DR. ZACHOS: YEAH, I DON'T RECALL EVEN SUBMITTING THE TITLE, BUT THAT'S IN THE PROGRAM.

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(LAUGHTER)

BUT THERE'S ACTUALLY A VERY SHORT ANSWER TO THAT QUESTION: IS THE PETM AN ANALOG FOR WHAT IS HAPPENING NOW AND IN THE FUTURE? AND I THINK THE SHORT ANSWER IS NO; AND I THINK WHAT YOU'LL SEE IS THAT WHAT THE PETM DOES FOR US, IT ALLOWS US TO TEST IDEAS ABOUT OUR THEORY ABOUT THE CARBON CYCLE, HOW THE CARBON CYCLE WORKS. AND THIS WILL BECOME APPARENT AS YOU MOVE THROUGH THIS PRESENTATION.

I START OUT WITH THIS SLIDE, WHICH SCOTT ALREADY TALKED ABOUT, THE C4M COMPARISON, THE COUPLED CLIMATE CARBON CYCLE MODEL COMPARISON; AND THE MAIN POINT OF THIS IS SIMPLE: AS WE MOVE FURTHER AND FURTHER INTO THE FUTURE AWAY FROM THE CURRENT CONDITIONS, ONCE WE START TO THINK ABOUT THE SYSTEM AS A COUPLED SYSTEM AND INVOLVE BIOGEOCHEMISTRY, TIE THAT IN WITH THE PHYSICS, THIS IS WHERE WE START TO FIND THAT OUR KNOWLEDGE IS SOMEWHAT LIMITED ABOUT HOW THESE SYSTEMS SHOULD FUNCTION, AND SO THIS IS A GOOD EXAMPLE HERE, IT'S ABOUT A 200-PPM SEPARATION BETWEEN THESE MODELS. PART OF IT HAS TO DO WITH CARBON UPTAKE ON LAND, AND PART OF IT HAS TO DO WITH DIFFERENCES IN CARBON UPTAKE BY THE OCEAN. AND SCOTT HAS ALREADY TALKED ABOUT WHY THAT IS.

CLEARLY, THERE ARE FEEDBACKS IN THE SYSTEM

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THAT WE NEED TO UNDERSTAND, AND THERE ARE POSITIVE FEEDBACKS AND NEGATIVE FEEDBACKS; AND FOR THE MOST PART, I THINK WE WORRY ABOUT THE POSITIVE FEEDBACKS, AMPLIFIERS.

THE ONE EXAMPLE THAT SCOTT TALKED ABOUT WAS THE OCEAN CIRCULATION, INCREASED STRATIFICATION, REDUCED VERTICAL MIXING, WOULD TEND TO ALLOW MORE CARBON TO BUILD UP IN THE ATMOSPHERE, SLOW THE UPTAKE OF CARBON BY THE OCEAN. AND THIS IS SOMETHING THAT WE PROBABLY HAVE TO WORRY ABOUT ON THE DECADAL TO CENTENNIAL TIME SCALE. IT IS A FEEDBACK THAT IS GOING TO OPERATE FAIRLY QUICKLY.

ON LONGER TIME SCALES, SCOTT ALSO MENTIONED ANOTHER POTENTIAL FEEDBACK, METHANE HYDRATES, A FAIRLY LARGE RESERVOIR OF CARBON, WHICH COULD POTENTIALLY BECOME INVOLVED IN RELEASING MORE CARBON INTO THE ATMOSPHERE ON TOP OF THE ANTHROPOGENIC CARBON. THIS IS SOMETHING, AS I SAID, THAT MAY HAPPEN OVER A MILLENNIUM. IT IS PROBABLY NOT IMMEDIATE FEEDBACK THAT WE HAVE TO WORRY ABOUT.

OF COURSE, THERE ARE NEGATIVE FEEDBACKS IN THIS SYSTEM; AND THESE NEGATIVE FEEDBACKS HELP EVENTUALLY RESTORE SOME SORT OF EQUILIBRIUM OR STEADY STATE TO THE SYSTEM.

THE REAL ISSUE IS THAT THE POSITIVE

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FEEDBACKS AND NEGATIVE FEEDBACKS DON'T NECESSARILY OPERATE AT THE SAME RATES, AND IT'S LOOKING LIKELY

THAT THE POSITIVE FEEDBACKS, AT LEAST SOME OF THEM THAT WE'RE CONCERNED ABOUT, CAN OPERATE AT VERY RAPID RATES RELATIVE TO THE NEGATIVE FEEDBACKS; AND THIS IS WHERE A RAPID OR AN ABRUPT CHANGE IN THE SYSTEM BECOMES SOMEWHAT MORE IMPORTANT.

SO RETURNING TO THIS FIGURE JUST SHOWING THE UPTAKE OF ANTHROPOGENIC CARBON BY THE OCEAN, WHAT WE DO KNOW IS THAT SOMETHING LIKE 380 GIGATONS OF CARBON HAVE BEEN RELEASED IN THE ATMOSPHERE, AND ABOUT 120 GIGATONS OR SO HAVE BEEN ABSORBED BY THE OCEAN ALREADY. WE KNOW THIS FROM THE WORK OF FEELY AND HIS COLLEAGUES.

NOW, IN ADDITION TO THE DIRECT MEASUREMENTS, THERE'S SORT OF INDIRECT EVIDENCE THAT THE OCEAN HAS BEEN TAKING UP ANTHROPOGENIC CO2, AND THIS IS IMPORTANT FOR HOW WE LOOK AT CO2 CHANGES IN THE PAST. OBVIOUSLY, FOSSIL FUEL CARBON HAS A VERY DISTINCT FINGERPRINT, AN ISOTOPIC FINGERPRINT, A LOW RATIO OF C-13 TO C-12; AND WE'RE ADDING THIS CARBON TO THE CARBON IN THE OCEAN AND THE ATMOSPHERE. AND AS A CONSEQUENCE, THE DELTA C-13 OF DISSOLVED CARBON IN THE OCEAN HAS BEEN DECLINING. WE CAN SEE THIS VERY CLEARLY.

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THIS IS A NICE FIGURE THAT BIHM, ET AL, PUT TOGETHER A NUMBER OF YEARS AGO, AND I HAVE JUST SORT OF PULLED IT APART. AND THAT'S JUST SHOWING THE RISE IN CO2, AND ONE POINT IS THAT, OBVIOUSLY, WE'VE BEEN MAKING DIRECT MEASUREMENTS FOR ABOUT 50 YEARS; BUT BEYOND THAT, WE'RE RELYING ON ARCHIVES TO RECONSTRUCT CO2; AND THAT'S, OF COURSE, THE ICE CORE RECORD. WITH THE CO2, WE HAVE AN ICE CORE, WE CAN ACTUALLY MEASURE THE CARBON ISOTOPE COMPOSITION OF THAT CO2. THIS IS SHOWING HOW THE DELTA C-13 OF THE ATMOSPHERE HAS DECLINED, STARTING ROUGHLY AT THE SAME TIME CO2 LEVELS STARTED TO INCREASE. AND THEN WE KNOW THAT THE EXCHANGE OF CARBON BETWEEN THE ATMOSPHERE AND THE SURFACE OCEAN IS FAIRLY RAPID AND THAT THIS SIGNAL SHOULD BE TRANSFERRED INTO THE OCEAN; AND THE WAY WE CAN RECONSTRUCT THAT IS BY LOOKING AT THE CARBON ISOTOPIC COMPOSITION OF A GEOLOGIC ARCHIVE OF CORALS WHICH ARE RECORDING THE RATIO OF C-13 TO C-12 IN THE OCEAN. SO, CLEARLY, THE OCEAN DELTA C-13 HAS BEEN CHANGING ALONG WITH THAT IN THE ATMOSPHERE, AS WE WOULD EXPECT. AND THE OVERALL CHANGE HAS BEEN CLOSE TO ABOUT 1-AND-A-HALF-PER-MILLION DECREASE IN THE RATIO OF C-13 TO C-12.

NOW, IN ADDITION TO THE EFFECTS, OF COURSE, OF THE SIGNAL ON CARBON ISOTOPES, DICK ALREADY TALKED

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ABOUT THE IMPACT OF CO2 ABSORPTION ON OCEAN PH AND CARBONATE CHEMISTRY. SO THIS IS JUST THE PROJECTION OUT TO THE FUTURE, 100 YEARS; AND YES, THE PH WILL DROP BY ABOUT .4 PH UNITS OVER THIS PERIOD OF TIME.

THIS PROCESS OF OCEAN ACIDIFICATION WILL CONTINUE WELL INTO THE FUTURE, AND WE HAVE JUST CARRIED IT OUT BASICALLY FULL COURSE WHERE WE ASSUME

5,000 GIGATONS OF CARBON ARE RELEASED INTO THE ATMOSPHERE OVER SEVERAL CENTURIES, AND THIS IS MODELING WORK THAT WAS DONE BY RICHARD ZEEBE AT UNIVERSITY OF HAWAII. AND IT SHOWS PATTERNS SIMILAR TO OTHER MODELS LIKE THIS ONE. THIS IS A CARBON CYCLE BOX MODEL. AND BASICALLY, THE CO2 LEVELS PEAK AT AROUND 1,800 PPM AND AT ABOUT 3 OR 4 CENTURIES. AND THEN YOU CAN SEE THAT THE LEVELS RECOVER FAIRLY QUICKLY; AND AGAIN, THIS HAS MAINLY TO DO WITH ABSORPTION OF CARBON BY THE OCEANS, AND THEN EVENTUALLY THEY STABILIZE, ALTHOUGH THEY STABILIZE AT LEVELS HIGHER THAN PRE-ANTHROPOGENIC LEVELS.

AND IT TURNS OUT THAT THERE'S A GOOD REASON FOR THIS. IT HAS TO DO WITH THE WAY THE OCEAN IS BUFFERING THE CHANGES IN PH. IT IS DOING SO BY DISSOLVING AWAY CALCIUM CARBONATE. IT IS TRYING TO MAINTAIN A CONSTANT CARBONATE ION LEVEL. IN DOING SO, ALKALINITY RISES, AS DOES DISSOLVED INORGANIC

CARBON. AS A CONSEQUENCE, THE EQUILIBRIUM PCO2 LEVELS ARE HIGHER, AND THEY STAY HIGHER FOR HUNDREDS OF THOUSANDS OF YEARS. THE MAIN MECHANISM FOR REMOVING THIS CARBON OR SEQUESTERING IT IS SILICATE WEATHERING.

THIS SHOWS THE EFFECT ON PH; AND AGAIN, IF YOU GO OUT TO 5,000 GIGATONS OF CARBON, PH WILL DROP SIGNIFICANTLY. AND THIS IS MAINLY IN THE SURFACE OCEAN. I'M NOT SHOWING THE RESPONSE IN THE DEEPSEA, WHICH IS MORE BUFFERED.

AND THEN, FINALLY, WHAT I WANT TO SHOW IS THE CHANGE IN THE CARBON ISOTOPE RATIOS. I ALREADY SHOWED YOU WHAT IS HAPPENING. INITIALLY, WE HAVE ALREADY SEEN 1-AND-A-HALF-PER-MIL DECREASE IN DELTA C-13 AT THE SURFACE OCEAN. IT WILL CONTINUE TO DROP UNTIL IT GETS TO ABOUT MINUS 5 PER MIL, AND THEN IT WILL START TO RECOVER. YOU CAN SEE THAT THE DEEPSEA, THE DEEP PACIFIC DELTA C-13 RATIOS AREN'T GOING TO DROP AS MUCH. THIS IS TO MAKE ANOTHER SIMPLE POINT; THAT THE RATE OF RELEASE OF CARBON, THE ABSORPTION, RATHER, IS BEING MAINLY -- THE ABSORPTION IS BEING BORNE MAINLY BY THE SURFACE OCEAN, A VERY SMALL RESERVOIR OF CARBON. THE DEEPSEA IS FAIRLY WELL BUFFERED.

OKAY. SO WE HAVE PREDICTIONS, NUMERICAL

PREDICTIONS OF HOW THE CARBON CYCLE IS GOING TO RESPOND TO ANTHROPOGENIC FORCING. AND IS THERE ANYTHING WE CAN DO TO ASSESS OR VALIDATE SOME OF THE PREDICTIONS FROM THESE MODELS? AND WE'RE FAIRLY LIMITED IN WHAT WE CAN DO, BUT IT TURNS OUT THAT WE CAN GO BACK IN THE GEOLOGIC PAST AND FIND TIMES WHEN CARBON DIOXIDE LEVELS MAY HAVE CHANGED AS MUCH AS THEY'RE GOING TO CHANGE IN THE NEXT SEVERAL HUNDRED YEARS. AND SO, OBVIOUSLY, I'M TALKING ABOUT THE PETM.

THIS IS JUST TO GIVE YOU SOME SORT OF GEOLOGIC TIME FRAME OR CONTEXT FOR THIS PARTICULAR

EVENT. WHAT'S PLOTTED HERE IS OUR BEST ATTEMPTS TO RECONSTRUCT PCO2 HERE. YOU CAN SEE THAT CO2 LEVELS HAVE BEEN FAIRLY LOW FOR THE LAST 20, 25 MILLION YEARS. YOU GO FURTHER BACK INTO THE CENOZOIC, THE CO2 LEVELS ARE HIGHER. AND OUR ABILITY TO RECONSTRUCT CO2, ABSOLUTE PCO2, IS NOT VERY GOOD; BUT THE MAIN POINT HERE IS THAT DURING THIS PERIOD OF HIGH CO2 LEVELS, THE CLIMATE WAS WARM, AND THIS IS AN OXYGEN ISOTOPE RECORD REPRESENTING GLOBAL CLIMATE; AND WHEN CO2 LEVELS WERE LOW, THE CLIMATE WAS RELATIVELY COLD.

THE OTHER POINT I WANT TO MAKE HERE IS SIMPLE: THIS IS THE ANTHROPOGENIC PCO2 PEAK AT 1,800 PPM. AND PEOPLE LIKE TO SAY THE LAST TIME THAT

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WE'VE HAD CO2 LEVELS THAT HIGH IN THE PLANET, YOU KNOW, GIVEN THE ERROR BARS HERE, THE UNCERTAINTIES, REALLY, THE LAST TIME WE'VE HAD CO2 LEVELS ON THIS PLANET THAT HIGH PROBABLY WAS AROUND 50 MILLION YEARS AGO, THE EARLY EOCENE, WHICH IS ABOUT THE WARMEST PERIOD WITHIN THE LAST 65 MILLION YEARS.

NOW, THERE IS ONE FEATURE ON HERE. IT'S HARD TO SEE, RIGHT THERE, RIGHT AT THE P-E BOUNDARY. AND DURING THIS PERIOD WE'RE SEEING GRADUAL GLOBAL WARMING; AND SUPERIMPOSED ON THAT GLOBAL WARMING EVENT IS A VERY SHORT-LIVED, A VERY TRANSIENT EXCURSION OF GLOBAL TEMPERATURE. AND THAT IS THE PETM. I'M GOING TO SHOW YOU A MORE DETAILED RECORD OF THAT IN A SECOND. BEFORE I GO THERE, I JUST WANT TO SORT OF REMIND YOU OF HOW WE RECONSTRUCT A CLIMATE USING THESE DEEPSEA ISOTOPE RECORDS.

THIS IS AN ISOTOPE RECORD BASED ON THE OXYGEN ISOTOPE ANALYSES OF BENZIE FORAMINIFERA. AND OF COURSE, THESE SAMPLES ARE BEING RECOVERED FROM THE SEAFLOOR VIA OCEAN DRILLING. THIS CORE RIGHT HERE ACTUALLY SPANS THE PALEOCENE BOUNDARY. I THINK EVERYONE CAN FIGURE OUT WHERE THAT BOUNDARY MIGHT ACTUALLY BE. OF COURSE, THE PRIMARY ARCHIVE OR ONE OF THE TOOLS THAT WE USE FOR RECONSTRUCTING PAST OCEAN TEMPERATURE AND CARBON CHEMISTRY IS THE

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CHEMISTRY OF SHELLS OF MICROFOSSILS THAT WE EXTRACT FROM THOSE CORES. WE MEASURE THE CARBON ISOTOPIC COMPOSITION, THE OXYGEN ISOTOPES. MIXED-LAYER FORAMS TELL US ABOUT THE TEMPERATURE OF SURFACE WATERS, THE OXYGEN ISOTOPIC COMPOSITION OF BENZOIC FORAMINIFERA, GIVE US DEEPSEA TEMPERATURES. AND SO THAT GLOBAL COMPILATION THAT I JUST SHOWED YOU WAS A COMPILATION OF BENZOIC FORAM OXYGEN ISOTOPE RECORDS FROM SOME 50 OR 60 DEEPSEA CORES.

THE CARBON ISOTOPES, OF COURSE, TELL US ABOUT THE RATIO OF C-13 TO C-12 OF DISSOLVED CARBON IN SEAWATER. AND SO JUST LIKE THE CORALS, BY MEASURING THE CARBON ISOTOPIC COMPOSITION OF THE PLANKTONIC AND BENZOIC FORAMS, WE CAN RECONSTRUCT PAST CHANGES IN C-13/C-12 RATIO OF DIC.

SO RETURNING TO THE PALEOCENE THERMAL MAXIMUM, THIS IS SORT OF AN ENLARGED BIT ACROSS THE

BOUNDARY, AND THIS TOP PANEL SHOWS THE CARBON ISOTOPE VALUES OF BENZOIC FORMIN FROM CORES IN THE SOUTHERN OCEAN, PACIFIC, AND SOUTH ATLANTIC; AND EVERY CORE SHOWS THE SAME PATTERN, WHICH IS THIS VERY ABRUPT DECREASE IN C-13 AND C-12. WE HAVE KNOWN ABOUT THIS NOW SINCE 1991. AT THE TIME WHEN WE PUBLISHED THIS, THIS WAS CONSIDERED TO BE A HIGH-RESOLUTION RECORD. IT IS ACTUALLY A VERY LOW-RESOLUTION RECORD NOW. BUT

THE POINT IS, THIS IS A VERY UNIFORM EXCURSION; AND WE HAVE RECORDED IT IN ALL MARINE SECTIONS AND ALL TERRESTRIAL SECTIONS, AS WELL. IT IS ACCOMPANIED BY THIS NEGATIVE EXCURSION IN THE OXYGEN ISOTOPES, WHICH IS REPRESENTING WARMING OF THE DEEPSEA ABOUT 5 TO 6 DEGREES CENTIGRADE; AND IN BOTH OF THESE, FROM THE ONSET TO THE RECOVERY TAKES SOMETHING LIKE 150,000 YEARS. VERY ABRUPT ONSET; GRADUAL RECOVERY.

AND THEN FINALLY, MORE RECENTLY, WHAT WE'VE DISCOVERED, THIS JUST SHOWS THE CARBONATE CONTENT OF SEDIMENTS FROM SEVERAL CORES IN THE SOUTH ATLANTIC; AND AGAIN, THIS IS A GLOBAL PATTERN. WE SEE ESSENTIALLY A GLOBAL DISSOLUTION HORIZON THAT CORRESPONDS WITH THE ISOTOPE EXCURSION. AND THIS IS CLEARLY EVIDENCE OF A CHANGE IN OCEAN PH AND OCEAN ACIDIFICATION AND WIDESPREAD CARBONATE EROSION OF CARBONATE SEDIMENTS ON THE SEAFLOOR, CHEMICAL EROSION.

OKAY. AS FAR AS TEMPERATURES, THE CLIMATE, I'M NOT GOING TO SAY A WHOLE LOT. I JUST WANT TO POINT OUT THAT THESE ARE JUST SOME OF THE ESTIMATES WE HAVE FOR SEA SURFACE TEMPERATURE ANOMALIES AT SEVERAL KEY LOCATIONS, AND I'VE ONLY PLOTTED THE RECORDS FOR THOSE SITES WHERE WE HAVE MORE THAN A SINGLE PROXY. WE HAVE USED MULTIPLE PROXIES TO

RECONSTRUCT TEMPERATURE. AND BASICALLY, IT'S A FAIRLY UNIFORM WARMING GLOBALLY, ANYWHERES BETWEEN 6 TO 8 DEGREES CENTIGRADE. IN A COUPLE OF CASES, WE HAVE ABSOLUTE TEMPERATURES DURING THE PEAK OF THE THERMAL MAXIMUM. SO THIS IS JUST GIVING YOU SOME INDICATION OF HOW WARM IT GOT IN PLACES LIKE ANTARCTICA, 20 DEGREES C. THIS IS A MORE RECENT RECORD SUGGESTING TEMPERATURES AS WARM AS 23 DEGREES C IN THE ARCTIC.

SO, CLEARLY, A FAIRLY SIGNIFICANTLY WARMER PLANET. WE DON'T ACTUALLY HAVE TEMPERATURES FOR THE TROPICS AT THE MOMENT, AND IT'S PROBABLY A GOOD REASON FOR THAT.

AS FAR AS THE OTHER CLIMATIC ENVIRONMENTAL PERTURBATIONS, THIS IS JUST A LIST OF SORT OF THE IMPORTANT ONES THAT WHEN YOU LOOK AT THE LIST, BASICALLY IT'S EVERYTHING YOU WOULD EXPECT WITH GLOBAL WARMING: CHANGES IN PRECIPITATION PATTERNS. WE'VE EVEN FOUND EVIDENCE NOW OF INCREASED FREQUENCY OF EXTREME WEATHER EVENTS DURING THIS PERIOD, WILDFIRES. THE EFFECTS ON BIOTA ARE SUBSTANTIAL.

WE DON'T GET MASSIVE EXTENSIONS. I THINK

THIS HAS SOMETHING TO DO WITH THE RATE AT WHICH THIS EVENT UNFOLDS, AND I'LL EXPLAIN THAT IN A SECOND.

BASICALLY, THE PATTERNS THAT WE SEE ARE

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VERY CONSISTENT WITH WHAT WE WOULD EXPECT WITH GLOBAL WARMING.

MORE RECENTLY, WE THINK WE'VE GOT A GOOD HANDLE NOW ON SEA LEVEL DURING THE EVENT, SOMETHING LIKE A 10-TO-15-METER RISE IN SEA LEVEL, 3 TO 5 METERS OF WHICH WE CAN DEFINITELY PUT ON THERMAL EXPANSION, AND THEN THE REST OF IT, THERE MUST HAVE BEEN SMALL ICE SHEETS ON ANTARCTICA. IT'S NOT INCONCEIVABLE THAT THERE WERE SMALL LANDLOCKED ICE SHEETS ON ANTARCTICA, AND IT'S LIKELY THAT THEY CONTRIBUTED TO THE REST OF THIS SEA LEVEL RISE.

OKAY. SO THAT'S ALL I'M GOING TO SAY ABOUT THE SORT OF CLIMATE ENVIRONMENTAL CONSEQUENCES AND START TO MOVE ON TO DISCUSSION ABOUT THE CARBON AND THE SOURCE OF THIS CARBON.

YOU'VE ALL HEARD ABOUT THE POTENTIAL DECOMPOSITION OF METHANE HYDRATE. THIS IS ONE IDEA THAT THERE MIGHT HAVE BEEN SOME SORT OF CATASTROPHIC EVENT THAT ALLOWED METHANE HYDRATES TO DECOMPOSE AND ADD SEVERAL THOUSAND GIGATONS OF CARBON TO THE OCEAN.

THERE ARE OTHER IDEAS. WE KNOW THAT AROUND THIS TIME THE NORTH ATLANTIC WAS STARTING TO OPEN, RIFTING BETWEEN GREENLAND AND EUROPE, AND THERE'S BEEN SOME SUGGESTIONS THAT THIS MIGHT HAVE INVOLVED SOME THERMAL DECOMPOSITION OF ORGANIC MATTER AND

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SEDIMENTS IN THAT PART OF THE WORLD.

AND THEN ANOTHER IDEA IS THAT THERE IS EVIDENCE TO SUGGEST WE HAVE DESICCATION OXIDATION OF ORGANIC-RICH SOILS OR EVEN LAKES LARGER THAN SEAS.

THE MAIN THING ABOUT ALL THREE OF THESE, THAT THESE ARE REALLY THE ONLY POTENTIAL SOURCES FOR THE AMOUNT OF CARBON THAT WE'RE TALKING ABOUT. WE NEED THOUSANDS OF GIGATONS OF CARBON TO BE RELEASED IN A VERY SHORT PERIOD OF TIME, AND THIS IS IT.

NOW, I WILL SAY AHEAD OF TIME THAT I THINK WHAT HAPPENED IS THAT THE EVENT MIGHT HAVE BEEN TRIGGERED BY THIS, BUT THAT THESE TWO SOURCES OF CARBON CAME IN LATER ON AS FEEDBACKS, STARTING TO -- ESSENTIALLY, DOUBLING UP OR TRIPLING THE AMOUNT OF CARBON THAT CAME INTO THE SYSTEM, AND I WILL EXPLAIN WHY I BELIEVE THAT IN A SECOND, AT THE END.

OKAY. SO WHAT WE HAVE BEEN TRYING TO DO IS TO FIGURE OUT WHETHER OR NOT WE'RE DEALING WITH SINGLE OR MULTIPLE SOURCES OF CARBON. THAT MEANS TO ME THAT WE NEED TO BE ABLE TO SAY SOMETHING ABOUT THE RATE OF RELEASE, HOW FAST WAS THIS EXCURSION, HOW FAST DID THE OCEAN CARBON CHEMISTRY CHANGE. AND THERE ARE DIFFERENT STRATEGIES THAT WE'RE USING TO TRY TO GET AT THIS. IT IS NOT THAT EASY TO DO, IN PART BECAUSE WE'RE DEALING WITH RECORDS THAT HAVE

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BEEN TRUNCATED BY DISSOLUTION OCEAN ACIDIFICATION.

AND THEN IF YOU KNOW SOMETHING ABOUT THE RATE, THEN YOU JUST HAVE TO GET A HANDLE ON THE MASS OF CARBON RELEASED. WE HAVE THE CARBON ISOTOPE EXCURSION; BUT IF WE START TO ASSUME THAT THERE ARE MULTIPLE SOURCES OF CARBON ISOTOPE EXCURSION, IT DOESN'T HELP US CONSTRAIN THE SOURCE. WHAT WE CAN USE ARE CHANGES IN OCEAN CHEMISTRY. CARBONATE SATURATION STAYING IN THE OCEAN MAY ALLOW US TO CONSTRAIN THAT. SO WE ARE DEALING WITH MODELS, ERROR PROCESS BETWEEN MODELS, TO TRY TO CONSTRAIN THE MASS OF CARBON.

NOW, WHAT I'M GOING TO JUST SHOW YOU ARE SOME RECORDS THAT WE'VE DEVELOPED THAT SUGGEST THAT THE CARBON ISOTOPE EXCURSION ITSELF WAS FAIRLY RAPID. THERE ARE LOTS OF RECORDS THAT HAVE BEEN GENERATED; AND DEPENDING ON THE TYPE OF MATERIAL YOU MEASURE AND WHERE YOU GENERATE THESE RECORDS, THE PATTERN OF THE EXCURSION ALWAYS LOOKS DIFFERENT. AND SO WHAT WE TRIED TO DO WAS SORT IT OUT AND GET IT RIGHT AND USE STRATEGIES THAT WE THOUGHT WOULD BEST REPRESENT THE ACTUAL CHANGES IN THE CARBON ISOTOPIC COMPOSITION OF SEAWATER.

I'M GOING TO SHOW YOU SOME RECORDS FROM TWO LOCATIONS: ONE RECORD FROM OFF OF ANTARCTICA, A DEEPSEA RECORD; AND THEN A SHALLOW MARINE RECORD FROM

A NEW JERSEY MARGIN. AND THIS IS FROM AN OLD PAPER. 2002, OKAY, NOT THAT OLD. BUT WHAT WE DID IN THIS CORE, THIS IS A SEDIMENT CORE, JUST LIKE THE ONE I SHOWED A PHOTOGRAPH OF EARLIER; AND WE SAMPLED EVERY CENTIMETER ALONG THIS CORE THROUGH THE EXCURSION LAYER, THROUGH THE P-E BOUNDARY; AND WHAT WE DID WAS TO ANALYZE SHELLS OF PLANKTONIC AND BENZOIC FORAMINIFERA INDIVIDUALLY RATHER THAN FROM EACH SAMPLE, GROUP 10 SHELLS. WE THOUGHT WE WOULD JUST ANALYZE A SINGLE SHELL, OR SINGLE SHELLS, AS MANY AS 10 FROM EACH LEVEL. AND THE REASON FOR THAT IS WE WERE WORRIED ABOUT THE EFFECTS OF MIXING OUR OBSERVATION ON SMOOTHING THE ISOTOPIC EXCURSION. AND WHAT WE FOUND WAS PRETTY INTERESTING, WHICH WAS, IF YOU LOOK AT THE MIXED LAYER OF PLANKTONIC FORAMS, TO GET PRE-EXCURSION VALUES AND THEN YOU GET TO THIS HORIZON WHERE ALL OF A SUDDEN YOU HAVE A MIXTURE OF PRE-EXCURSION AND EXCURSION FORAMS, AND WHAT THIS WOULD SUGGEST AT FACE VALUE IS SIMPLE; THAT THE DELTA C-13 OF THE SURFACE OCEAN CHANGED BY 4 PER MIL IN A GEOLOGIC INSTANT. AND THEN IF YOU LOOK AT FORAMS THAT GO DEEPER IN THE WATER COLUMN OR BENZOIC FORAMS, IT LOOKS LIKE THE DELTA C-13 OF THOSE RESERVOIRS CHANGED LATER; THAT THERE WAS A LAG EFFECT. AND THIS WOULD ACTUALLY BE CONSISTENT WITH THE IDEA THAT

CARBON WAS RELEASED INTO THE ATMOSPHERE AND THEN WAS GRADUALLY SWEPT INTO THE DEEPSEA. AND SO THIS WAS ONE OF THE INTERPRETATIONS THAT WE PUT FORWARD TO EXPLAIN THIS RECORD.

NOW, THE OTHER THING, OF COURSE, IS THAT THIS COULD JUST BE AN ARTIFACT. I JUST TOLD YOU THAT

THERE IS MASSIVE CARBONATE DISSOLUTION DURING THE EVENT, AND MAYBE THIS RECORD IS TRUNCATED; AND THAT IF WE HAD THE FULL RECORD, IT WOULD BE MORE GRADUAL.

SO TO GET AROUND THIS, WE DECIDED TO GET OUT OF THE DEEPSEA AND MOVE UP ONTO THE SHELVES, WHICH SHOULD HAVE STAYED OVERSATURATED WITH RESPECT TO CALCIUM CARBONATE; AND THIS IS WHERE WE'VE BEEN WORKING ON THESE SECTIONS FROM NEW JERSEY AND ELSEWHERE. THIS IS WHAT THE COASTLINE LOOKED LIKE 55 MILLION YEARS AGO. HERE'S NEW JERSEY. IT'S MOSTLY UNDERWATER. SOME PEOPLE THINK THAT'S A GOOD THING.

AND WHAT WE LIKE ABOUT THESE SECTIONS IS THAT THEY'RE REPRESENTING MID-SHELF ENVIRONMENTS. WATER DEPTH WOULD HAVE BEEN LESS THAN ABOUT 200 METERS AT THIS PARTICULAR SITE. WE HAVE OTHER SITES FURTHER TOWARDS THE COASTLINE, WHICH WOULD HAVE BEEN RIGHT ABOUT HERE.

THE SECTIONS HAVE MOSTLY SILICICLASTIC

SEDIMENT, CLAY-RICH. IN THE EXCURSION LAYER, THE CLAY IS PREDOMINANTLY KAOLINITE, WHICH IS CLAY THAT IS PRODUCED MAINLY IN THE TROPICS. AND THIS IS SOMETHING THAT YOU SEE THROUGHOUT THE MID AND HIGH LATITUDES, AND EVERY ONE OF THESE COULD BE BOUNDARY SECTIONS.

THERE ARE SOME FORAMINIFERA. THEY'RE VERY SCARCE, BUT THEY'RE REALLY WELL PRESERVED. AND THEN THE OTHER THING THAT'S APPEALING ABOUT THESE SECTIONS IS THAT THE SEDIMENTATION RATES ARE MUCH HIGHER THAN THE DEEPSEA SECTIONS; AGAIN, BECAUSE OF THE SILICICLASTIC FLUX. AND THIS GIVES US A HIGHER FIDELITY RECORD.

THOSE ARE SOME PHOTOS OF SOME FORAMS. OVER HERE IS JUST THE CARBONATE CONTENT, AND THIS IS THE PERCENT SAND FRACTION. AND THE PATTERNS THAT YOU SEE IN BOTH OF THESE ARE CONSISTENT WITH RISING SEA LEVEL. SO THAT'S ALL I'LL SAY ABOUT THOSE RECORDS.

THIS IS THE OXYGEN ISOTOPE RECORDS. THIS IS THE CARBON ISOTOPE RECORD. AND WE FIND THE SAME MIXED-LAYER FORAMS THAT WE GET IN SOME OF THOSE OCEAN SECTIONS, BENZOIC FORAMS AND SO FORTH. AND SO THERE'S THE EXCURSION, AND IT'S FAIRLY ABRUPT, OKAY.

WHAT WE DID WAS TO DO THE SAME THING THAT WE DID WITH THE PELAGIC SECTIONS, WHICH IS TO LOOK AT

INDIVIDUAL SHELLS OF FORAMINIFERA, AND SO THIS IS THE CARBON ISOTOPE RECORD. THESE ARE MIXED-LAYER FORAMS, THESE ARE BENEDICTS (PHONETIC), THESE ARE THERMOCLINE FORAMS. AND ALREADY YOU CAN SEE THAT THE PATTERN IS SOMEWHAT SIMILAR TO WHAT WE SEE IN THE DEEPSEA; THAT IS, THAT WE GET A SUDDEN JUMP FROM THESE PRE-EXCURSION VALUES TO EXCURSION VALUES. AND SO THE QUESTION IS -- SO, YOU KNOW, IS THIS TELLING US THAT THE CARBON ISOTOPE EXCURSION IS GLOBALLY RAPID?

I THINK SO. AND WHAT I DID WAS I JUST TOOK THE VALUES FROM THIS PARTICULAR SITE, AND I PLOTTED

THEM, ALONG WITH THE VALUES OF MIXED-LAYER FORAMS FROM THE SOUTHERN OCEAN SITES, AND THE IDEA BEING THAT THE CARBON ISOTOPIC COMPOSITION, THE CHANGES PRE-EXCURSION TO EXCURSION SHOULD HAVE BEEN ABOUT THE SAME, THE ABSOLUTE RATIOS PLUS THE MAGNITUDE OF THE EXCURSION.

SO IN THIS PANEL OVER HERE, THESE ARE THE VALUES FROM THE SITE OFF OF ANTARCTICA. AND THESE ARE THE BASS RIVER, NEW JERSEY SITE VALUES. AND BASICALLY -- AND THIS IS A CROSS PLOT OF CARBON VERSUS OXYGEN. AND YET, WE SEE THE SAME PRE-EXCURSION VALUES IN CARBON, THE SAME EXCURSION VALUES; AND VERY FEW OR NO VALUES THAT WE CONSIDER TRANSITIONAL.

SO YOU COULD ARGUE THAT, WELL, MAYBE THERE WASN'T DISSOLUTION THERE; BUT I THINK WHEN YOU LOOK AT THESE RECORDS -- AND THERE ARE OTHERS NOW WHERE WE'RE MEASURING ORGANIC CARBON, CARBON ISOTOPE RATIO. AND EVERYTHING INDICATES THAT THE CARBON ISOTOPE EXCURSION WAS FAIRLY ABRUPT. IT WAS A VERY RAPID EVENT, GEOLOGICALLY RAPID. WHAT DOES THAT MEAN? WAS IT A HUNDRED YEARS? WAS IT 500 YEARS? OR A FEW THOUSAND YEARS? AT THIS POINT, YOU KNOW, WE'RE COMFORTABLE IN SAYING IT WAS PROBABLY LESS THAN FOUR OR FIVE THOUSAND YEARS.

SO, FINALLY, I JUST WANT TO TALK A LITTLE BIT ABOUT THE MASSIVE CARBON; AND HERE, AS I SAID, WE HAVE THESE TWO CONSTRAINTS. I WANT TO TALK ABOUT THE CHANGES IN OCEAN CARBONATE CHEMISTRY. AND I'M JUST GOING TO TAKE YOU TO ONE RECORD, PROBABLY OUR BEST ONE, THIS ONE OFF OF SOUTH AFRICA IN THE WALRUS (PHONETIC) RIDGE, WHERE WE DRILLED A DEPTH, TRANSECTED FIVE SITES FROM ABOUT 2 AND A HALF KILOMETERS TO ABOUT 4.8 KILOMETERS WATER DEPTH; AND AT ALL THE SITES, WHEN WE DRILLED THROUGH THE BOUNDARY, WE ENCOUNTERED THIS CLAY LAYER, OKAY, SO THIS IS CLEARLY INDICATING THAT THE OCEAN BECAME -- THE DEEPSEA BECAME UNDERSATURATED WITH RESPECT TO CALCIUM CARBONATE DURING THE PETM.

WE SEE THIS CLAY LAYER, EVEN AT THE SHALLOWEST SITE. AND SO THIS PATTERN FROM THE SHALLOWEST SITE TO THE DEEPEST SITE SIMPLY SUGGESTS THAT THE OCEAN CARBONATE COMPOSITION THAT'S SHOWN VERY QUICKLY AND THEN GRADUALLY DESCENDED. AND THIS TOOK SOMETHING LIKE -- THE INITIAL SHOALING, WE DON'T KNOW EXACTLY HOW FAST THAT OCCURRED BECAUSE BASICALLY WE'RE DISSOLVING AWAY SEDIMENTS AS WE GO. BUT THE RECOVERY TAKES SOMETHING LIKE 50,000 YEARS, WHICH IS FAIRLY CONSISTENT WITH WHAT YOU WOULD EXPECT IF YOU WERE TO SUDDENLY DUMP IN SAY SEVERAL THOUSAND GIGATONS OF CARBON INTO THE OCEAN AND ACIDIFY IT. THIS IS ABOUT HOW LONG IT WOULD TAKE FOR THE OCEAN TO RESTORE SOME REASONABLE SATURATION FOR CARBONATE TO ACCUMULATE.

OVER HERE IS THE BULK CARBONATE CARBON

ISOTOPE RECORD. THE ONE THING I WILL SAY ABOUT THIS IS SIMPLE; THAT ALL THESE SITES THE RECORD LOOKS DIFFERENT, AND I THINK THIS PATTERN IS PURELY A FUNCTION OF -- IT'S AN ARTIFACT OF DISSOLUTION AND REWORKING. THE CARBON ISOTOPE EXCURSION, AS I ARGUED EARLIER, IS PROBABLY VERY ABRUPT. AND SO THIS PATTERN WHICH HAS BEEN PICKED UP IN A LOT OF DEEPSEA SECTIONS IS AN ARTIFACT. THE SIGNIFICANCE OF THAT WILL BECOME OBVIOUS IN A SECOND.

0466

WHAT DOES THIS MEAN? THE CARBONATE DISSOLUTION PATTERNS ARE GLOBAL, AND WE'VE MODELED THIS IN SEVERAL DIFFERENT WAYS. WE'RE USING THE 3D OCEAN MODELS AVAILABLE, THE GE MODEL, ALSO THE HAMBURG MODEL, AND THEN WE'RE USING BOX MODELS, AS WELL. AND THE BOTTOM LINE IS THAT FOR A VERY SUSTAINED PERIOD OF TIME, SEVERAL THOUSANDS YEARS, THAT THE DEEPSEA HAD TO HAVE BEEN SIGNIFICANTLY UNDERSATURATED; AND TO DO THIS, YOU WOULD NEED AT LEAST THREE TO FOUR THOUSAND GIGATONS OF CARBON. BETWEEN ALL THE MODELED ONES THAT WE HAVE DONE, THAT SEEMS TO BE THE MINIMUM TO SUSTAIN THIS DEGREE OF UNDERSATURATION.

SO COMING BACK TO THIS RECORD AND AGAIN LOOKING AT THE CARBON ISOTOPE RECORD HERE, WE HAVE STARTED TO TRY TO USE THE MODELS IN COMBINATION WITH THE CARBON ISOTOPES TO COME UP WITH SORT OF A UNIQUE SET OF CARBON FLUXES IN TERMS OF MASS AND ISOTOPIC COMPOSITION; AND I TOLD YOU EARLIER THAT IF YOU PLOTTED THE BULK CARBON ISOTOPE RECORDS, CARBONATE CARBON ISOTOPE RECORDS FROM VARIOUS SITES, THE PATTERN YOU WOULD GET WOULD LOOK LIKE THIS. IT WOULD SUGGEST THAT THERE ARE MULTIPLE STEPS IN THE RECORD, AND IT WAS GRADUAL IN THE EXCURSION, AND THAT IT TOOK SOMETHING LIKE 50,000 YEARS.

0467

SO IF YOU TRY TO SIMULATE THIS WITH A BOX MODEL, YOU COULD DO SOMETHING LIKE THIS. YOU COULD TAKE CARBON, AND IN THIS, WE'VE RUN A NUMBER OF SIMULATIONS. THE BOTTOM LINE IS WE NEED FOR THIS SOMETHING LIKE 5,000 GIGATONS. WE'RE USING CARBON THAT HAS A DELTA C-13 THAT'S MIDWAY BETWEEN A SOURCE OF METHANE AND SAY ORGANIC CARBON; AND YOU CAN PULSE THE CARBON TWICE LIKE THIS AND THEN LEAK IT FOR AWHILE. AND THIS IS SORT OF THE CARBON ISOTOPE PATTERN THAT YOU PRODUCE FOR THE DIFFERENT OCEAN BASINS. AND SO THIS IS SOMETHING THAT WOULD FIT THESE BULK CARBONATE CARBON ISOTOPE RECORDS. BUT I JUST GOT DONE TELLING YOU THAT WE THINK THOSE RECORDS ARE WRONG; THAT THE ACTUAL ONSET OF THE EXCURSION WAS FAIRLY ABRUPT.

AND THIS IS ANOTHER RECORD FROM BASS RIVER. I TOLD YOU WE HAVE -- I SHOWED YOU THE FORAM, THE CARBONATE RECORDS; BUT WE ALSO HAVE ORGANIC CARBON RECORDS, AND THEY SHOW THE SAME THING. THEY WOULDN'T BE AFFECTED BY THE DISSOLUTION, THESE SILICICLASTIC SEDIMENTS; BUT AGAIN, WITH THE ORGANIC CARBON, WE

ALSO GET A VERY ABRUPT CARBON ISOTOPE EXCURSION.

SO IF YOU MODEL -- IF YOU WANTED TO SIMULATE THAT, THEN YOU CAN -- IN THIS PARTICULAR SIMULATION, WE'RE USING 3,600 GIGATONS OF CARBON WITH

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A DELTA C-13 CLOSER TO A METHANE SOURCE. YOU PULSE IN 2,200 GIGATONS AND THEN LEAK IN THE REST FOR SEVERAL TENS OF THOUSANDS OF YEARS, AND THAT PRODUCES AN EXCURSION THAT LOOKS MORE LIKE WHAT WE SEE IN THE PLANKTON AND THE BULK CARBON ISOTOPE RECORDS.

SO WE'RE AT THE POINT NOW WHERE WE'RE RUNNING THESE SORTS OF SIMULATIONS USING THE BOX MODELS, BUT ALSO THESE 3D OCEAN MODELS, BECAUSE THE PATTERN OF CARBONATE DISSOLUTION SEEMS TO VARY FROM BASIN TO BASIN.

THE ONE THING THAT I WANTED TO DO HERE WAS START TO TALK ABOUT WHAT THIS MEANS IN TERMS OF THE OCEAN SATURATION STATE, ACIDIFICATION IF WE JUST ASSUME THAT THIS PARTICULAR SET OF EXPERIMENTS BEST REPRESENTS WHAT WE SEE IN THE DEEPSEA RECORD. WE'RE ACTUALLY ADDING THIS 2,200 GIGATONS OF CARBON OVER SEVERAL THOUSAND YEARS HERE, AS YOU CAN SEE. SO IT'S NOT QUITE AT ANTHROPOGENIC EMISSION RATES, BUT IT IS SORT OF UP THERE. AND IN DOING SO, IF YOU START TO LOOK AT THE EFFECTS THAT THAT HAS ON THE SATURATION STATE OF THE SURFACE OCEANS, AND WE'RE JUST FOCUSING ON SURFACE OCEANS, YOU CAN SEE WHAT HAPPENS HERE. YEAH, THERE IS A DROP, BUT WE DON'T GET TO A POINT WHERE THE OCEAN'S UNDERSATURATED. AND AGAIN, THIS IS SOMETHING THAT WE'VE ALWAYS BELIEVED. WE HAD THE

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SUSPICION THAT THE RATE OF RELEASE WAS SLOW ENOUGH THAT YOU DON'T GET TO UNDERSATURATION IN SURFACE OCEAN.

NOW, FOR COMPARISON, YOU CAN JUST TAKE THE MODERN OR THE PREDICTED OR PROJECTED ANTHROPOGENIC FLUX, BUSINESS AS USUAL, AND THEN CALCULATE THE CHANGE IN THE SURFACE SATURATION STATE. AND, OF COURSE, IT IS MUCH MORE SEVERE HERE. AND DESPITE THE FACT THAT IN TERMS OF MASS, OKAY, IT'S DOUBLE, BUT STILL -- AND, YOU KNOW, THE MAIN POINT HERE IS SIMPLE, WHICH IS THAT THE RATE OF RELEASE IS REALLY IMPORTANT. THE BUFFERING CAPACITY OF THE OCEAN IS IN THE DEEPSEA; IT'S NOT IN THE SURFACE OCEAN. AND IT TAKES SOMETHING LIKE 500 YEARS OF THE OCEAN TO TURN OVER. SO IN THE CASE OF THE PETM, WHERE THE CARBON IS BEING ADDED OVER SEVERAL OCEAN MIXING CYCLES, THE OCEAN IS ABLE TO BUFFER TO SOME EXTENT THE CHANGES IN PH WITH DISSOLUTION OF CARBONATE ON THE SEAFLOOR; WHEREAS, IN THE PRESENT-DAY SITUATION, THAT'S NOT GOING TO HAPPEN. THE RATE OF RELEASE IS MUCH FASTER THAN THE TURNOVER TIME OF THE OCEAN. SO THE SURFACE OCEAN ENDS UP BEARING THE BRUNT OF THE CHANGES IN PH AND ALSO IN TERMS OF ABSORBING OR TRYING TO ABSORB THAT CARBON. OF COURSE, THAT'S WHY THERE'S THIS CONCERN ABOUT THE EFFECT OF PH CHANGES ON CALCIFIERS.

0470

NOW, IT'S USUALLY AT THIS POINT IN THE TALK OVER THE YEARS WHERE PEOPLE WILL SAY, WELL, WHAT HAPPENED TO CALCIFIERS? WHAT HAPPENED TO CORALS, FOR INSTANCE, DURING THE PETM? AND UP UNTIL ABOUT A MONTH OR TWO AGO, THE ONLY THING I COULD SAY IS THAT WE DON'T KNOW; THAT WE KNOW FROM STUDIES THAT PALEONTOLOGISTS HAVE DONE OVER DECADES THAT THE DIVERSITY OF CORALS IN THE EARLY EOCENE IS LOWER THAN THE DIVERSITY OF CORALS IN THE LATE PALEOCENE PRIOR TO THE EVENT, BUT NOBODY KNEW WHY OR WHEN THAT HAPPENED. MORE RECENTLY, A PAPER WAS PUBLISHED WHERE TWO PALEONTOLOGISTS LOOKED AT DATA FROM A NUMBER OF SECTIONS SURROUNDING THE TETHYS; AND WHAT THEY HAD TO DO WASN'T EASY. THEY HAD TO THINK ABOUT -- WELL, THERE WAS STRATIGRAPHIC ISSUES; BUT ULTIMATELY WHAT THEY WERE ABLE TO DEMONSTRATE OR CLAIM WAS THIS: THAT THIS REPRESENTS CORAL DIVERSITY FROM THE PALEOCENE INTO EARLY EOCENE. AND PRIOR TO THIS STUDY WE WOULD SAY THAT DURING THIS WHOLE EARLY EOCENE DIVERSITY WAS LOW COMPARED TO THE PALEOCENE.

WHAT THEY'RE SAYING IN THIS STUDY IS THAT THAT CHANGE IN DIVERSITY OCCURRED VERY ABRUPTLY AND IT OCCURRED RIGHT AROUND THE PALEOCENE AND EOCENE BOUNDARY, DURING THE PETM. AND THERE IS STILL A LOT MORE WORK TO BE DONE TO SORT OF RESOLVE THE SCALE OF

THIS CHANGE AND THE TIMING, BUT THE POINT IS SIMPLE; THAT THERE IS THIS CHANGE IN DIVERSITY. THERE IS ALSO A DROP IN THE DIVERSITY OF LARGER FORAMINIFERA, WHICH WOULD HAVE INHABITED THIS SHALLOW MARINE CARBONATE SHELF ENVIRONMENTS. AND SO IT LOOKS LIKE THAT THESE CHANGES IN DIVERSITY ARE OCCURRING RIGHT AROUND THE P-E BOUNDARY.

NOW, COULD YOU ASK THEN: WELL, DO YOU THINK IT HAS TO DO WITH THE CHANGE IN THE SATURATION STATE? OR MAYBE IT'S TEMPERATURE? WELL, IT'S PROBABLY BOTH. YOU CAN PICK YOUR POISON, THE COMBINATION OF THE TWO, WARMING.

WE BELIEVE THAT TROPICAL TEMPERATURES GOT UP TO AS HIGH AS 40 DEGREES CENTIGRADE DURING THE PEAK OF THE PETM; AND I SAY WE BELIEVE BECAUSE IN ALL THE SHALLOW MARINE -- OR IN ALL THE MARINE SECTIONS, WHEN WE GO TO LOOK FOR THE MIXED-LAYER FORAMS THAT WE NORMALLY RECONSTRUCT TEMPERATURES WITH, THEY'RE ABSENT IN THE TROPICAL SECTIONS DURING THE PETM. AND IT FINALLY DAWNED ON US WHY THEY'RE GONE. BECAUSE IT'S TOO WARM, AND THEY JUST LEAVE. AND FROM WHAT I UNDERSTAND, ON LAND, THE SAME THING IS HAPPENING; THAT DURING THE PEAK OF THE PETM, PLANT DIVERSITY BASICALLY GOES TO ALMOST NOTHING; THAT THERE IS A HUGE DROP IN BIOMASS AND DIVERSITY DURING THE PEAK OF

THE PETM, SO THE TROPICS OVERHEAT, AND SO CORALS WOULD PROBABLY RESPOND TO THAT, AS WELL AS CHANGES IN PH.

SO, HERE'S MY SUMMARY: THE MAGNITUDE OF THE CIE, WE THINK IT IS FAIRLY RAPID. WE'RE CLOSING

IN ON A NUMBER OF SOMETHING LIKE 4,500 GIGATONS OF CARBON RELEASE DURING THE PETM. AND WHETHER IT IS 4,500 OR 5,000 OR 6,000, AT THE MOMENT, IT DOESN'T MATTER. BUT WHAT'S IMPORTANT ABOUT A NUMBER THIS LARGE IS THAT IT ALMOST CERTAINLY REQUIRES MULTIPLE SOURCES OF CARBON; THAT WE CAN'T SAY THAT ANY ONE OF THESE SOURCES ALONE COULD PROVIDE THIS MUCH CARBON, WHICH IS WORRISOME BECAUSE THEN IT MEANS THAT, YOU KNOW, IF THIS WAS ONE SOURCE AND ONE OR BOTH OF THESE WERE INVOLVED, THAT THESE ARE PROBABLY COMING IN IN FEEDBACK MODE, CONSISTENT WITH THE IDEA THAT WHAT'S HAPPENING AT THE PETM IS A THRESHOLD EVENT; THAT THE SYSTEM HAS CROSSED OVER SOME SORT OF THRESHOLD, AND IT STARTS TO REALLY -- WE START TO LOSE CARBON FROM A LOT OF THESE RESERVOIRS THAT HAVE BEEN ACCUMULATING CARBON FOR A LONG TIME. OKAY.

SO WHAT ARE THE IMPLICATIONS? WELL, OBVIOUSLY, UNABATED CO2 EMISSIONS WILL LEAD TO A SEVERE DROP IN PH OF THE SURFACE OCEAN, AND WE ALL KNOW THIS. THAT'S NOT A SURPRISE.

THE QUESTION IS WHETHER WE HAVE TO WORRY ABOUT POSITIVE FEEDBACKS. AND I THINK THIS IS A CONCERN. I THINK IT IS SOMETHING THAT THERE SHOULD BE A LOT OF AND OBVIOUSLY THERE IS A LOT OF EFFORT TRYING TO UNDERSTAND WHAT THOSE FEEDBACKS WILL BE AND HOW SIGNIFICANT THEY WILL BE. AND THESE ARE THE ONES THAT WE'RE LOOKING AT THE MOMENT.

AND THEN AS FAR AS WILL METHANE HYDRATES DISSOCIATE, WILL THEY BECOME PART OF THIS PROCESS OF RISING CO2? AND, REALLY, IT DOES DEPEND ON THE MAGNITUDE OF WARMING. THE OCEANS ARE COLD. YOU HAVE TO PROPAGATE THE HEAT INTO THE OCEAN, DEEPER INTO THE OCEAN, AND INTO SEDIMENTS; AND THAT TAKES TIME, AND WE'RE TALKING ABOUT A FEEDBACK THAT COULD COME IN IN CENTURIES AND MAYBE MILLENNIA.

NOW, A LOT OF PEOPLE ARE SKEPTICAL THAT HYDRATES, THAT WE HAVE TO WORRY ABOUT HYDRATES; AND WHAT I'M GOING TO SHOW YOU -- I WAS GOING -- I WAS NOT GOING TO SHOW THIS, BUT THE PAPER IS GOING TO COME OUT IN "NATURE" IN A COUPLE OF WEEKS ANYWAY, NOT THAT IT MEANS ANYTHING. BUT IF WE GO BACK TO BASS RIVER, WE HAVE MULTIPLE PROXY TEMPERATURE RECORDS, ONE OF WHICH IS THE TEX86 RECORD HERE, AND THERE IS SOME CONTROVERSY ABOUT HOW WELL THIS PROXY WORKS. BUT WE GET THE SAME ABSOLUTE TEMPERATURES THAT WE GET

WITH THE OXYGEN ISOTOPES, AND THIS IS AN ORGANIC-BASE PROXY OF TEMPERATURE. AND IF YOU LOOK AT THE DETAILS HERE, AND THESE ACCUMULATION RATES ARE VERY HIGH, IN DETAIL WHAT WE FIND IS THAT THE CARBON ISOTOPE EXCURSION OCCURS UP AT THIS LEVEL, THIS HORIZON, WHERE WE THINK THE WARMING AND AS WELL AS SOME OTHER ENVIRONMENTAL INDICATORS OF WARMING -- THIS IS A DINOFLAGELLATE SPECIES THAT BLOOMS GLOBALLY DURING THE PETM -- THAT THESE SORT OF PRECEDE THE CIE; THAT THE WARMING INITIATES SEVERAL THOUSAND YEARS BEFORE

THE MAIN CARBON ISOTOPE EXCURSION. THIS IS ABOUT THE ONLY SECTION WHERE WE SHOULD BE ABLE TO SEE THIS LEAD/LAG RELATIONSHIP; AND ALL THE DEEPSEA SECTIONS, THAT WOULD BE MERGED BECAUSE OF DISSOLUTION. WE NEED THESE SORT OF HIGH-FIDELITY SECTIONS.

SO YOU COULD ARGUE JUST BASED ON THIS ONE RECORD -- AND THAT'S WHAT WE DID -- THAT THE WARMING DOES LEAD THE CIE; THE CIE CARBON ISOTOPE EXCURSION REPRESENTING ONE OF THOSE POSITIVE FEEDBACKS, MOST LIKELY, METHANE; THAT AT SOME POINT, METHANE STARTS TO GO, THE HYDRATES START TO DISSOCIATE, AND THEN THEY START TO AMPLIFY THE WARMING. SO THAT'S AT LEAST ONE WAY THAT WE CAN INTERPRET THIS; AND OBVIOUSLY, WE NEED MORE SECTIONS LIKE THIS TO REALLY DEMONSTRATE WHETHER OR NOT THIS IS A REAL PATTERN,

THIS IS A GLOBAL PATTERN.

SO I THINK I'LL END THERE.

THANK YOU FOR YOUR PATIENCE.