[SQUEAKING]

[RUSTLING]

[CLICKING]

JOHN SOUTHARD: And this is where we are, cross-stratification. As I remember, this is what we got to-- very useful for depositional interpretations. Here's the official definition, and just make sense. That's the official definition of cross-stratification. I think that it's probably the best way of making interpretations from looking at Strata. So it's caused by the action of bed configurations in a flow during aggradation. And we typically see sets of conformable laminae, called sets, separated by truncation surfaces. Or maybe not-- Maybe no truncation surfaces in there. You're going to see what I mean by that.

So the basic idea is pretty simple. There's a flow over a sediment bed, and there's deposition. And then at a certain time later, the flow changes. Flows change all the time. It erodes downward into that deposit. And then it starts to deposit again. And you're left with two sets separated by a truncation surface. That's the basic idea. And I don't think I'm telling you anything new.

But there's a problem, because if you have erosion, there's a certain amount of time that's not recorded. Only when there's aggradation enough so there's never any truncation do you have a complete record of the time involved in the process, which is unfortunate, but that's the way it is. So the way you can get around that is to run the flow over a bed of sediment over a wide range of conditions, either in the laboratory or in the natural environment, and keep track of what's happening, because then you do have a record of it. Even there's some erosion later on, you know what's happening through time. But the problem is only in certain situations can you actually do that, unfortunately.

So I've been interested, fascinated, by cross-stratification since I was a grad student in the early '60s, and not a lot was known about it then. We've made a lot of advances since then. Oh, look at this. Oh, thank you. And so in the old textbooks you'd see diagrams like this and like this. They're sets separated by laminae, separated by truncation surfaces. But when you look more closely, if you look at a block diagram, you often see something like this-- I'll be getting to this-- in which these are not really different from each other, they're just different sections through a unified deposit.

I was looking at this upside down once and, holy mackerel, large scale trough classification in a cookbook. Isn't that amazing? You're going to get the impression that I see cross-stratification wherever I look. OK, so if you're lucky, you have two angles like that, two right angles, or at least at a considerable angle. So you can get different views. Just on the face, it can be difficult to tell what's going on. If you want to try to back out paleoflow directions, you really need more than one face to look at. And sometimes we have it, but often we don't.

So let's start with ripples. I told you all about ripples, ripple bed configurations and what they look like and how they behave. And even with a single ripple train, that's just one train of current ripples, technically it's cross-stratification, but typically the ripples are climbing because there's deposition going on while the ripples are doing their thing on the bed. And so that leads us to what's called climbing bedform cross-stratification. And I have to tell you a little bit of how bedforms climb. And we're dealing with unidirectional flow now.

So here's my favorite terminology. You won't see this much in the literature. Erosional-stoss, climbing ripples, the stoss side is the upstream side and the lee side is the downstream side. So erosional stoss, angles climb low enough so that a given ripple cuts partway into the next ripple downstream and produces a set of laminae that's separated from later deposits by a truncation surface. But sometimes the angle of climb is large enough to produce to preserve the entire ripple profile. And then there are no truncation surfaces, and you can see the whole thing, which is nice, but it's not nearly as common as low angle erosional stoss.

Oh, and I should mention that. In the official terminology, in the literature, people call it subcritical klein versus supercritical, but that doesn't tell you much. So I prefer erosional stoss and depositional stoss. So let's start out. But here's a little train of ripples. And here's one ripple in the train. We cut the ripple with an imaginary vertical section parallel to flow. And do that for a large number of sections, and all those points where the low point was in the trough are connected with a rather sinuous, snaky-looking little surface, connecting all the low points all along the trough, which varies considerably in its depth and its shape. You keep that in mind.

And that leads to what I could call a cheesewire effect, because cheese wires are straight, linears. But this is a snaky cheese wire that moves down with the ripple and changes its shape as it goes like this, this kind of thing, and eats into the next ripple downstream. Every ripple is doing it to every ripple just downstream. And that gives you the key to what you will get. Here's an old profile and here's a new later profile.

This is a rotor from the stoss side, and it's deposited. I mean, this is ho-hum stuff. I mean, you're aware of that. But that's what's going on when the ripple climb is low. So this is the preserved part of the laminae. This is now eroded completely and gone down that way. And that's just what-- every ripple comes along and leaves another set of what are called four sets. And in your copies of the PowerPoint, I wrote it not fourth, but forests. Forests-- I left out an E. A spell checker won't catch that. I corrected it on the slide that's coming along that you have.

I spent a long time making this block diagram once long ago. Here's a rather garden variety set of sinuous, crested, and variably deep trough across. And it's climbing at a fairly low angle. And we have all these foresets separated by trunking services. Because remember, I told you how varied ripples are. They change their shape. They change their size. Some of them get formed, others disappear. And so these are not quite straight, regular, tabular sets of foresets.

And then if you look at the cross, vertical cross flow direction sets, you can see how trophy it is. You get sets of concave upward laminae separated by one, or usually two, truncation surfaces. And we call those truncation cross sets. And I'll be talking later about what we see on a stratification parallel section. But just keep that in mind. I'll be talking about that when the time comes.

Now, that was for a low angle of climb. At a high angle of climb-- Now, I'd like to redo this because it's too regular. Even though they're climbing at a large angle, they're still fairly regular. Although it's clear to me that the higher the angle of climb, the more regular the ripples are. And I don't know why that is, but that's been my experience and the experience of others. So there are no truncation surfaces-- so maybe occasionally, when ripples act up and do something a little bit different from their surroundings. And this should be a somewhat more sinuous. But there wouldn't be any truncations in here for the reasons that I think should be clear to you.

Now, here's my favorite ripple again. And you can see that this ripple, it's classic. It has foreset laminae faring out into the trough. And it has been-- not now-- it has been eroding, the ripple underneath. So here are the preserved foresets underneath the truncation surface. This is an unusual ripple-- not unusual, but it's irregular in the sense that early on, when the crust was here, the upstream side, the stoss side, was being eroded. But then more sediment came in somehow, and now the stoss side is aggrading, rather than cutting down into the underlying stuff. So these come and go. Things change because of the irregularity of the ripples.

Here's a single ripple train. And maybe I shouldn't have put it in here at this point, because they don't look like the one I showed first because they're more nearly symmetrical, and they do have internal laminae. You can see vaguely internal laminae. This is more likely to be oscillatory, oscillation ripples, starved or semi-starved oscillation ripples, rather than current ripples. And we'll be dealing with the differences presently.

Here's a close up of a single ripple in a ripple train. And there is some asymmetry. This is more gently sloping than this side. And you can see the internal lamination. But again, this is likely to be oscillation ripples. And I may be arguing-- maybe I'm going to show you this again when we get to talking about oscillation ripples. This is more like a train of current ripples. But there's a tip-off here that maybe it's oscillation influence, because you see, the stoss surface is arched. And that suggests to me they have an element of being like oscillation ripples. And toward the end, if I get a chance to get there, there'll be a section on combined flow cross-stratification, which is a difficult topic to manage, and I hope I get there.

Now-- oh, Kristen is not here today. This is a photo of a plate I have that was made in modern sediments. They cut a surface with a machete-- all sedimentary geologists use a machete. I own a machete. And you take an epoxy plate and you put it up against there. And because the differing permeability of the various laminae, you get a relief surface. And this is a photo of it.

All right, so this is classic erosional stoss cross-stratification. But it's not entirely so, because here a ripple got especially vigorous and ended up with depositional stuff. But it's mainly erosional stoss. And we know from where he made this-- my colleague, Dick Mayall from Mobile Research, gave me this thing as a gift. I really, really loved to have it. This is a flow parallel section. And we're not showing what it would look like at right angles.

OK, now here's a chunk. And this is in Kristen's lab. And I'm showing you one way and then the other way. And I want you to look at this. I'll give you maybe almost half a minute here. Maybe you don't need that long. You have to tell me which way is up. Is this upright or upside down? Is this upright or upside down? You don't need to tell me now. We're going to take a vote. So look at it carefully. See if you can spot a feature. And it's a little bit complicated. Can you spot any feature that would tell you which way is up?

So let's take a vote. You can vote-- you can vote the top is up or the bottom is up, or you don't know, or you can abstain. How many people that the top shows that it's upright? How many people the bottom is upright? One, two, three, four-- almost all of you. How many people aren't sure, don't know.

OK, this is clearly, when you look at it carefully, you see a set of four sets tailing off into the trough and being cut by a truncation surface. And there are some other places right in here, which are less obvious here and here and right in here. But you'll have to look closely. See, it doesn't jump right out at you. But you did really well.

This is a cut through modern sediments. My valued colleague, senior colleague, John Harms, one of my mentors early in my career, cut this through unconsolidated sediment, a view perpendicular to flow. And you can see the troughiness. I like that word, troughiness. All these little troughy sets here with convex, concave upward laminae cut by one or two or sometimes even three truncation surfaces. In the scale here, these are inches over here. So you see it's like a few centimeter scale, small scale trough cross-stratification.

Now, tell me about this. What do you think about that? Does that look right to you or not? I see a shaking head. OK, well, the next slide shows it in the other way. And that's clearly small scale trough cross-strat. So you have to make sure-- troughiness, I like that word. I'm not sure how to spell it, and it's probably not a real word anyway.

OK, so here's some examples-- erosional stoss, but there's some places where it's almost depositional stoss. And the ripple profiles don't quite look like current ripples. So I'm figuring this may be a combined flow feature. Maybe there's an oscillation influenced, largely unidirectional flow. And you have to look close to guess whether it's purely unidirectional or whether it's oscillation influence. It's often a problem. A matter of fact, it's a much bigger problem if you're dealing with-- this is something, I don't know how this got in here in this particular place. This is the thing I showed you, except not as nice. But you see all the troughiness in here. So it's a face that's largely perpendicular to flow. It gets a little messier down in here. I'll talk more about messiness when we get there.

My wife wanted to put this in the church yard sale. And it was sitting on the table and looking at it, says, that's erosional stoss cross-stratification right there. We kept it. We didn't give it up. I see cross-stratification everywhere.

This is a messier example, a real life kind of example. But it's clear that there's climbing ripples and there's ripple drift. Incidentally, some people use the term ripple drift cross-stratification. But I don't like that term. But it's in the literature. This is an interesting slide. This is a surface in a turbidite that was deposited with Normanskill. It's a deep basin turbidite-- big, thick stack of sand, sandstone, shale, interbedded sandstone and shale.

And the ripples are climbing depositionally. But look at their shapes. They're very undulatory. And if I'd looked at that without knowing where it came from, I'd say, well, that's a combined flow, a combined flow. But it isn't. It's in a turbidite. And I don't understand it. So I certainly don't have all the answers.

John Harms gave me this, too. This is a cut in the Chaco river, New Mexico, parallel to flow. There's a sidebar. And you can see there's lots of climbing ripples. Down here, they're climbing at a low angle. And they climb higher or higher. And there's some kind of hiatus in there. Then they start to climb again, and they go up to vertical. And at the top, they're being draped. The ripples start moving, but sediment is still showering down. So you're draping the ripples.

This is maybe one event bed or two event beds. But things change during the deposition of an event bed. So you have to look at it layer by layer to try to make sense of how the flow changed with time. Here's another example. This is from glacial Lake Hitchcock. My valued colleague, Gail Ashley, took me out and showed me the stuff, a flow parallel section of erosional source, rock climbers going into depositional source and then into drapes, a waning flow kind of situation. And we got together and made some experiments, the lab got it-- paper out of it long ago, in the '70s sometime.

So we started out with a preexisting rippled bed. And then we were showering sediment. This was a narrow, long flume, about 5 meters long. And we set up a shaker apparatus all along above, which would shake sand in. And so it would gradually upgrade the bed while the ripples were working. And we arranged it so that we gradually decreased the flow velocity while the sediment was falling and so just the same way we go from low angle to high angle to drape.

So you do see that in various places. We actually did the same by starting out with a rippled bed at low velocities, draping, going to high angle climb, low angle climb, back into high climb, and back into drapes. It's an almost symmetrical climb.

STUDENT: Climb directly related to the velocity, the change in angle?

JOHN SOUTHARD: Well, it's a combination of how fast the ripples are moving and how fast the bed is degrading. So look at the ratio of aggradation to bed form movement. And the higher, the stronger the faster the flow and the stronger the ripples are moving for a given aggradation, the more likely there is to be low angle stratification. And only when the ripples move slow relative to the rate of aggradation, you get a high angle of climb until finally, the ripples start moving and it's just draped. Does that make sense?

This is also from the same place. But we made a cut, not just a vertical cut parallel to flow, but we made a horizontal cut. And you can see there are packets of laminae, sets of laminae, separated by the truncation surfaces. But we're seeing the truncation surfaces from above. And I'm going to get back to what these features on that horizontal surface will show you. I've looked at a lot of the Moenkopi, and there's some interesting, really nice section of stuff in the Moenkopi just north of one of the arms of Lake Mead. And so that's classic, low angle erosional stoss cross-stratification.

At a higher angle, there are also erosional stoss mainly, but there's some arching over. And that's the kind of thing that we say, well, might that be a combined flow with both, maybe unidirectional dominated and oscillatory oscillation influence. And the lower the angle of climb, the more ambiguous it is. The one I just showed you looked clearly like unidirectional flow cross-stratification.

But maybe the angles climb is such that you're only depositing the very lowest part of the foresets. And you don't see the whole profile. So you're never can be sure whether you're dealing with purely unidirectional flow or maybe oscillation influence. It's one of those problems you have to live with. And I've been struggling with that for a long time.

When it gets to this point, they're clearly climbing depositionally, and you look at the profiles of the ripple. It sure looks like they're partly oscillation ripples. I think you'd agree with me that they don't look the standard stoss side, a sharp break at the brink, and then a slip face to form the foresets. Here's a case of climb ripples, where the truncation surfaces are obvious and the foreset lamination is there, but it's much less obvious. You have to look closely to see it.

All right, now a ribbon furrow. Have you ever turned ribbon furrow? It's a terrible term. I think it's a terrible-- it doesn't tell you anything. So we look at a flow parallel, a stratification parallel section. And I showed this to you. So when you see this in outcrop, it's really nice because it tells you the flow is flowing from left to right. And those truncation surfaces are just what you saw when you look at the vertical section. This is a section through those truncation surfaces.

Now, why are they convex downstream? Can you think of that? Can you give me a simple answer for why they're concave, why they're concave downstream? Well, I'll tell you why. A trough is being filled. And you're filling on the upstream side of the trough, which is concave downstream. So the laminae that are making-- doing the filling-- are all concave downstream. So you make the cut. You see these concave downstream laminae. And that gives you the paleoflow direction. It's nice to have, but it's a terrible term.

This is that same slide I just showed you. And you can see on the flow parallel section, the horizontal section, you can see the flow is definitely going that way. Of course, you already knew that from the vertical section. But sometimes, all you see is the horizontal section. And then you really know.

Here's another example I forget where I took this picture. This one I took in Sochi in Russia at a tea plantation. They had paving stones. And I forgot about the tea and just got down and looked at them, looked at the rocks. But it happens on large scale, too. Now, we're going to talk about dune cross-stratification.

Here's a horizontal surface through large scale dune cross-stratification. Here's a set of these curving laminae and another set with curving laminae this way. And the flow is like in this way somehow. So it's not as common to see as with small scale, because you need a big outcrop, a nice big outcrop, to see that.

So dune cross-stratification-- same kind of diagram. Remember that at low flow velocities, dunes tend to be two-dimensional. They look the same at every cross section. And at high velocity, it's the three-dimensional. This is-- I drew this, and it's really too regular. But you can see you have these sets of foresets, which are less irregular. I think I can say less irregular than in the three dimensional case. And again, you see. I probably should have made these more sinuous, but it gives you the idea.

But there's also another one of the three dimensional ripples. It's more likely than dunes. It's more likely to see 3D dunes and their structures than 2D dunes. And again, this is pretty much like what you see for ripple-- climbing ripple cross-stratification. But it's dunes, much larger. And you often see dunes, small dunes on the large dunes. If there's enough surface there and the velocity is right, it'll make dunes anywhere, including on the backs of large dunes.

That's Paul Heller, Marianne Amarto, and my former student, Chris Paola, with a block that just happened to be lying there with two faces almost at right angles to each other. And I was a photographer. And so this is detail. So one side shows pretty good flow parallel or nearly full parallel cross-stratification. The other side is sort of trophy, but somewhat irregular. And I'm thinking-- just think about, what's the direction of flow? And I think, it's not straight into the board. It's probably something like this, to produce that kind of surface on both sides.

Here's a close-up of a similar view of large scale trough cross-stratification, but erosional stoss, flow from right to left, obviously. And that's just 6 inches there. But how about erosion? How about depositional stoss, climbing dunes? I have seen it twice in my long life. I'm going to show you one picture here. It's very uncommon, because you don't usually get a situation, strong flow and dunes, but a very high rate of aggradation. And I'll show you a slide. This is from the Brushy Canyon in Delaware Mountains. And you can see, it's not a great picture, but it's the best one I have.

You can see this dune shape like this, arching over. And this is-- that's a lens cap. So it's pretty good size. I think there's a turbidite basin. I think there was a pre-existing hollow, good sized hollow, which got filled during-- the ripples were still moving in there, but the rate of climb, because the accumulation of sediment in the depression, was high enough to make a depositional stoss-- very uncommon.

This is a nice cut. We did this in the Arkansas River, the flow. And we knew the flow direction. It was a sidebar. It's this way. And you see the standard erosional stoss, large scale erosional stoss, and the flow perpendicular troughiness of the dunes. This is a close-up of that last slide. It's just a classic kind of trough cross-stratification. And there's even a detail of the detail if you want to see what it really looks like. And I won't go into it, but I always like that photo. And here's some stuff in the ancient that's clearly trough cross-stratification, but not always easily perceivable.

Now, the Nubian Sandstone. I don't know much about it, but it's known to be a subaqueous deposit. It's marine sandstone. And look at these sets. They could be called planar tabular sets, but with regular foresets, erosional foresets. And I'm guessing that was made by relatively low velocity 2D dunes, rather than 3D irregular dunes, which would produce a lot of variability in set settings.

I like this because you get of the two little sets with stratification this way and this side, and although you can't see it well on this side. So it's coming right out. The flow is coming right out at you. Does that make sense to you? I took this close-up to show how the foreset laminae come down and flare out into the trough very nicely. And, of course, there's erosion there at that surface. That's pretty large-scale.

Another example, pretty classic. Now, look at this. And you should see by now that looks fishy, right? This was a block. And you turn upside down. Now it looks right. So it's easy to spot when you attune your eye to it. I just-- I'll mention this. One thing that's nice to know would be, how do you get the bedform height? How do you back out the bedform height from what you see in the cross-stratification?

And it seems like a difficult problem. But my former student, Chris Paola, and his colleague in the math department at University of Minnesota wrote a paper back, quite some time ago, developing the idea that the average set thickness is only slightly less than the average bedform height and not very sensitive to the angle of climb. And I read the paper. I can be convinced by it. But that's nice to know. You can back out the size of the bedform just by looking at the cross-stratification, no matter what the angle of climb is.

Well, how about backing out flow depth from cross tread? How do you do that? Well, for ripples, you can't do it because, as I mentioned to you in the last presentation, the size of ripples is almost independent of flow depth unless the flow is really shallow and make for little ripples. They do vary with grain size. I think I mentioned they're somewhat longer spacing for coarser grain sizes.

But with dunes, there's general agreement that if you look at the ratio of flow depth to dune height, it's around 7, which makes us-- if they're at equilibrium. And so that gives you a handle on how deep the flow was when you see the dune height, which you would see from the cross stratification. I mean, that's-- backing out.

Now, I'm not going to say anything about antidune cross-stratification. I don't have any photographs. But it's reported in the literature, and it does happen. Here's a case-- here's a flow, supercritical flow. And the waves are moving, are migrating upstream, not downstream. And the bed geometry is going along with the upstream, moving antidunes. And you're leaving foresets going upstream.

Then eventually, the waves break. This gets messed up, and it doesn't preserve them all that well. And I've never gotten a photograph of one, so I can't help you with that. You often see this at the beach. A small stream flows across the beach to the water. And it's high Froude number flow, fast flow, shallow depth. And you get these standing waves. Sometimes they're standing, sometimes they're migrating upstream. And they break, and then they reform. Those are antidunes. They're not a major part of the stratigraphic record.

So now we have to talk about oscillatory flow features. So remember this-- there's UM, that's the maximum velocity during an oscillation, period T of the oscillation, and D0, which is the orbital diameter, how far it moves. And only two of those are independent of each other. The third depends on the other two. And so we did this with bed configurations. And sometimes you see a vertical climb. You'd think it'd be very common, but it isn't common at all. I've seen it just a few times in my field observations.

Why? Why not? I can think of two reasons. You think about reasons why, even in purely unidirectional flow-- Do you remember I told you that, because of the asymmetry of the oscillation, fast and strong, one way, slow and weak the other way to make an oscillation? So the sediment transport rate and shoaling waves is toward the beach. And so that could cause the ripples to climb at some non-vertical angle. And that's very common.

The other is, of course, you can always have a slight unidirectional flow component. And how would you tell the difference between the one and the other? I don't know. Maybe other things about the section might be able to tip you off on that. But it's not an easy thing to deal with. I showed you this before. This is from the Wappinger Cambrian in New York, in the Hudson Valley. And it's pretty clear they're oscillation ripples. But they're moving because you can see the laminae inside them. Almost symmetrical, but they're shifting.

Another example, close-up, the same kind of thing. We can be pretty sure they're oscillation ripples. This is one of the few places I've ever seen where the ripples really are climbing vertically for a long distance. Now, it's not a matter of draping, because if they were draped, they'd die out much more rapidly upward. So these really are, whatever the environment is, whatever the oscillatory environment is, they're climbing almost vertically. But I've seldom seen that.

Here's another example from the Ferron in Utah. And they're climbing at a pretty steep angle, but that's very uncommon. It's more common to see something like this. They're clearly oscillation ripples. They're depositional stoss. And in this case, their angle of climb suggests that it's because it's combined flow, rather than a purely unidirectional flow.

This is one of my favorite photographs. It's also from the Moenkopi. So there they are, climbing, climbing, climbing, for a long distance throughout this deposition of the bed. Flow conditions stayed pretty much the same for a long time, in that case.

I showed you this already, and I mentioned to you that it looks fishy to be current ripples. And I'm pretty sure that's it's either oscillation influenced, as well as unidirectional influence at a medium angle of climb. That's a close-up. So you can see exactly what I'm talking about.

I think I showed you this, too, now that we're coming to unidirectional versus oscillatory. I'm guessing that's in between oscillatory unidirectional influence. That's my guess. But I can't pin it down particularly, either.

All right, now, I'm dealing with how you can tell between unidirectional flow, depositional source, climbing ripple, and combined flow climbing ripples without erosion. And the only thing I can think of is try to look at the profile and see whether it looks like unidirectional flow ripples or oscillatory flow ripples. And when you have deposition in the stoss, on the stoss, as well as in the lee, you can do that. But it's not all that common to be able to do that.

So is this combined flow, or is it unidirectional flow? And you look at it, and from what I've said, oh, that's unidirectional-- that's unidirectional flow climbing ripple cross-stratification. But from what I've just said, you have the suspicion that maybe it's combined flow. And I don't see any way of telling. And yet, combined flow features must be pretty common, which I'm going to talk about soon if I have the time. Here's another example from the Moenkopi, same problem. It's nice to think that it's always unidirectional flow, but it doesn't have to be that way.

And the other thing is, we see climbing oscillatory flow bedforms. And they're usually on a small scale, not on a large scale. And I'm going to get to that presently when we talk about combined flow features. So I'm going to repeat a slide that I showed last time, a graph, a diagram, that you may remember. And it's orbital velocity versus oscillation period. And you can see that in the lower left, this is for weak flows. The ripples are small, and they're three-dimensional-- they're two-dimensional. But above this line, they become larger, and they become three-dimensional.

Now, so it's down in here that we usually see these small scale oscillation ripples. And they're understandable. But this is-- it's not exactly terra incognita, but it's close to it. And we know the bedforms exist because they've been observed in many flume experiments and in some natural environments. And we know they're three-dimensional. So what kind of stratification do they present?

That's where we get the hummocky cross-stratification. This is a term that's been around since the 1970s. It's a kind of medium scale to large scale cross-stratification, which I think, and I think most people think, it's produced by oscillatory bedforms during aggregation. But they're large in a three-dimensional.

Aggradation in the presence of 3D large oscillation ripples and what we're dealing with here. It's been controversial, but the general belief is it's purely oscillation-dominant flow. I showed you my favorite outcrop last time. Remember that 45 degree dipping bedding surface, where the hummocky-- where the hummocks and swales arranged around it. And they're all very isotropic. They're not moving in one direction or another.

And so we know that happens. It was a purely oscillatory flow produced these large, three-dimensional hummocky valley bed configurations. And I wish that I had gone around the corner and taken a picture of the section through that bed. We saw only the top surface of it. And it was classic, medium-scale hummocky cross-stratification. So that tips me off that maybe everything we're talking about across-- everything we're talking about, oscillatory flow cross-stratification, involves large 3D bedforms aggrading in various ways. And I'm going to go through some slides. I might not get to combine flow features right now.

Irregular shifting, but isotropic shifting. Now, there's a term swaly cross-stratification. They usually spell it with an E in there, and I don't like that, because it's like shaly. We spell chailey without the E. But anyway-- and they think of it as something else, SCS instead of HDS. To me, there's a gradation between SCS and HCS depending on the rate of aggradation relative to the shifting of the bedforms. If the rate of aggradation is slow and they're acting that way, you're going to see lots of trough fillings and very little by way of swales. But for a higher rate of aggradation, you're going to see not just erosion in the troughs, but you also see deposition over the crest of the swales.

This is the classic block diagram. We gave a short course way back in 1975, John Harms was the one. He originated this term. He was the first to perceive that it's a distinctive style of cross-stratification. And he thought about how it would happen. And in later years, he would say, there are people nowadays who make their careers out of HCS. But he was the one who started it. It's an illustration of that there's a saying, I wouldn't have believed it if I hadn't seen it. You can reverse it and say, I wouldn't have seen it if I hadn't believed it. Everybody was seeing HCS, but they never gave any particular credence or significance to it until somebody, Harms, came along and realized this is a very specific kind of depositional model. So that's what HDS is now. And everybody is seeing it, whereas nobody saw it before.

And one of the prime characteristics is you have places where conformable laminae end up going into a truncation surface and then maybe back out into conformity. That's if you see-- that's a tip off that we're dealing with HCS. That's what I just showed you. But also, we see places where hummocks turn into swales during deposition and where swales turn into hummocks. I got that right-- yeah, right. That's very characteristic. And I can show you some photos pretty soon.

Let's ignore this. This was an attempt on my part, some years ago, to organize everything about HCS and other oscillatory flow, large scale bedforms. It doesn't quite work, because I can't draw the sketch as well. And I invite you to look at it if you want to look at it. So let's get on to other things.

OK, here's the swale going to a hummock. It happens. Here's a hummock growing from a flat surface, planar surface. Here's a nice, big, broad hummock all by itself. Here's a swale going into planar. Here's a hummock going into a swale with the same kind of thing-- from conformable to truncation to conformable over there. That's another tip off. When you see that kind of thing, you must be dealing with HCS.

There's a hummock going into-- there's a swale going into a hummock. And a hummock going into a swale with erosion, trailing off into conformity over that way. That's very common.

I carried this out of the Wood Canyon Formation in the Southern end of the Nopah range once. And it's not that big. It was heavy, but I could carry it out. It shows medium scale, hummocky swale topography on the bed surface. This is from the Wood Canyon, right at the precambrian-cambrian boundary. And although you can't see it very well in this picture, it shows medium scale hummocky cross-stratification.

I was going to bring it, but I can't find it. It's somewhere around the house or in the barn, and I couldn't find it. But it's one of my prized possessions. Here's a better view of the cross-stratification, which looked like medium-scale cross-stratification.

This is the classic John Harms photo when he developed the concept. He showed this photo in the short course we gave. This is very characteristic. You can see truncation surfaces going into conformity and being overtopped by another hummock. This is pretty large-scale. I mean, this is 6-inches. So this is, like, this is meter plus scale we're dealing with here.

Same kind of thing-- look at this, conformability into truncation and then back into conformity over here because of the way those hummocks and swales are interacting with one another. A swale overtopped by a hummock and another hummock on top with that same erosion surface, truncation going on.

Even more classic HCS-- conformability into truncation, and probably back to conformability over there. When you see that, that's a tip-off. This is from the Johnnie formation in the Nopah range in California. And a lot of indistinct planar lamination, but then it got hummocky and swaley. But then it stopped over top, I guess I should say, by planar lamination again. As the current velocity changes, as the water flow velocity changes, you can go from one to the other.

This is more like what they call swaley cross-stratification. You see a fair number of hummocky-looking features, shallow features. And it doesn't look much like what I just showed you, because I think the aggradation rate is low relative to how fast these things are shifting around. That's my that's my colleague, Roger Walker, explaining swaley cross-stratification to a bunch of students long ago.

And I guess this is HCS, too, on a small scale-- very small scale, medium scale. Look at that big hummock, same kind of features going on there that we've seen before close up. This is interesting, because there's pretty deep scour over here that truncated this stuff. And it got overtopped by this and goes to conformity again.

And I tell you-- I've told you some things about combined-flow stratification, but I want to just show you a couple of slides. You can look at them yourself. You've seen this before. This is from Simon Dumas' experiments over in the laboratory in building N9. And these lines are fakey. These are all gradational-- symmetric small, symmetric large, asymmetric small, asymmetric large. And so this is purely oscillatory. That's purely unidirectional.

And look at this broad range of possibilities in between. It's a jungle. I mean, in Grotzinger's terminology, the dog's breakfast. And we don't know as much about combined poststratification as with the more classical unidirectional flow and oscillatory flow classification. Progress has been slow. Unless I missed some very recent papers, Nobody has really come to grips with the whole systematics of these intermediate features. But they must be important out there, because it can't always be purely unidirectional, purely oscillatory. There must be combinations. And as I told you when we dealt with bed configuration, combined flow bed configurations, there's a wide range of possibilities. And when they're grades, it's going to produce a wide range of cross stratification. And we've only begun to understand how we recognize where we would be in this vast sea of possibilities.

And I think that's probably about all I have. This is from Simon Dumas' paper. And you can see this-- concentrate on small scale bed forms with mainly oscillatory, but partly unidirectional. And it's a very three-dimensional. And when they agrade, they're going to leave a particular kind of cross-stratification. And I'm not sure what it's going to look like, frankly.

All right, this is going to be the last slide here, a bunch of things to say about how you make interpretations. Now, if you have vertical climb, asymmetric, you know it's oscillatory flow right. If you have depositional stoss climb of asymmetrical ripples, you have to look at the ripple shape and try to back out, whether it's combined flow or unidirectional flow.

STUDENT: Does that have to do with [INAUDIBLE], when you say look at shape, do you mean concavity?

JOHN SOUTHARD: Well, the shape of the ripple that you can see in the structure, to some-- you can always see that. At low angles of climb, you don't know that. And I think that's mentioned here. When it's erosional stoss, very asymmetrical ripples. It's probably unidirectional flow, but it may be not purely oscillatory, a unidirectional flow. Isotropic HCS, on a good sized scale, it's almost certainly oscillatory flow. I've convinced myself of that. I think the general feeling is the truth. If it's anisotropic HCS-- well, you see that sometimes. But I haven't seen it very often. And that must be influenced by unidirectional flow.

If you see large scale trough stratification-- and I showed a lot of it-- we assume, when we look at it, it's unidirectional flow. But it may be unidirectional flow with an oscillation influence. And we can't back out the oscillation influence. It's one of those things that become difficult to manage. And now there's a spectral gap that I mentioned last time. Ripples are always about 10, 15 centimeters, thereabouts-- maybe 20. And dunes seldom get below a meter or half meter at the least, unless the flows are really shallow. And so if we see cross-stratification that looks like it's scales in that spectral gap, we almost can conclude that it's oscillatory flow because you don't make oscillatory flow ripples in that spectrum, unidirectional flow ripples in that gap.

So I'm going to quit there. I had a few comments about the fact that many beds, a single event, don't have uniform conditions throughout. I showed you some. It can start slow and go fast and start slow, or the other way around. And I had just a few slides that aren't particularly needed at this point.

So that's my pitch on cross-stratification. I've been a fan of cross-stratification since I was a grad student in 1960, early 1960s. And it wasn't all that well-understood at that time. It wasn't totally mysterious, but people have made a lot of progress up to now in interpreting cross-stratification. And I've tried to cover the ground rules, cover the ground on that.

So that's my pitch. [? Lyle. ?]

STUDENT: You showed a bunch of different sizes of Hummocky Cross-stratification, HCS. What's the significance of the size of HCS?

JOHN SOUTHARD: In presentation 3, I showed you my favorite outcrop with a meter scale HCS. And I showed you another slide-- it wasn't a good one, but it's the only one I had-- of three, four decimeter scale, which must be common. If the larger scale is common and the smaller scale is common, the intermediate scale must be common, too, judging from the various experiments of the kind that Simon Dumas did and others. There are a couple of others' really good studies. And I don't know how to deal with that.

STUDENT: Does it have to do with wave period? Or what's controlling the--

JOHN SOUTHARD: Well, you remember I mentioned-- I mentioned along the way, and I showed you this dimensionless 3D diagram of oscillatory flow features and the fact that when you make lab experiments, you could fill any of that whole 3D diagram with points. But when you're dealing with real waves, there are certain constraints on how the waves themselves work that only some subset of space in that 3D diagram can be occupied by natural flow oscillatory features. I tried to make that point, and it's generally agreed that would be the case. So is that relevant to your question?

STUDENT: I think so. Yeah, I don't know. I think people, HCS is commonly used as a storm [INAUDIBLE]

JOHN SOUTHARD: Yes, What else-- what else could it be? That's how I look at it.

STUDENT: And I'm just wondering if there's further you can go based on the measuring the size, like anything you can learn.

JOHN SOUTHARD: Well, I did show you a medium scale one, my favorite little piece there. And so I haven't seen many like that. And I don't know why it's scarce compared to the larger scale. I don't know that. There's some reason for that, and I haven't come to grips with that. But that's all I can say about it. Other questions, comments? Thanks for staying to the bitter end.

STUDENT: Could you mention what that reference-- you had that reference for the-- I didn't quite write it down-- for the average set thickness.

JOHN SOUTHARD: Yes, OK, Paola and Borgman-- well, you have the PowerPoint, don't you? And you can-- I don't know the reference. We can go back. It was 1990 something. I don't remember.

STUDENT: Because Bill Arnot told me that-- I was on a field trip with him. He said he always assumes one third of the bed thickness is--

JOHN SOUTHARD: Well, they seem to think that it pretty much scaled with the set thickness. But read the paper. I read it once. I have to confess it was only once. And it seemed reasonable to me. Bill Arnot is another close younger colleague of mine. I was on his thesis-- I was examiner on his thesis committee. Went to Edmonton for his defense. And then after, we drove down. We were 400 some miles to his field area in Montana, had a great time for a whole week. So we've been a close colleague ever since. He and Paul Meyer are my closest younger colleagues. OK, so that's it.