So "opportunistic" is a nice word. Current ripples and even dunes are opportunistic. Whenever there's a stretch of temporarily planar bed, there's enough distance, and enough-- strong enough flow, you can make dunes-- you can make ripples of dunes that are superimposed on other dunes. I think "opportunistic" is a good adjective to use for that.

Parker River estuary, covered with ripples-- and again, there's the same problem, whether those ripples were in equilibrium with the dunes when the dunes were moving or superimposed during waning flow. I would vote for the latter. But I'm not sure. That's a meter stick for scale.

Another view-- this is from Bay of Fundy, Cobequid Bay, part of the Bay of Fundy, largely straight-crested. You can see superimposed dunes-- not too clearly, but they're there-- on the large dune.

This is an island. Isn't that a strange-looking island? The spring tidal range up in this end of the Bay of Fundy is 50 feet. Isn't that amazing? So when you go work on this, you have three, four, maybe five hours at most to work. You have to get off as the tide comes in. And the saying around the Bay of Fundy is, the bay never gives up its dead.

[LAUGHING]

It's tricky. Otherwise, you lose-- you swim to shore and you lose all your equipment. It happens.

Here's a better view of that. Here's a better view, close to it, from the right to left, where you can see the typical troughs of the superimposed dunes and ripples on the superimposed dunes.

Another place in the Bay of Fundy where the flow is stronger and it makes semi-three-dimensional dunes, not grossly three-dimensional. And you can see as the water-- the water stands in the troughs here and there. That's Gerry Middleton, my older colleague, one of my mentors. He took me out. He had three students working on the Bay of Fundy at one point.

Even more three-dimensional-- there's some small river whose name I don't remember near Atlanta. I was there doing consultation from some guy who had a business next to this. That's a Dr. Pepper scan right there-- can. And you can see the prominent scour pits in this three-dimensional pattern of dunes.

Dave Mohrig gave me this. You know who Dave Mohrig is, I guess. He did his thesis work on the Platte River. He had a balloon that he parked in some big, cavernous warehouse. And every day, he would bring it out. It was inflated. And it was positively buoyant.

He and his assistant would bring it out, park it above the river with a camera, down-looking camera, and they would-- these are people. That's a person. That's a person. I think that's a person. I know that's a person. It gives you a good idea of what ripples really look like in a river system.

Dunes can get enormous. Here we are on the crest of a big dune on the left flank of the Mississippi River near Kentucky. And we're all standing at the crest. And the lee slope goes way down there. So dunes can get as big as the flow allows.

You're going to see very soon that ripples form in sands coarser than a-- finer than about half a millimeter. Dunes can form in a wider range of sizes. We did some experiments at the University of Tsukuba in Japan, north of Tokyo, using gravels. And the reason they're all colored is we colored each size a different color so we could see sorting during the motion of the dunes.

And you can see some of these particles are whipping up the stoss side and being projected over the crest. And that's the big one right there that came in. It's going to fall down on the trough. It's exciting to watch.

We're back to Cobequid Bay. We cut a section through one of these dunes. I don't know how well you can see. But you see a set of laminae up here. And you can see a set of laminae down here. And then there are other things going the other direction. And my feeling is that because of the tide-- there's a strong tide going one way. And then it shuts off.

And there's a weaker tide going the other way, current going the other way. And it flips things over and makes the inner structure of this dune very complicated rather than being all nicely regular foresets. And that tells you something about the flow. The flow is reversing. There's an asymmetry of flow. But it's a reversing flow.

That's the same picture-- shows the same thing. I thought this would look better. But the other one looks pretty good, too.

Out offshore, you can take sonar images. We were doing a survey in the-- what's the name of the water body between the coast-- south coast and Martha's Vineyard? Vineyard Sound. That's it. This is in Vineyard Sound. And they look sort of like the other ones I've shown you.

Snow dunes-- it was a bitter, bitter, cold day, January day. This was back-- must have been in the early '70s, mid '70s. And I saw these dunes. And I couldn't resist going out on the Harvard Bridge on the west side and taking this photograph of snow dunes because snow particles are particles. And they're less dense than quartz sand. They make dunes. And they're not all flakes. There are all kinds of different shapes of snowflakes. And so I'm glad I did that.

Now, here's a factor that's different from ripples. The spacing goes as the flow depth. And with a factor of something like 7 for fully developed dunes, if you have a flow, an open channel flow, over a sand bed and you make dunes, the dunes, when they reach equilibrium, are something like a factor of 1/7 of the depth of the water. It varies, plus or minus. But it's-- Lyle?

AUDIENCE: Is that pure empirical-- purely empirical?

JOHN SOUTHARD: Yes. Yeah. I don't know whether anybody has tackled the problem of predicting why they're the size they are. I don't know. But that's a general observation. But of course, they may be smaller because they haven't fully developed, or may be-- they may be larger as a function of water depth because the flow is decreasing. But in equilibrium, that's a pretty good predictor.

All right. Now it's almost time to quit. But I'll get started on this. Now we're going to do the dimensional analysis. You probably suspected that I'm going to get into this. Remember the-- from the first lecture, you do dimensional analysis? And it's very useful as a framework.

So what do we have to deal with? Well, depth and velocity of flow, obviously, particle size, fluid density. And you know what I forgot in this slide? The viscosity of the water. Sediment density, specific weight, and gravity, g--

Now, I don't want to belabor this. But you clearly need the specific weight, the weight per unit volume of the sediment, because it has a weight. That's what makes it fall. But you also need the fluid density in itself because of inertia. And I'll talk about that in a minute. But I left off-- I knocked off the viscosity. So I got to think about that for next time.

So why do we need specific weight rather than just density and viscosity? Well, it has to do with buoyancy. You know about Archimedes' principle, I guess, about buoyancy, why things pop up when they're less dense in the water, because the water pressure forces above are less than the water pressure forces below. And they go up to the surface. He's one of my all-time heroes, Archimedes, one of the greatest minds in human history.

Anyway, so given that, you need sediment density as well as the weight per unit volume. Why? Because solid particles moving through the flow to the fluid have inertia. They want to travel in straight lines without any interruption.

And so this inertial effect is really separate and had to be in addition to the-- and so I did a thought experiment. We're in a spaceship-- no gravity, a big tank of water. You can do that. And then you have a little port-- gunport that you shoot a particle, a dense particle, into the water.

Now, it has no weight at all. It's weightless. It's no weight. But it still interacts with the fluid in the tank. It has inertia. If the flow is turbulent in the tank, it would want to make it move. But it has this inertia-- does this thing. So you need density as well as specific weight. That's a side point, I guess. But it's important to deal with.

So there are various ways of non-dimensionalizing. Remember Buckingham's theorem that I mentioned in the first presentation? And there are various ways of doing it. But the way that's most useful for us as sedimentologists is to non-dimensionalize the flow depth and the flow velocity and the sediment size. And of course, you have the density ratio, too.

And so the natural thing would be, and we're going to do it-- oh, incidentally, I don't know whether you-- I said that you can do this. And there's a little section in the notes, if you want to look at my notes, on how you do it.

It's a simple procedure. You pick out three repeating variables. And the rest fall into place to make these dimensionless. And it's just basically high school algebra. It's easy to do, just so you know.

So we can draw three-dimensional-- dimensionless diagram-- dimensionless flow velocity, dimensionless flow depth, dimensionless sediment size. And we can make sections through it in various ways. I'm going to be almost out of time here.

And I'm going to show you-- I think this is probably where I'm going to have to quit. I want to show you some sections, some depth velocity sections for a given grain size and some velocity size sections for a given flow depth.

I did this long ago. And I got all the literature data I could find and plotted up some of these section graphs. And I'm going to say quite a bit more about them. But I have to quit. So this is a good place to stop. And so any further questions?

AUDIENCE: I was wondering if I could ask a quick question about [INAUDIBLE]?

JOHN SOUTHARD: I wish people would ask more questions here.

AUDIENCE: So is it well understood why you jump from ripple spacing to dune spacing without some gradual-- are you going to get--

JOHN SOUTHARD: I think I have a slide in here. There's a spectral gap between the standard ripple size and dune size, which is always larger than the ripple size. But they vary with flow conditions. And that's the way it is.

And I'm getting ahead of myself. But I'll say that there have been various attempts to do theoretical solutions to figure out the mechanics of why there are ripples and why there are dunes. And I've read through the literature. I can't tell you anything really intelligent about it.

But you do a stability analysis. You start out with a planar bed. You introduce a disturbance. Is the disturbance-- is wiped out as for when we're dealing with high-speed plane bed flow, or does it magnify itself until it reaches an equilibrium? And there have been several attempts at stability analyses like that. And we just have to accept that it works that way for our purposes. That's all I can say about it. Does that make sense to you?

AUDIENCE: Yeah.

JOHN SOUTHARD: All right. So I will hope to see you-- oh, I'm sorry. Kristen?

AUDIENCE: I have one more. And so I can understand in a flume that you're most often starting from a lower plane bed that gets disturbed--

JOHN SOUTHARD: Well, typically, you screed the bed. You use a screed. You mount a blade that goes a little bit deeper in the sand. And you run it down some guide bars parallel to the bottom. And you screed it off very nicely, and you start. But of course, that's unrealistic. It seldom works. And I showed you the dinosaur footprints. Sometimes, it works. Yes?

AUDIENCE: So the beach example-- how often is it an upper plane bed that then you initiate ripples from as opposed to a lower plane bed, like in a storm to--

JOHN SOUTHARD: Oh, well, if you're dealing with pretty fine sands-- you will see soon, in the next few slides, that there's a range of flow for which there's no movement, and then ripples set in. And then there's plain bed and no dunes. Dunes don't develop in very fine sands. And so then you could wash the ripples out to plain bed. And then if the flow velocity decreases again, you develop ripples on it. I have a slide that shows that that we did in the lab. So does that answer your question?

AUDIENCE: Yeah.

JOHN SOUTHARD: So I hope to see you next week. But if not, it'll be maybe the week after, or maybe even later. So we're about halfway through this PowerPoint number 3. And that'll leave us, I think, enough time to do all of number 4, which is pretty long and heavy.