[SQUEAKING]

[RUSTLING]

[CLICKING]

JOHN SOUTHARD: So these are the variables you'd have to take into account if you're going to capture the reality of bed configurations and the usual flow depth, flow velocity, sediment size. The fluid density is important. The fluid viscosity is important. And then there's sediment density and gravity.

Now, I have to make a few comments about it. The particles have weight. And that's a combination from the density and gravity that makes weight. But also, density, fluid density-- sediment density itself is important by itself. And I want to show you now-- let's see how lucky I am here. Yeah.

They act together. And obviously, weight is important. That makes the sediment negatively buoyant. But particle density gives the particle inertia going through the fluid. So if you had a turbulent fluid, the particle tends to go by itself and not be affected by the turbulence.

And here's the thought experiment. Did I tell you about thought experiments? I love thought experiments. Einstein loves thought experiments. His whole theory of relativity was based on some thought experiments. I saw Einstein once. What do you think of that? 1952, in Princeton. He was walking on a sidewalk near his home, and I was sitting there in the car, and I watched him walk by.

So look, you're in a zero-gravity spaceship up there in space. And you have a big tank of water, closed-in tank of water. And you have a way of shooting a particle into the tank and watching what happens with it. Now, the particle has no weight at all. But the difference in density still is important because it has inertia. And if the flow in there were turbulent, and you shoot the particle, it would try to take its own path, not affected by the turbulence.

And I showed you this. I think I showed you this. It's to remind you about what buoyancy is in the first place. And here's one of my all-time heroes, Archimedes. So rho s And g together account for the motion of the particle. And we don't need to worry about the weight per unit volume. Rho s and g take care of the weight per unit volume, so we don't need to worry about it.

So what's most important for us are, I think, depth velocity and sediment size. And there are various ways of non-dimensionalizing. And this one, I think, is useful. This is different from the PowerPoint number three you had, different in some ways. But anyway, there it is. So we can use the three dimensionless variables, flow depth, flow velocity, and sediment size, nondimensionalized. But what I'm going to do-- and you can make a three-dimensional diagram out of it, section this way, section this way, section that way, and I'm going to show you some results.

It's non-dimensional. But the graphs that I'm showing you have-- these variables are normalized to 10-degree water temperature so that it all comes out nicely on the graph. And I'm going to make some more comments about that soon. So here's the sections. All the diagrams are normalized to 10 degree. I don't expect you to see a lot of this. But I'm going to show you the next slide in more detail.

This is a flow depth versus-- so what you see is for low velocities, there's no movement. Then you have ripples. Then you have dunes. Then you have upper plane bed. But these lines down here are for equal Froude number, Froude number about 1. And beyond that, you get anti-dunes. And if you made dunes way down here somewhere, you'd find that the dunes and the anti-dunes would interact with each other somehow. And I've never done that in the lab. I can't tell you what it would look like.

This is one of my favorite slides. This is another section, U versus-- velocity versus sediment size. This is for a flow depth of about 0.25 to 0.4 meters, so a lot of data. Almost all these data come from the laboratory, my laboratory, a lot of other people's laboratories. And it plots very nicely, interestingly, I think. For fine sediments, you find ripples, and then they change to upper plane bed at a certain point. I told you that already, I guess. For another range of sediment sizes about in here, ripples go into dunes, and the dunes go into plane bed.

But beyond about half millimeter, there are no more ripples. Ripples don't form, only dunes. As soon as you go from no motion, you develop dunes. And the anti-dunes would be way up in here somewhere. This is Froude number 1 right here. Does that make sense to you? And I think I have a cartoon of this in your notes, which shows this. And let me go back here. What I like about this is you can fit a curve, a very natural, normal curve with no scatter. It really works, which means we're doing something right.

I have a colleague named Dave Rubin. We've been together for a long, long time. And he picked up on this. And he and Dave McCulloch made-- this is a little complicated. But this is the three-dimensional graph that I just told you about. But it extends up to a considerable depth. And you get stuff out in here. These are sections through that graph.

And you have to imagine volumes of existence fields. And as far as I know, nobody's improved upon that, which seems strange because it's really important to think about greater flow depths, not just the typical flow depth like this in laboratory channels. It's seldom greater than about a meter because you have to have an enormous, enormous channel to make different things.

So now, we're limiting ourselves for water on Earth, gravity, and sediment particles, quartz density, sediment density, and water. But you can easily adjust this for different gravity. And I'll make a few comments pretty soon about Mars. But there are zillions of planets out there in the universe that would have flowing liquids, moving sediment particles under some gravity.

And there are some constraints. There aren't too many liquids that have different densities and viscosities. You can use motor oil and honey, I suppose, to have higher viscosities. But condensed matter liquids don't have a great range of densities. But just keep in mind that this is just one little thing on Earth, and we have a wide range in the universe that we're not going to know anything about.

Oh, and here's an issue. I don't know whether you've been thinking about this. It's the boundary shear stress that moves the sediment. So why don't we use the boundary shear stress on that graph instead of depth and velocity? But there's a problem here. Now, this is an old, old, old slide that I made in 1975. And I was calling it flatbed instead of upper plane bed. And this is a graph of bed shear stress versus mean velocity. And it doesn't just go up, monotonically upward. There's that little bump there. And the next slide explains it more.

So this is the boundary shear stress versus velocity. And here's that curve I showed you. And there's a range of boundary shear stresses for which you can have 1, 2, 3 different flow velocities. Now, why would that be? Can you think about why that would be? Strain your brain a little bit here. I don't get any responses, so I may go on ahead.

So as you increase the velocity over rugged bed forms, dunes, and ripples, the boundary shear stress, the total boundary sheer stress is high because of all that form drag. Remember form drag? But then the dunes wash out to plane bed. And all of a sudden, there's no form drag, only skin friction. So you'd expect to have overlap in the graphs.

This is just to glance at. And there's a cartoon of it. There's an area, a couple of areas in here, for which there is overlap of data. It gets really messy in here. And that's just because we're dealing with a non-monotonically increasing value of the flow stress, of the stress. And there it is. You have to live with it. So do you get around it? So when?

AUDIENCE: From the three-dimensional graph that you showed, are those just for subaqueous dunes? Or are they also applied to eolian?

JOHN SOUTHARD: They're for water-- well, water or they would be good for any other liquid. But let me point this out. I forgot to point it out. These graphs are for a given ratio of Rho s over Rho, density ratio. That was one of the dimensionless variables. There were three, velocity, flow velocity, and water depth and sediment size. But there's another one. This is all for that density ratio, quartz sand and water, for example.

So you have a whole different diagram with whole different existence fields, similar but not the same, if you have a different density ratio. Now, we made some experiments with tungsten grains. We bought a ton of tungsten particles. Tungsten has density almost as high as gold. And we made bed forms. This is a project I did in South Africa with some colleagues in South Africa. I don't have a copy of the publication. If I had, I would have tried to put something in here.

But anyway, that's the way you could do it, is to somehow partition the drag so that you look only at the skin friction part. And there are various techniques that have been developed for drag partitioning, and none of them works perfectly. Some of them work OK. But if you didn't do that, if you didn't do that, then you can't use total boundary shear stress. It's just a point that you need to know about.

This has probably occurred to you. Are ripples and dunes different? Well, obviously they are. They're different in size. They're different in behavior. And they're different in origin as well. And there's something called a spectral gap. Current ripples in water on Earth are seldom bigger than about a decimeter.

Dunes, however, are seldom less than about a half meter, even in shallow flows. So there's a gap, a spectral gap, in sizes there. Ripple spacing is almost independent of flow depth. You can have flows that are half meter deep, and you make ripples. You can have flows that are 10 meters deep, and you have the same ripples down there, if you have the same near bed flow velocity.

Dunes, on the other hand, the dune spacing goes as the water depth by something like a factor of 5 to 10. So they really do change with water depth considerably, which is good for interpretation because if you can back out dune size from your outcrop, then you'd have something to say about the water depth.

This is something I'd like to address. And I've been thinking about it for years. There have been various papers written by various people on making stability analyses to explain the dynamics of ripples and dunes. You start with a planar bed, and you have a flow over it, and you make a little disturbance. And sometimes that disturbance generates bedforms. And you saw that when I was talking about the incipient ripples earlier, last time.

But sometimes it gets washed out again, and it's unstable. And so you have to do that kind of thinking to try to account for why there are ripples in the first place and why there are dunes in the first place. And I'm not addressing that. But you should be aware that's a problem.

How about Mars? I'm going to come back to Mars because these planetary sedimentologists have to worry about things on Mars. And so you could redo this diagram just the way it was, but plug in different gravity, which you can do. And here are the results that I figured out a long time ago. From one kind of bed form to another takes place at lower velocity on Mars by a factor of about 0.74.

And if you look at the change from one kind of bed form to another takes place larger by a factor of about 1.36. That's, I think, my almost total contribution to planetary sedimentology. No, there's going to be another one coming along, too, that I'll mention later.

So now we're on to oscillatory flow bed forms, which are just as important. How do you make oscillatory bed forms in the laboratory? We've done this. It's a tank, a horizontal tank, sediment bed. And you have a wave generator, either paddle back and forth, or you could have a piston going up and down, and the waves go down to the other end. And what you have to do is put in a total wave absorber at the other end, so you don't get reflected waves, because then you'd have standing waves. And we don't want that.

But you can also do this. And we did this big time in building N9, back about 20 years ago with Bill Arnold and one of his students. You can have a liquid pendulum in which you take a tank with reservoirs, and you move the level of water in the reservoirs back and forth with some sort of piston. And it works. And you can make nice bed forms that way.

This looks very clever. You have still water and a thing that moves back, oscillates back and forth, and you can make ripples with it. But the ripples aren't the same as the others. So people have written papers about that. They have to admit that it doesn't really work for natural environments. But they've done it.

So this is the first order here. This is the big message, if you want to look at it that way. Details later. So as you keep increasing the oscillatory velocity-- there's no current involved here. You have straight to two-dimensional ripples, regular straight two-dimensional. And then at a certain point-- and I'm going to get into this more in a couple of slides. They're small, but they get three-dimensional. And then they get larger and larger into large three-dimensional. And finally, at the highest velocities, you get a plane bed again. That's the basic message here, what goes on. But we'll try to go beyond that.

So here we go again. We're going to make another dimensional analysis. And so just-- assuming that you're doing it. And so we're going to use either oscillation period T, orbital diameter d0, or maximum velocity, orbital velocity, Um. And it turns out-- and I'm going to show it in the next slide-- those three are not independent of one another.

There's a relationship, Um T equals pi d0. So only two of them can be chosen independently. And what we're going to do is choose period and velocity for that. But I just want you to be aware that those are the only two you need to account for what waves do on the bottom. And so you get another three-dimensional graph. I keep giving you these three-dimensional graphs, oscillatory velocity Um, oscillation period T, sediment size d. And this is what I mentioned here, that you have this relationship, which I'm not proving to you. But there it is.

Now, you can section various ways. There's three ways you can section. And it gets a little complicated. But I have to point out that in a laboratory tank or channel with waves-- I'm sorry. Let me start again. If you had an oscillatory flow duct, like that liquid pendulum thing, you're at liberty to specify any orbital diameter, any orbital velocity, any wave period you want. But real waves don't work that way because the way waves work, there's a certain range. There's only a certain range of those variables that are actually produced at the bed under shoaling water waves.

So if you think of that three-dimensional graph, there's some volume in there, which is realistic for waves. And the other areas are not realistic for waves, even though you can make them in a laboratory. That's how we have to live with that. But in this permissible volume, if I can call it that, there are existence fields, three-dimensional existence fields, same way there was for unidirectional flow. Does that make sense to you? You can picture in the-- there's this volume in there that things could be happening under waves. And there's various kinds of small versus large, straight crested versus three-dimensional are going to be in there somewhere.

Every ripple you can possibly make would be in this three-dimensional diagram. But the trouble is not every point in the diagram is occupied by a bed configuration. That's what I just pointed out to you.

So how do you get data on these things? Well, experimental tanks and channels have been done often. There's a size limit. You can build an enormous, enormous wave channel and make real waves. And they had one at the US Army Corps of Engineers Waterways Experiment Station. They had one of these enormous tanks. But you're still limited.

Out in nature, there are plenty of 10 to 15 second wave periods. And you can't make one of those in a laboratory. So there's a definite limit. Or you can make observations of shallow ocean. And there's been studies to do that. But it's tough because it has to endure storms. You have to record the stuff somehow. You have to wait a long time until a storm comes along. But people try to do it, and it's a valuable thing to do.

So this is a graph that I took from my notes. It's just one section, a velocity period section, for sand size about point 0.01, 0.02 millimeters of fine sand. And let me tell you some things about this. These downward sloping lines are contours of equal d0, which has to be in there because you've collapsed a three-dimensional down into two dimensions. And these planes of equal d0 would come out as lines through the graph.

I'm not showing you all the nature of the data points. But all of the solid diamonds and the open circles are relatively low velocities and oscillation periods. And then the ones up in here the squares, the open squares, solid squares, and some other things, are for much larger oscillation ripples that get produced. And I've tried to contour. These are-- and I don't think-- did I say this? Yeah, dashed curves, ripple spacing. I tried to contour the ripple spacing. And they increase very regularly up from lower left to upper right.

But there's another curve in here, the solid curve. And that's an important curve. Everything below that curve is two-dimensional bedforms. And up above that is three-dimensional bedforms. It's not a definite cutoff. It's not like one of those boundaries in ripples and dunes in your directional flow. There's a gradation. There's a range in here around that line in which the ripples start to be three-dimensional and then become three-dimensional. I made that long ago. And I never followed up and made others like it. But there it is.

Some pictures-- it probably won't surprise you, ripples, oscillation ripples, small-scale oscillations, typically straight-crested and regular. There are tuning forks, often, you see. This is from the Moenkopi near Vegas. It's a nice section, a lot of interesting stuff in it. And there again you have a tuning fork junction and still another from the same place.

I don't know where that's from. That's a lens cap up on the top, but again, straight-crested regular. They're rounded off at the top. And I'm not sure why. This is classic, classic small-scale straight-crested oscillation ripples from the Ferron sandstone member of the Mancos and looking straight down on it. There's a pen or a pencil for scale over there and a similar kind of thing from the Cardium up in Alberta.

Now, what's going on here? Explain that to me. The hint, of course, is that we're dealing with oscillation ripples. So what do you make of that? I have to challenge you guys now and then. Well, what I should have done is put the next slide in and turn it upside down because if you did that, it would just look oscillation ripples. This is a slab that came off something, and it fell upside down. That's what a ripple bed looks like upside down. I've never seen that, except just in one place.

And now, on a broader scale, this is a big flat tidal sandbar off the coast of Eastham in Cape Cod, in Mass Bay. And you see, if you looked at just a little area here, it would look sort of like what we were doing. But when you look at all the whole field there, there's a lot of sinuosity and tuning fork junctions and things like that. There are a whole series of these bars, one here, one here. You can count four or five bars at spring low tide where the water is lowest. It's an amazing place.

Some ripples-- you can see, this one looks symmetrical. This one is asymmetrical, but you can see the laminae inside the ripples, indicating the ripples. We're moving in one direction, shifting in one direction. And that can happen. That can happen in oscillatory flow, even when it's purely oscillatory. And I'll tell you more about that. They can get really big. We made this in an oscillatory flow duct with a long period. And they're big. These are centimeters here.

This is an amazing photograph. I didn't take it. My long-term colleague and mentor, John Harms, gave me this slide, copied this slide for me. And this is a half a meter, I think, half a meter scale. And these are big. They're a meter plus scale. They're probably in coarse sand, I'm guessing. They're very straight-pressed and regular. And I've never seen one of those in my doings. But he showed it. Now, this my favorite outcrop. It's a win.

AUDIENCE: Does the spacing between the oscillatory ripples vary with flow depth the same way you have with unidirectional flow? And can you backtrack?

JOHN SOUTHARD: Well, go back to the graph with all the data points on it, remember. And we contoured the spacing. So it varies with both variables, not just one. That's a rock hammer. You see the rock hammer. And if you look at that, you can recognize there are hummocks, and there are swales. And they're isotropic in the sense that they don't bend one way or bend the other way.

And I remember looking at this outcrop-- it's a little bigger than what I took the picture of-- and you can sense that the hummocks are arranged in a hexagonal pattern. And in the middle of the hexagon, there's a swale. And I even, in one place-- and I can't point it out to you-- there's a place where within the swale, there's a little miniature hummock right in the swale. It's amazing, my favorite outcrop.

But I went back here some years afterward, maybe 8 or 10 years. It had fallen apart, a tragic loss. It had fallen apart. And it's not there anymore. I don't remember where I took this photo. There's a rock hammer there. But it's, again, hummocky swale, although it has some lineation to it, and it's somewhat asymmetrical. And this I want you to keep this in mind when we talk about combined flow bedforms. It's not that great a picture, but it shows some interesting things.

Here's a close-up from straight down on a hummock. And you can convince yourself that it's three-armed, one this way, one that way and one that way, with a peak to it. And I think this was from somewhere-- somewhere in Canada, I was looking at it with Roger Walker, but I can't remember where.

This is another one of my favorite chunks. I carried this out of the outcrop from the wood canyon in the Southern Nopah Range. And here's the scale, a hummock here, a swale, a hummock over here. And the whole bed, presumably, was like that hummocky swale, on a medium scale, a couple of decimeters. And if you look closely-- and this is getting ahead of ourselves-- the stratification here is medium scale hummocky cross-stratification. And I'm going to say a lot more about that coming up soon in the next session.

Now, I'm going to take a shortcut here and show you a couple of graphs that show that there are things called orbital ripples, spacing consistently just a little less than the orbital diameter, through a transition in what are called suborbital, and orbital ripples, largely independent of the spacing, but it is dependent on particle size.

You get, in fine sand, only in fine sands, and in very long excursion distances, you get ripples that look like current ripples. This is from a classic paper written by my colleague, Ed Clifton, way back-- he died a few years ago-- in which he plotted-- and I think I have the axis, lambda-- that's the spacing-- over the square root of D. I don't know why he did that because it's not dimensionless. And the horizontal axis is the d0 over D. Let me go back.

And so there's a trend here. And those are the orbital ripples. And then it breaks through some messiness and comes out to a big group of anorbital ripples. These are data from both laboratory and field. It's not the only one. I can skip that. In a more recent study-- this is from Pat Wiberg and her colleague back in the late '90s, the same kind of-- they plotted spacing over D and d0 over D, so it's a real dimensionless.

And you can see, there's a whole bunch of points here, both from field and laboratory data that are orbital ripples. They go with the space. They go with the spacing. But there's a whole bunch out here, which are totally separate. Those only field data. And those are an anorbital ripples. So it seems strange, doesn't it, that you can make both orbital ripples and anorbital ripples in the lab, but the only ones you see in the field are anorbital ripples.

There's another example from a paper we wrote in 2005, in which these are the-- I won't go into details, but these are the vortex ripples, and these are the orbital ripples. And those down in the left-hand corner are anorbital ripples. So this summarizes what I'm trying to tell you here without a lot of details. But somehow they're different. There's some of instability that makes them different.

I've wondered for a long time, and my colleagues have also wondered at the same time with me, about whether anorbital ripples are really just reversing current ripples because suppose you have a very long orbital diameter and a fairly substantial velocity over the bed. So for the 10, 15, 20 seconds that the flow flows this way, current ripples want to try to form. They're opportunistic. They form whenever the current velocity is right. And then it reverses. You go back the other way. They're still there.

But they flip over and grow some more. And you go back and forth and back and forth, and you end up with anorbital ripples that are basically current ripples that can't make up their minds which way to go, if you want to look at it that way. I'm not sure I'm right about that. And I've talked with colleagues about it, and there's some agreement among us that that's the way it works.

Now, there's something called ladder-back ripples or cross-ripples, which, to me, are mysterious. Look at that. I forget where I took that. That's my scale. So I took that picture. And you can see, there's some major oscillation ripples. And then in the troughs, there are some minor, smaller oscillation ripples. They're almost the same size, I guess.

Here's another example. That's a watch for scale in the middle. So these are the main oscillation ripples. But look at all the smaller ones in the-- now, is that because of something, how it works under these conditions? Or is it you made the large ripples first, and then things changed, and you got oscillation from the other direction, which seems to me to possibly. And I don't know how you tell the difference.

So here's the two ways you maybe could make them, non-parallel oscillations or a single component under certain conditions. And that's what I want to get to next. Ed Clifton, who I mentioned, organized some data from various places, shoaling waves, waves coming in, shoaling, finally breaking on the shore.

And out in the fairly deep water, you get active, long-crested or oscillation ripples we're looking at. Then they get irregular. Then you get cross-ripples for reasons I have no idea why. And then when the waves break and run up the beach, you get what you call lunate megaripples. They're not oscillation ripples anymore.

I have no idea how this formed, pentagonal oscillation ripples, no idea how it formed. I took that when Palmeiro was just finishing his doctoral thesis up there in St. Johns, in Newfoundland, and we went across to Bell Island and a lot of interesting stuff. And there it is. I don't know anything about it. So now, this may be counterintuitive to you, but oscillation ripples formed in purely oscillatory flow--

AUDIENCE: What if one of the orientations of variables was 3D, and one was 2D?

JOHN SOUTHARD: Are you talking about the pentagonal ripples now? Maybe there are three or more different oscillation components, maybe something like that. I don't know.

AUDIENCE: It's so cool.

JOHN SOUTHARD: I know. It's amazing. So ripples formed under purely oscillatory flow aren't always symmetrical. Now, way back in hour one, I told you about how under shoaling waves, there's fast and short, slow and long. The water doesn't go anywhere on a net basis, but because sediment transport rate is so steeply climbing, a function of the flow velocity, that you end up getting net transport towards shore, and you can get asymmetrical, purely oscillatory flow. It seems counterintuitive, but it happens.

Now, a little bit on the eolian bed configurations-- I'm not going to say a lot about it. I mentioned barchans early on when we talked about sediment transport. Those are miniature. These are major. These are big, big ones. I forgot where that is even. And here's a more distant view from the air of an isolated barchan. So I'm not going to say anything more about barchans. Read Bagnold's book if you want to know about barchans.

So classic wind ripples-- now, at first glance, you look at and say, oh, they're oscillation ripples underwater. But they're very distinctive in their shape. They're asymmetrical, and they have grain-size segregation that's very different from what you'd find in oscillatory flow ripples. They can get fairly good size. Here are some that are getting up pretty big. There's not a scale in there, except for the bush, unfortunately. I should have put a scale in. But they're decked with smaller scale wind ripples as well.

Now, if you look at the dunes, there are a lot of active coastal dunes along the coast of Oregon, for example. I'm out there with my colleagues. They take me out there to show me this stuff. And you can see the stoss surface of the dune, strong eolian transport, no ripples, plane bed transport, reach the crest, and the grains that are deposited at the crest slide down the crest. This is a view of the same dune with-- here's a slip face at angle of repose, and the grains slide down as little miniature grain flows out onto the-- this is an earlier dune that this one is overriding.

Now I have to say some things about combined-flow bedforms, but I'm not happy with it because I don't know much about it. I don't think anybody knows much about it. It's a jungle, when you think about it. You have all the things that go on in unidirectional flow, everything that's going on in oscillatory flow, and everything in between, when you combine the two flows in various ways, and you get an enormous variety of bed configurations, and therefore, an enormous variety of sedimentary structures. And it's a jungle. It's a dog's breakfast, as John Grotzinger likes to say.

So that's the topic. How do you make combined-flow bed configurations? Well, you can do it in the lab. If you have a unidirectional flow and a parallel oscillation, it's pretty easy to do. And we've done it in our laboratory. But if they're at right angles, it might be doable in the lab. I once thought about writing a proposal to build a flow channel with flow and reservoir tanks on the side. And you can rock the channel back and forth to make an oscillation while the current is flowing. I never did it. But I thought it would be a cool idea to do. It didn't do it. Oh, wait a minute, wait a minute.

And the third would be to-- if you have more than one oscillatory component plus the unidirectional flow, this would be very difficult to do. And I think it's been done. And I'm not into the literature. You'd have to have a big wave tank with wave makers here, and wave makers over here, and wave makers over here. Plus, you'd have to pump water from one side of the tank to the other and produce the current. And that's a big job. And I don't think much has been done on it.

So here we go again, another dimensional analysis. You need not just max orbital velocity, you need directional flow velocity and period, period and size. So here you have four variables instead of three. Well now, I cannot, and I don't think anybody can, visualize a four-dimensional diagram. I think that's beyond our capabilities. So what you'd have to think about is, you make one of those three-dimensional graphs for every value of the fourth variable. And you could do that. It's an enormous job, and it would take a lifetime of experimentation to fill in a graph like that.

So this is from before and from earlier. And now, we're dealing with this oscillatory velocity, versus oscillation period, versus sediment size. And you'd have to do one of those for every value of unidirectional flow added on to it. It gets really messy. We don't have to do this. There's another way of-- there's a velocity symmetry value, but it's not important. Don't worry about. I'm not going to say anything. So we're far from filling these diagrams. It's just the way it is.

Here's some nice papers. In case you're interested, you can pursue some of these papers. Ours is one of them. There was a student, one of Bill Arnott's students from University of Ottawa, Simone Dumas, came down to build and operate a giant flow channel, oscillatory flow channel, with unidirectional flow as well. She and I built this thing with some help from other employees. She was the person who was the best arc welder of any of the employees and students I've ever had. Now, I teach these people how to do that because we build things. And she was really good at it.

So here are some of the ripples that she got. This is for-- small-scale bed forms range from, as you might imagine, symmetrical to somewhat 3D to very 3D and on into basic current ripples. And you can do the same kind of thing for large ripples, again, symmetrical for almost purely oscillatory flow. They get a little three-dimensional, and they're somewhat asymmetrical.

Then they get to be more three-dimensional, and then you finally get to dunes and your directional flow. So that's a way of looking at it. She made these conclusions based on all the experiments, all the runs she made in the duct. And this is her graph, which is a good one, oscillatory flow velocity versus unidirectional flow velocity. And this is for a particular size, 0.14 millimeters size, 8 second period, which is pretty realistic of things in nature. And you can see, you get no movement, lots of rugged bedforms, plane bed.

And she has these lines, but she explains in the text of the paper that those are gradations. There's a gradation between symmetric large ripples, asymmetric large ripples, asymmetric small ripples, and symmetric small ripples with no definite boundaries. So this is one of these diagrams where we don't have a lot of nice boundaries the way we did in unidirectional flow, which we have to live with.

This was one that I did with Bill Arnott. And we published a paper earlier than that. And it shows the same kind of thing with data points. And there's another one-- oh, there's not another one. There's one in the addendum, which I didn't include here, a more recent paper by Perillo et al, Mauricio Perillo, my young colleague, and they did a very similar kind of duct and similar experiments. Look at this. And they produced just the same kind of graph. But it's nice to look at because it has colors in it. And that's in the addendum there. I'm pretty sure it's in the addendum if you want to look at it sometime.

Photo to come, but I don't have any photos. I've never taken a photo of what I think to be or are know to be a combined-flow bed form. And that's just the way it is. There are photographs from the experiments. And I don't have access to them. I tried to get them, couldn't get them easily enough.

So now, it is getting late. And it's time to start on number four. So now, we're dealing with sedimentary structures. We're going to look at rocks now and see what the structures are like. Now, I don't want to insult your intelligence, but a stratum or stratum, distinctive layer of deposited sediment. And it can be tabular. It can be non-tabular. And there's a conventional lamina versus bed.

This is a terrible term. Never used this term, laminations. It's either lamination or laminae, one or the other, but not laminations. This is the editor. This is the copy editor in me speaking-- no, really, I'm serious. A lot of people say that. And you know the difference between texture and structure, right? We're dealing with structures here, not textures.

Modes of deposition-- this is pretty simple to understand. You can have fallout without traction. Clearly, you can do that. And this happens many times. Or you can have fallout with traction. Particles are coming down, being added to the bed, so we get aggradation. Differential transport is a little tricky. I want to show you that. And of course, there's mass deposition, like debris flows grinding to a halt, which is outside the scope of this presentation.

So here's the flow, a non-uniform flow. It's deepening and slowing as it goes downstream. You have a flow velocity U, a sediment transport rate Qs at both sections. But you can see that the sediment transport rate is greater here than down here. So sediment must be being stored on the bed. That make sense? That's bookkeeping. And so that's-- well.

Deposition, you have to think of, it can be one or both of two of those factors. And we'd like to know how to figure out which is which. I don't think that's an easy job. But you have to be aware that's how deposition works. Mass deposition-- I'm going to not go through this very fast. I'm going to go through this very fast. Debris flows are important. The bouma A, the lowest part of a turbidity current deposit, here's the bouma sequence. You probably know about the bouma sequence. This part down here is massive. And it involves mass flow. We did some experiments on that once with a master's student.

So here's another way of looking at it. If you have flow of a thick mass of sediment, but it's flowing, the shear stress, the shear, is least up in the top. So that means it will freeze earlier at the top and freeze gradually downward, until finally, the whole thing is a plug of sediment, immobile, which I think is a nice way of looking at it.

So we can deal with planar lamination. Sometimes people call planar lamination plane-parallel. Don't call it horizontal lamination because it's not horizontal. It may have started out horizontal. It may not have. But when you see it, it's usually not, so planar lamination. It's called planar lamination.

Two kinds-- one, obviously, you get a flow dropping sediment without further traction. And if the surface is planar, it's going to be building up a deposit, planar laminated deposit. But you can also-- and I think I've made this clear to you already-- you can have deposition during traction, active traction, in the plane bed regime. And so you build up a planar laminated bed during transport.

I think this is from Bill Arnott's field area. I was on his thesis committee, and we went out for a glorious week in Montana at his field area after he passed his thesis defense, and nice lamination. That's a 15-centimeter scale. So these laminae are a fraction of a centimeter thick, which is very typical.

It gets a little more complicated. I think this is in the same section we were looking at, and planar laminated, planar laminated. But looking here, you can see some vague foresets in here. So something happened to the current, and it decreased. And then it started up again, and that's how I interpret that anyway. It's a little tricky.

A couple more slides-- you've probably seen planar lamination in the field. So there's an idea floating around, and one of my grad students, Chris Paolo, was partly responsible for this-- the idea that the bed isn't perfectly planar. There's very low amplitude, very long spacing features that move along the plane bed surface in the upper plane bed regime. And this is what makes the laminae as they go by, little laminae, about a centimeter, about a couple of millimeters thick. I can believe it.

Now, I don't need to tell you this, difference in grain size within a lamina. That's how you see them. Now, here's an interesting question. I've tried to do this in the field, next time you're in the field and looking at plane planar lamination. How far can you trace a given laminate before it disappears, replaced by another, changes in some way? And typically, it's something like from well less than a meter to as much as a few meters, if you have a nice enough outcrop. It's nice to play around with.

Now, there's something called parting-step lineation. You may have heard of parting-step lineation. So you have a lithified plane-bedded succession. And when it's brings up to the surface, it's weathered. It splits. It often splits along bedding planes, bedding surfaces that happen to be-- during plane bed-- that are weaker than the surrounding strata above and below it.

And the nice thing about it-- this is from the sidewalk going to a tea plantation in Sochi. And you can see because of the orientation of the grains as they're being transported under plane bed conditions, produce an anisotropy. And then when it parts along a bedding surface, that anisotropy shows up as these parting steps. It's pretty understandable. Here's another one. I can't remember where that's from.

So that's all I'm going to say about parting lineation. But now we get into another major part of the presentation. How do you interpret the flow conditions by looking at the cross-stratified bed? That's a major undertaking, and I need to make some comments about it. There's a forward problem. You know about forward problems and inverse problems, right? The forward problem is you have a flowover bed. It forms bed configurations. During aggradation, sedimentary structures are formed, and you get stratification.

But the inverse problem is trickier. You see the stratification, and you try to figure out what the bed configuration was. And then from the bed configuration, you want to know plus aggregation, what was the flow like? That's what you want to back out. That's the whole purpose of doing this kind of thing, is make interpretations like that.

And it's not easy. Why? It can be difficult or impossible because there's local erosion. Time gets unrecorded. And so local deposit geometry, which existed at one time, isn't there anymore. So that's a universal problem that we have to deal with. Anyway, here are a few more thought experiments coming along.

I got to quit in a few minutes, but let me just go through this. How could you do this? You could set up a flow over the bed to make a bed configuration. And that's been done many, many times. You can add sediment above, at a constant or varying rate, while flow velocity is either constant or varying, and you degrade a bed under varying conditions. And then you can section the deposit vertically downstream, cross-stream orientation, parallel to the bed if you wanted to, and you can see what the structures look like.

But if this was made by differential transport, it might be difficult to figure this out. But anyway, that's the kind of thinking you have to do. So another thing you could do is what's called synthetic aggregation. We've done some of this in the laboratory. You set up a flow and make a bed configuration. Then you make time-series maps of the bed, and you artificially aggrade them in time steps, and you end up with a cross-stratified deposit. And it does pretty much mimic what would happen if you actually degraded the bed, which of course, is very difficult. I guess you could stack them by computer.

This is fairly easy in the sidewall, transparent sidewall, of a channel. But it's not easy if you're looking at a whole area. How would you do it? You'd have to do a sonar profile, sonar profile, sonar profile, and then stack them up. It could be done. And I don't know how much it's been done. We did some of it.

In the natural flow environment, the obvious thing is to go out to some station out offshore, in the shallow offshore, and instrument it with some of permanent tripod structure, looking down at the bed, and also measuring the flow. And there have been some good studies. But that's really difficult because it has to resist big storms. And there are all kinds of technological problems in actually making it work. But there is some of that. And that's very valuable to do.

So I think that's a good place to quit. It's after 4:00. I'm going to point out that facies models-- you probably know about facies models, models for interpreting sedimentary environments. This is a nice statement, well worded in the introduction of the SEPM Special Publication 84 in 2005. A model is a point of comparison, a guide for further observations, serves as a base for hydrodynamic interpretation, and it acts as a predictor, a predictor for new situations. That's really valuable to be able to do.

And what we're dealing with here is a kind of a subset of facies models. And that's depositional models. Look at a particular bed in a given facies. What can you back out of that bed in terms of making interpretations of flow conditions and sedimentation? And I think that that's all I'm going to deal with. Next time, I'm going to start in with cross-stratification, which is really the main thing in this presentation. And so that'll be two weeks from now, remember, two weeks, same time, same place. And I'll finish up the presentation talking about cross-stratification in various kinds of flow environments with lots of pictures. See you then.