That was begun in 1999, and the report was issued in June 2000. We also put the results of the report on a web page to get further public input. We had a total of eight public meetings, and four were in 1999, I believe, and four in 2000. We had them in Pahrump, Nevada and Las Vegas and here in White Flint, to get as broad a cross-section of comments from the stakeholders as possible. Then also we got direct comments on the website.

This is a list of stakeholders that we would include as people who have interest in this particular area, but certainly nuclear industry groups, transportation groups, DOE, DOT, state and local and tribal governments, public interest groups, and then just other members of the public as well. We got comments from all of them on 6672.

The results of Phase I of the Issues Report really formed a basis for the work scope as identified in the Package Performance Study. It really focused on five main areas that needed to be addressed to better define and fill some of the gaps were in 6672.

The first work scope item there is perform 3-D finite element analyses to capture the cask and fuel behavior in severe mechanical loadings. One of the constraints in 6672 was in the bolt area, in the closure area, because of computer limitations, we had to do a fairly coarse meshing of the bolts. We feel that to properly capture bolt behavior that needs to be much better, the meshing needs to be much better refined. But that has a tradeoff because it really increases geometrically the amount of computer time that you need as well.

One of the big comments from the public is, how does the fuel really behave in these severe mechanical environments? There's not a lot of data out there in terms of how this fuel behaves. So this is one area that we have put in test protocols as one of the main things, principal things that need to be looked at.

The second bullet here is perform 3-D finite element analyses to capture cask and fuel behavior in thermal environments. We did a 1-D finite element analysis in the thermal environments. Because of that, we were not able to very accurately determine the seal performance and temperatures around the seals. We need to do a 3-D finite element analysis to make sure that we properly capture that performance.

Conduct impact tests on fuel elements to characterize rod and fuel behavior in dynamic loading environments. Not only do we need to do the analysis up here, but we also have to have some empirical data, so that we can benchmark the analysis behavior results that we get to actual test results. Again, there is not a lot of data out there on fuel behavior from the pellet to the pellet inside the rod, to the assemblies.

Then, finally, reconstruct the accident event trees and accident speed and fire distributions. We used basically the event trees that were in the Modal Study in 1987. There was a lot of comment during the public meetings that there is a lot of new data out there. We went from 55 miles an hour on the highways to 75 miles an hour on the highways, and we needed to update the accident event trees and associated probabilities in those as well.

So we are working that as part of the Package Performance Study, but you will not see that in the protocol document because that doesn't involve testing. That is strictly looking, evaluating databases and doing the analysis on the databases.

Okay, so let's talk about -- that's the Issues Report, and that's what kind of got us to identify and define the five main areas in the Package Performance Study. Looking at the preliminary analyses and test recommendations is the responsibility of the test protocols.

Again, this is a document that we have done over the past six months or so that includes preliminary structural and thermal finite element analyses on a cask to determine appropriate orientations for a test, appropriate speeds for a test, to again demonstrate the safety of this cask, to be able to demonstrate that we can properly capture the response analytically of these casks during these very severe environments.

So here I define what's in the protocols. Again, a conceptual level for impact fire and fuel tests is defined in the protocols, and for the impact and the fire they are supported by preliminary analyses. These protocols will be published very soon. I think sometime in July they will be available for public distribution and then review and comment.

Then we will use these protocols, along with comments we get from the ACNW, the NAS, and the public, to define the test plans, the actual test plans that will be used to conduct whatever tests that are decided on that need to be conducted. Again, as I said earlier in the last viewgraph, the non-test issues in the Package Performance Study are not handled in the test protocols. They are handled separately, but are still part of the Package Performance Study. That is basically the reconstruction of the event trees, as we have described.

Okay, let's talk a little bit about the testing analyses that have been done and associated proposed tests. We picked a cask to do the initial analyses, and the cask that was picked was the HOLTEC Hi-Star 100. Again, in the public meetings we had a fair number of comments from people who raised their hand and said, "Show us a test. We want to see a cask that is currently certified by the NRC that is going to be rolling down the road at Yucca Mountain, and it needs to be big. It should probably a real cask."

So using that as part of the criteria -- we had other criteria as well, but we chose the HOLTEC Hi-Star cask as the cask to look at for these protocols in our preliminary analysis. Again, I want to stress that no decision has been made on what actual cask will be used for these tests, but this is what is used in the protocol document.

This just gives a axis symmetric view of the cask, and here a bolt detail. Again, the bolt details for these preliminary analyses is the meshing is rather crude. For the final test analyses, we will do a much more detailed job on the bolt and closure area.

For the protocols, we looked at analysis on three different orientations, kind of classic orientations: end-on, CG-over-corner, and the side-on. Again, this is CG-over-corner with the closure end at the down position.

We did those three analyses for two different impact speeds, one at 60 miles an hour, one at 90 miles an hour. This is with impact limiters on an unyielding target.

For a point of comparison, the regulatory environment is a 30-mile-an-hour impact onto an unyielding target. So you can see that this is really a much more severe impact or insult to the cask than what's in the regulatory environment.

I might also point out that in the regulatory environment that 9-meter drop test onto an unyielding surface captures about 99-plus percent of all real accidents. So what we are looking at here in this 60-to-90-mile-an-hour regime is really the tail-end of the accident distributions in terms of severity for mechanical and thermal impacts. It is an important point.

CHAIRMAN HORNBERGER: But it is credible?

MR. SORENSON: We have looked at the databases, and we have seen impacts or, excuse me, we have seen accidents up to 90-100 miles an hour. Now you could argue whether it is done yielding surface or not, probably not. So I guess the point is, what is credible, what is incredible in terms of how far you take this?

DR. LEVENSON: But in translating the vehicle speed, which is where the database is, I think, to this impact, you are ignoring any energy absorption in this thing tearing itself loose from the truck?

MR. SORENSON: You are ignoring that, and you are ignoring soft targets as well.

DR. LEVENSON: Right. Well, you're ignoring most hard targets because the hard target you have is significantly harder, I think, than any -- what is it, 25-foot-thick concrete slab?

MR. SORENSON: Yes.

DR. LEVENSON: Not many roads like that.

MR. SORENSON: Okay. This just gives a couple basic results.

DR. LEVENSON: Not to belabor this, but you say you're out at the tail-end of the distribution. Can you give me some feel how far out? Are you --

MR. SORENSON: Like how many sigma?

DR. LEVENSON: Yes.

MR. SORENSON: No, I really didn't -- Jerry, do you care to comment on that?

MR. SPRUNG: Probably four nines or so.

DR. LEVENSON: Four nines?

MR. SPRUNG: There aren't many accidents up there, and it is probably further out, if you take the accident speed and ask what's the chance of there really being something like an unfractured assault on igneous rock to hit, of all there is out there that is really close to an unusual target.

MR. SORENSON: Thank you.

This shows a finite element analysis result of the 60-mile-an-hour CG-over-corner center gravity over corner onto an unyielding target. You see a lot of damage to the impact limiter, but really no damage at all to the cask. Again, the important thing to look at here is the closure area with the bolts and basically there's no problem here. It maintains its integrity.

This shows accelerations. This is up about 50-55 Gs are so is the load on that. So it is not real huge. But, again, the regulatory accident, hypothetical accident condition is about a 30-mile-per-hour impact.

By the way, just to let you know for this particular cask design, this is a very complicated impact limiter and a very, say, conservative design. There's three different impact crush materials in here, a honeycomb with different compressive strengths. There's internal piping and gussets in here as well to provide additional structural strength in it.

CHAIRMAN HORNBERGER: Am I correct in assuming, if we look at this versus the 30-mile-per-hour, this would be more than a linear extrapolation? This is more than twice as bad as the 30-mile-an-hour test?

MR. SORENSON: Yes. If you look at it in terms of kinetic energy --

CHAIRMAN HORNBERGER: Yes, it's squared, right?

MR. SORENSON: Yes, it's V-squared. That's correct.

This is the 90-mile-per-hour impact. One of the things, I will touch on this in a couple of slides. We had an expert panel review. Some structural experts from around the country looked at the protocols, and also the public said that, you know, we would like -- if you say you can really capture the response of these casks, to do a regulatory drop, the cask remains in a linear elastic regime and you really don't measure anything. What they really said, what we would like to see is some plastic deformation of the cask itself, the cask by itself.

You will see here right around the flange shoulder of the cask body you do get some actual plastic deformation in this area. This is the closure lid, and then this is part of the cask body, where you actually do get some plastic deformation.

CHAIRMAN HORNBERGER: Who is it who wants to see plastic deformation?

MR. SORENSON: Well, some people in the public made that comment, not from the standpoint of, can you really capture cask response, and it's a "No, never mind" to capture cask response if it remains linear elastic, but if you can show plastic deformation and capture that appropriately with your analysis, that is what they want to see. The expert structural panel also mentioned that as well.

This shows a G loading here. Again, this answers your question that we go from about 55 Gs up to 140 Gs, and it's 50 percent higher impact velocity and about three times the G force.

MR. KOBETZ: Do you know what's happening to the bolts up there?

MR. SORENSON: Yes. Boy, you have a great segue. That's the next viewgraph actually.

The bolts, this is at -- let me superimpose this real quick here. The highly-strained bolts are on this part of the impact, the upper part of the impact. You can think of the cask impacting this way and the bolts up here are the ones that are highly strained.

This shows there's 54 bolts; they are an inch and five-eighths diameter bolts around the cask lid, but this shows a strain plot of individual bolts in the highly-strained area and this shows a plot going around the circumference of the enclosure, where the bolts are, in terms of opening. That shows, I think, about a .2-inch opening at the worst highest spot.

What we are looking for here is, these are metallic seals in this cask. So if you take that opening and you subtract out the compliance of that seal, that's how much of a gap you are going to have in that closure area. You can integrate those specific gaps between each bolt and get a total opening around that.

So we have a case for these preliminary analyses, 60-miles-an-hour, where we have no opening of the cask lid, and 90-miles-an-hour, where we have a small opening of the cask lid.

MR. KOBETZ: Ken, can I also ask, how come you didn't look at slapdowns? Because I know I have seen one test at Sandia where that was the worst drop for a cask.

MR. SORENSON: It is very difficult to analyze properly, for one thing. In terms of the objectives of the test, we felt this was a good orientation for doing the actual testing.

It depends really on the cask design, particularly like the LD over R ratio, the length versus the diameter of the cask, which is the worst orientation, the slapdown and CG-over-corner, and so forth.

So the recommendations from the structural part of the protocols are to conduct detailed finite element analyses on the HOLTEC Hi-Star cask with impact limiters for the final procedures. Again, if we decide on the cask orientation of CG-over-corner, we will only do detailed analyses for that particular orientation.

Right now the recommendation is to do the impact speed of somewhere between 60 and 90 miles per hour, and, again, as I said, to have increased attention on the modeling of the closure lid and the bolts and the impact limiters. The other thing I need to put in here that I missed is the recommendation to actually do the test of that cask as well, based on these analyses.

For the thermal analyses, we looked at really three cases. Regulatory cases, let's say it's just 1 meter above. We looked at 1.3 meters. This is a nuance of the meshing that we did in our particular program. It was either 1.3 or less than 1. So we wanted to put it at 1.3.

But we looked at three different locations in the pool fire and what the effect of that fire would have on the cask itself 1.3 meters above the pool, .3 meters above the pool. You think about it, in most accidents the cask is probably on the ground in the fully engulfing fire. So we thought it was important to look at this case in particular.

Then Case 3 was 3.3 meters above the pool. I will show you some pictures of the actual fire envelope. You have a vapor dome underneath the cask that does not have enough oxygen to combust the fuel mixture there. So you have a relatively cool spot right underneath the cask, which is called the vapor dome. So to put this a little bit higher, it gets you above that vapor dome and it gives you a more uniform heat load on the cask itself.

This is the regulatory case. Here you can see the vapor dome, where you have a relatively cool area on the lower surface of that cask. This actually looks at temperatures of the cask, and part of the vapor dome actually extends up the side of the cask and the middle part of the cask as well.

This is the cask on the ground, and you can see relatively, if you remember the last picture, you have the relatively cool bottom area of that cask, as you would expect.

DR. GARRICK: Ken, I remember reading that you are going to, among other things, determine gas flow velocities and heat fluxes, and that the gas flow velocity measurements are going to be partly based on pressure differentials.

Are you actually going to measure the pressure inside the simulated fuel rods?

MR. SORENSON: Oh, in the fuel rods?

DR. GARRICK: Yes.

MR. SORENSON: That's not the plan right now, John, but there is some pretty good data on there on burst rod temperatures. What we are really looking at right now is internal surface cask temperatures and time to reach those temperatures, because burst rod temperatures are about 750 degrees C. So once we get to that point, you can make the leap to say you are vulnerable to burst rod temperatures, but we don't have any plans at this point on measuring internal pressures of the pins, and so on.

DR. GARRICK: Okay, thank you.

MR. SORENSON: Then this is the cask located 3.3 meters above the pool, and here you can see the vapor dome is much less of an effect on the cask itself. Okay, you still get vapor dome issues on the ends here as well, but you get a more uniform temperature gradient over the cask surface.

DR. LEVENSON: Ken, is your thermal model for fuel temperature a fairly sophisticated one, element by element, et cetera, or are you going by the temperature on the inside surface of the cask?

MR. SORENSON: Well, we are doing both, Milt. We're looking at doing traditional fire modeling, which provides heat fluxes to the cask surface and then heat transport from the cask surface to the inside cask wall. We are also using an inverse heat conduction code which takes the response of the cask and backs out what the surface fluxes should be, so that we can tie those two together, so that we are confident that the fluxes that we are getting on the surface and the surface temperatures are right, so that we can properly model how this --

DR. LEVENSON: Because when you are going the other direction, and you've got fuel that is generating heat --

MR. SORENSON: Right.

DR. LEVENSON: -- it's damned hard to get the heat from the inner elements out to the cask.

MR. SORENSON: Right.

DR. LEVENSON: So the reverse process must also be true --

MR. SORENSON: Right.

DR. LEVENSON: -- that elements won't heat very fast.

MR. SORENSON: Right. As you know, we are not going to have the fuel elements --

DR. LEVENSON: You're not going to have it full of elements, we know.

MR. SORENSON: That's right.

DR. LEVENSON: But, I mean, just using the internal cask temperature, it is not really representative of what would be fuel temperature.

MR. SORENSON: I agree. Yes, I agree.

Okay, then recommendations for the thermal analyses, based on these preliminary -- the thermal analyses and testing, based on these preliminary analyses are, again, conduct more detailed modeling analyses. We are recommending in these protocols to do calorimeter tests, so that we can properly get the heat flux on the cask surface as well as initial heat temperatures, so we can make sure we get the proper boundary conditions in these fire environments.

We are recommending doing two full-scale calorimeter tests, one above the vapor dome -- we don't specify an actual height at this point, but somewhere above the vapor dome -- then one on or near the ground, and then conduct detailed modeling analysis for full-scale casks based on these calorimeter tests. Finally, do two full-scale casks full-fire tests. Well, one on the ground is recommended and then one above the vapor dome.

Okay, I am going to talk a little bit about the fuel test program that we have. Again, in 6672 and all the earlier reports they talked about there was lots of assumptions and inference made in terms of how spent fuel is going to behave in these very severe mechanical and thermal environments. As I said earlier, there's just not a lot of data out there.

So when you do finite element analysis, mechanical response and thermal response, and then you take the leap and look at how, if you breach the fuel, how that fuel deposits on the inside of the cask perhaps or how it becomes aerosolized and gets outside into the environment, you have to make a fair amount of inferences and assumptions on how that is done.

So this part of the Package Performance Study is to get some data, so that we can have a much better basis to tire our analysis to in terms of how this fuel behaves during these very extreme environments.

So here the objective: Given a particle release from the failed spent fuel rod, the goal of the rod, pellet, and CRUD impact test is to develop data that can show -- and then think about there's the spent fuel pellet, the centered pellet inside the Zircalloy tubing, and then all those tubes make up the assembly.

Also, on the outside of the assembly there is a CRUD that is formed. This is an acronym that stands for Chalk River Unidentified Deposits. It is basically in the BWR. It is a nickel-iron spinel that that precipitates out of the spent fuel pool and attaches itself to the outside of the zircalloy tubing, and it turns into cobalt-60, radioactive cobalt-60.

So how that CRUD behaves and performs on those assemblies is important to know because right now a lot of people say you need to assume 100 percent of that becomes aerosolized and gets out and contributes to dose. So we are looking at doing some experiments to better quantify what really happens with that CRUD.

So the first objective we show here is to determine whether fuel fines -- and these are the actual centered pellets -- form particle beds inside the spent fuel rods as a result of a mechanical impact. Then if these particle beds form, whether they efficiently filter other particles that pass through them, so that some of these crushed particles then cannot escape out into the environment; whether CRUD particles will spall off spent fuel rod surfaces, and if the rods are subjected to mechanical impacts or thermal stresses, and then what is the size distribution of these released particles? Are they respirable particles or not? Will they settle out quickly? What is the size distribution of these particles that get out?

We have quite a few tests planned for this. This shows one of the testing aerosol chamber. Actually, there's a very good company in Germany that is very good at aerosol physics and testing, to get this kind of data, particle size distribution and those sorts of things. We are actually going to use them to do these types of tests, so that we don't have to replicate them.

This just shows a schematic of one of the test apparatus that will be used to get that data.

MR. KOBETZ: Ken, are you going to use high-burnup fuel or medium-burnup fuel, or does it matter?

MR. SORENSON: Right now we are going to use, the plan is to use regular and high-burnup both and see if there is a difference between those in terms of how they behave.

That, frankly, is one of the issues. In doing the testing, the plan is to do the spent fuel testing at Sandia. One of the ES&H issues is, what happens to that fuel after you do the testing? Can we ship it back to Germany from whence it came? Will they accept it or not? If we keep it here in the United States, who becomes the proprietor of that spent fuel? So those are some of the detail issues that we are working out right now.

Okay, that is the spent fuel testing. I did want to take a little bit of time to cover the expert panel. At NRC's guidance, we formed two expert panels for review of the work that we are doing, and specifically the protocols. One was a structural panel and the other as a thermal panel. We got experts from academia and industry. Well, we had one from the underwriters' company, and we tried to get a very broad cross-section of people. One is the ex-president of ASME International. So we thought we got a very good cross-section of experts. EPRI was another source that we went. We got a very good cross-section of people to look at this and give it a critical review.

The composition: five members on each panel. We vetted this with the NRC. Then on April 10th and 11th, we actually had a review or we actually had some international participation as well. There was a person from Ontario Hydro and then a person from the BAM in Germany who were on the Committee.

We sent the protocols out ahead of time for them to review, and then we had a two-day meeting where they came in and gave us their critical comments on the protocols.

These show the principal results of these reviews. The structural review panel agreed with the basic approach, as was developed in the protocols. One of their recommendations is not only should we conduct an extra-regulatory test, but we should also conduct one regulatory test. This is to tie the testing and analysis and make a hard link from the regulatory regime to the extra-regulatory regimes.

They said the extra-regulatory tests should focus on closure damage, and the drop height should be such that we bottom out the impact limiter. Again, it is specifically for the HOLTEC Hi-Star; it was a very robust limiter. Even for the 60-mile-an-hour impact loading, we did not use the full stroke of that limiter.

So their recommendation was, regardless of what cask you choose, you should configure the design, the test design, such that you bottom out the impact limiter and you achieve closure deformation. What they mean by that is actual plastic deformation of the closure, again, so we can show or demonstrate that we can properly capture cask response under these environments analytically.

DR. LEVENSON: Ken, what was the charge to these panels? Because what kind of recommendations and review, having been on a number of such things over the years, makes a big difference in what kind of recommendations you get, as to what their charge was. How was their charge worded?

MR. SORENSON: Well, let's see --

DR. LEVENSON: Was it to test what really happens or was it to maximize the technical information you would obtain, whether it is directly related or not to safety? I mean, what was the charge to them?

MR. SORENSON: I understand the question. I'm trying to think back, how we worded the actual call letter.

We tied it to the objectives of the Package Performance Study, which was to advance the technology --

DR. LEVENSON: These three that you have here?

MR. SORENSON: Yes, we tied it to that, and I think with special emphasis on the technical aspect, to make sure that the technical aspect was sound, the approach was sound, to do this.

Does that answer your question, Milt? That is basically what we did. Again, the objectives in the Package Performance Study and gave them pretty free reign in terms of -- and we had a lot of discussion in terms of, you know, well, what is the extra-regulatory test? Because the 60-miles-an-hour impact, for example, you get an elastic response onto an unyielding surface? Is that really something that needed to be tested at this point, if you don't show any plastic deformation?

DR. LEVENSON: Well, you know, I could interpret extra-regulatory to say anything from 10 percent more than what's required by the regulations to two orders or three orders of magnitude more than required by the regulations. So I'm not sure I know what this means.

MR. SORENSON: Well, I think if I can bound that a little bit, from the recommendation here, it is that they wanted it to be severe enough that we would actually show closure deformation, plastic deformation.

DR. LEVENSON: That's not what it says. It just says, go beyond what the regulations are.

CHAIRMAN HORNBERGER: But the qualifying

phrase suggests that it is going to have to be five times what the regulatory thing is, because you are not going to get closure deformation unless you go to something like 65- or 70-miles-an-hour.

MR. SORENSON: May I go on?

CHAIRMAN HORNBERGER: Yes, go ahead.

MR. SORENSON: Okay. The fourth bullet is, you know, there was also a lot of discussion on what's a successful test, what's your metric? We haven't completely closed that loop yet, but one of the strong emphases is for the mechanical regime to focus more on deformations as opposed to accelerations and the strains, because of the uncertainties that are involved in some of these measurements for these very severe environments.

For the Thermal Review Panel, again, they agreed on the basic approach. They recommended that we add three additional calorimeter tests because of the wind concerns. You actually go out there and you do the test. If you have a breeze or a wind, it is going to significantly affect the fire environment and, subsequently, the boundary conditions on the cask during these fire tests. So they recommended that we do additional testing under wind conditions with the calorimeters.

Yes?

CHAIRMAN HORNBERGER: Is it likely that having a wind would somehow make the fire worse?

MR. SORENSON: Less worse.

CHAIRMAN HORNBERGER: Yes, that's what I was just saying --

MR. SORENSON: We assume fully engulfing.

CHAIRMAN HORNBERGER: Right.

MR. SORENSON: So it would be less.

CHAIRMAN HORNBERGER: So I am not sure that I see, if you are going to these extreme tests, why do you want to have a wind to make them slightly less extreme?

MR. SORENSON: Well, the point is, we want to demonstrate that we can capture the response analytically. If we have a test where we have a wind condition and we have an analytical condition where it is fully engulfing, they are not going to match. So we want to be able to bound that condition.

Jerry, did you have a comment?

MR. SPRUNG: An engulfing pool of fire is not a well-mixed fire. So the wind may cause more oxygen to enter the flame; it burns hotter, but if it blows the flame away from the cask, then it is less severe. But if it is offset fire and you engulf the cask and it tipped over, wind-driven flame, it could be worse.

MR. SORENSON: Okay. Some of the outstanding issues that are still unresolved: final configuration of the calorimeter and the cask thermal tests; the configuration of the impact tests, but also the cask. Again, as I said at the outset, there's not been a final decision made as to which cask will be used for the test, and with that, what the scale of the cask will be.

There is, I think, some good suggestions that we also do some pre-test predictions on commercially-available codes. To the extent that that is possible, I think that is probably a good idea, and then also possibly do some round-robin analyses as well, to have other analysts analyze these test configurations and see how well we can match the analyses, and give us, again, confidence in the ability to properly capture cask response for these types of environments.

VICE CHAIRMAN WYMER:: Who is qualified to participate in round-robin analyses?

MR. SORENSON: Well, that is something I think we would have to look at and see how we set up that criteria. We haven't done a lot of thinking about that, to be honest with you, but to do this properly we would have to make sure that whatever organization or laboratory did those analyses had the proper experience and educational background to do it properly. We certainly couldn't just give it to anyone out there who volunteered to do it.

CHAIRMAN HORNBERGER: So I noticed on this slide you have scale model tests possible. So are some of the more extreme tests, like 90-mile-an-hour impacts, would you envision doing those with scale models?

MR. SORENSON: No, actually, we envision doing them full-scale. I just put this up here as a caveat, just to make sure that it's stressed that no final decision has been made.

CHAIRMAN HORNBERGER: Wouldn't a scale model test for some of these extreme things make a lot of sense? Wouldn't it save you a lot of money?

MR. SORENSON: Well, yes. We have done a fair amount of scale model testing actually. Again, from public comments we've gotten, there has been a strong indication that people want to see full-scale testing because we really haven't done full-scale testing of rail-sized casks.

CHAIRMAN HORNBERGER: Do you have any

doubts that your scaling laws don't work?

MR. SORENSON: No, I don't personally.

DR. LEVENSON: Is "full-scale" a truck cask or a railroad cask?

MR. SORENSON: Well, Milt, for this particular protocol, the preliminary analysis, it is the rail cask. It is the Hi-Star 100 cask that we are looking at.

Then the final viewgraph here gives some approximate dates that we are looking at in the near-term for the Package Performance Study. For the field testing, we actually have made some good progress in getting started on that, and we plan on doing these testings in the fall of this year.

Thermal testing, the calorimeter test, that is to be determined yet, but we are looking at the cask fire test in the fall of 2004. Then for the impact test, we are looking for that test in the summer of 2004. So the intent is to do the impact test with the cask, and then take that cask, after that impact test, and do the fire test with it.

VICE CHAIRMAN WYMER:: You talk about surrogate pellet impact test. What are your surrogates?

MR. SORENSON: Well, we will use glass,

Pyrex, and also an irradiated UO2 -- or DU, is it DU, Jerry?

MR. SPRUNG: Yes.

MR. SORENSON: I'm sorry, DU.

VICE CHAIRMAN WYMER:: Spent fuel is sort of, it has been irradiated and it is kind of fragmented, and it is not a whole lot like glass.

MR. SORENSON: Go ahead, Jerry.

MR. SPRUNG: The impact facility doesn't like radiation too well, so the impact test will be done with surrogates and then we will go to a facility that can handle radioactive materials and do so bare pellet impact tests where we look at both some low- and high-burnup pellets and compare them to the way the surrogate behave, so that we get some feeling for the differences, if any, between surrogate brittle materials and pellets that have been degraded by radiation.

The available data suggests that most brittle materials fracture fairly similarly, at least in terms of the size distribution you get for impact at any particular speed.

VICE CHAIRMAN WYMER:: It would be 30,000-40,000-megawatt-a-day-per-ton burnup?

MR. SPRUNG: That and some high-burnup,

too, up at 55 to 60.

VICE CHAIRMAN WYMER:: Oh, that high?

MR. SORENSON: That's the plan.

MR. SPRUNG: That's the plan.

VICE CHAIRMAN WYMER:: You will have a hard time finding it.

DR. LEVENSON: Would those tests be done before you use the surrogates in all of the other tests? The context of the question is, do you validate the surrogates before you use them?

MR. SPRUNG: The surrogates are fairly well-validated in a sense already, in that there is some data on fracturing of DUO2, and it fractures quite similarly to -- the centered DUO2 pellets fracture quite similarly to glass. The German scientists who conduct this think that's already, in terms of the precision of risk assessment, well inside the ball park, but we would like to confirm that with the tests on the real stuff.

The order at the moment is conducting tests with highly radioactive materials is never simple, and particularly when we are trying to get some German support for the funding of those tests.

DR. LEVENSON: Was there any consideration to just using unirradiated UO2 pellets?

MR. SORENSON: Was it just DU we looked at or did we consider --

MR. SPRUNG: Fresh -- no, we will use DUO2 pellets in the German tests. When we go to a radiation facility, we will use DUO2 glass and then actual spent fuel pellets.

MR. SORENSON: But, Milt, your question was fresh pellets?

DR. LEVENSON: No, no. My question was, I thought you were using the glass pellets or irradiated UO2.

MR. SPRUNG: No, glass or depleted uranium dioxide in the facility that doesn't handle high radiation. In hot cell tests we will look at a Plene Hammer that is drop-weight tests for fracturing of glass pellets, depleted uranium pellets and high-burnup spent fuel pellets.

DR. LEVENSON: I guess we follow up on Ray's question. We need to ask the same question about the surrogate CRUD. How does it get qualified?

MR. SPRUNG: Do you want me to try that?

MR. SORENSON: Yes, go ahead. This is his specialty.

MR. SPRUNG: The hard part there is the adherence question. We know the chemical formula or range of formulas of surrogate CRUD. We know what its structure is, and it is an inverse spinel. We know how to synthesize this and deposit it onto a zircalloy surface so we get deposits that look like the scanning electron micrographs of real stuff.

What we don't know about the real stuff is actually, how hard is it in some measured way to scrap it off or make it come off a surface? So we have to assume that, if we make something with the right chemical composition and make it form deposits on the surface of zircalloy that has the right morphology, that it will have something like the right adherence.

DR. GARRICK: Where are you going to get your data for the CRUD synthesis exercise? In other words, that's very much dependent upon burnup and a lot of other things.

DR. LEVENSON: The water chemistry.

DR. GARRICK: Yes.

MR. SPRUNG: There were a number of reports that gave the characteristics of CRUD on real fuel rods that were looked at. So we have -- it is all over the map, of course, the surface coverages, but in order of magnitude the variations in the chemical composition, the average is about a nickel point six iron, 2.404 is sort of the average composition of PWR CRUD, and we have figured out how to synthesize that and make it look like the real surface deposits. Whether that is an exact surrogate is problematic.

DR. GARRICK: So you've got a problem of the precursor information being all over the map and then, after the impact tests, the distribution is going to be all the map.

MR. SPRUNG: But, remember, what we are dealing with is trying to answer, does 100 percent come off, 10 percent, or 1 percent?

VICE CHAIRMAN WYMER:: This is all PWR, no BWR?

MR. SPRUNG: Yes, the BWR is usually softer and not quite as -- sometimes not as radioactive because there's not so much nickel in it.

DR. GARRICK: Let me ask a couple of questions about the data. You said, in going from the Modal Study to 6672, you got better estimates for a number of reasons, among which was newer and better data, and you noted, Ken, that you especially got better data in the area of routes. A couple of questions there.

What did 6672 tell you about the sensitivity of risk to different routes, LNT notwithstanding?

MR. SORENSON: The way we looked at the routes was we looked at about 400 total routes between truck and rail and broke those into rural, suburban, and urban segments, and out of that, came up with the representative routes that we used for the risk assessment.

I think what we can say about that is there is not a lot of sensitivity with respect to the final risk estimate. There may be higher accident rates along one specific route, but in terms of the effect of, if you have an accident and release a source term, there's not much sensitivity in the actual route that anybody could select.

I mean, a lot of people raise their hand and say, "Well, what about going down, you know, Highway 287? You're going over a bridge and a chasm, and it goes off the edge and rolls down the hill?" Well, it may be a relatively dangerous route, but from the standpoint of if you have an accident and you have release of material from the cask, it is still a pretty remote possibility that will happen. So you really don't have much effect on the --

DR. GARRICK: So you think you have substantial evidence that it is pretty much routeinsensitive?

MR. SORENSON: Yes.

DR. GARRICK: Route-independent?

VICE CHAIRMAN WYMER:: As far as accidents are concerned, not as fa as radiation is concerned.

MR. SORENSON: Well, as far as -- now you may have higher accident rates on specific routes, but --

DR. GARRICK: No, I think it is the other way around.

MR. SORENSON: Yes.

VICE CHAIRMAN WYMER:: No, it's not.

MR. SORENSON: But what I am trying to say is that, if you do have an accident, it is a higher accident rate route and you have an accident, chances are you are not going to have a release. As I mentioned earlier, the Modal Study said that, looking at all the accidents that have occurred in what we have records in the database, 99.4 percent of them are captured by the regulatory environment, which says that the cask will maintain its integrity.

VICE CHAIRMAN WYMER:: The does to people is much more likely to be from passing by it than it is from releases.

MR. SORENSON: That's right.

VICE CHAIRMAN WYMER:: That would be route-dependent.

MR. SORENSON: That is correct.

DR. GARRICK: That's the chronic dose, yes.

DR. LEVENSON: Was there any measurable or any significant difference between truck and rail, aggregating all of the routes in two different categories?

MR. SORENSON: Jerry did that work; I'll let him respond to that.

MR. SPRUNG: Let me go back, first, to your question. We looked at actually about almost 800 real routes, point-to-point routes, and aggregated the properties of those routes into distributions, and then sampled the distributions to run 200 representative routes. So that the results of the risk calculations give you 200 complementary cumulative distributions. If you've ever seen what Sandia calls a "horsetail plot," if you plot them all, you get a black band.

Now if you look at the X axis down here, the risks are ranging over eight orders of magnitude. I mean, excuse me, the doses, population doses are ranging over eight orders of magnitude, and the risks are going over something like twelve orders of magnitude. The band is about an order of magnitude thick from bottom to top.

Okay, so that in a sense, I mean, if you say an order of magnitude sounds big, compared to how the variation to everything else, the route is not having a big effect.

DR. GARRICK: That's right.

MR. SPRUNG: Now can I have your question again, Milt?

DR. LEVENSON: Yes. If you split that aggregation and aggregated truck versus rail, would the horsetails fall on top of each other or would there be significant displacement?

MR. SPRUNG: My recollection is that the Y intercepts of the CCDF and the band started about the same place, but, of course, the rail cask has much more fuel in it. Therefore, it comes down further off to the right in the plot. Of course, there's far fewer shipments because there's more stuff per shipment, and I don't right off the top of my head know how those two tradeoffs --

DR. LEVENSON: You didn't specifically look at that?

MR. SPRUNG: No. No.

DR. GARRICK: I wanted to ask another data question because I was always struck by the absence in these documents of much reference to the crash tests of 1975 through 1977, or whatever it was. What can you say about the use of the crash test in, say, 6672 or even the modal analysis, the crash test data?

MR. SORENSON: We can use those I think in a qualitative sense. We didn't do a lot of instrumentation on those tests. We had some basic accelerometer data, photometrics, and those sorts of things, but the main purpose of those tests was to get some global behavior of the cask, to help benchmark some early code work that was being done back in the late seventies, and also to look for just gross behavior of the cask, and particularly if there is going to be any gross failure of the cask.

So from that standpoint, how that relates to the Modal Study and 6672, I think we, as engineers, had a good sense that these packages would perform in a robust and sound way, but we weren't able to really take data that we got from those tests and benchmark them to the analysis that we did in 6672 for those early rail tests and those sorts of things.

Jerry, would you agree with that?

MR. SPRUNG: This is a personal opinion.

I think those tests provide a visual demonstration that the cask is hard and the things that are likely to strike it are soft, and if you remember the rail locomotive test, the locomotive just deforms around the cask. Similarly, with the test, I think it was BNFL ran, where they slammed a train into a cask.

If you were trying to use those as a technical basis for a pre-test prediction, we didn't do it back then, and after the fact there wasn't instrumentation available to try it after the fact. So my sense was they generally gave us a sense that real accident environments that are within the credible range, not often these tiny tails that we address in a risk assessment, suggest that the casks are going to survive pretty much unscathed.

DR. LEVENSON: I guess, Ken, I've got to ask you one of your "stop beating your wife"-type questions.

(Laughter.)

You made the comment that in the area of fuel you have very little data and, therefore, you need the tests, but 6672 uses test data. I'm not vouching for how good that data is. I personally think it probably came from studies of reactor accidents. It may not be directly relevant.

But why do you exclude that data? I mean, do you think, like I do, that maybe it isn't the best data?

MR. SORENSON: Well, no, I wouldn't say we exclude it, but we're adding onto it. I think that is the Lorenz data, is that right, Jerry?

MR. SPRUNG: Yes. The --

DR. LEVENSON: I was talking about your comment that there's essentially no data on fuel.

MR. SORENSON: I should say little data.

MR. SPRUNG: There is a lot of data on how brittle materials fracture, and there's a lot of models on how a particle bed filters. None of it, though, applies to spent fuel or to depleted uranium dioxide.

So the question of whether it is obvious that the particles that are present, the fuel fines that are normally in the rod, and the additional ones produced by impact or maybe thermal loads, whether they will form particle beds that will filter, it seemed to us it would be wise to do some tests that showed that the standard and traditional aerosol mechanics that everyone believes actually is applicable to spent fuel rods with spent fuel pellets in them, subject to severe impact loads. We expect, of course, to find that this quite true.

DR. LEVENSON: I understand that, but isn't the material referenced in 6672 based on experimental work at Oak Ridge with real fuel?

MR. SPRUNG: The Oak Ridge Lorenz experiments are all thermal. There is no impact fracturing. Therefore, it is not clear to what degree the release is inhibited by particle bed formation in filtering. So that we wanted to do something that would produce the amounts of particles you would see under a severe accident and then see whether they did do as much filtering as we claimed it did in 6672.

VICE CHAIRMAN WYMER:: Most of those were through pinholes that they deliberately drilled into the cladding, and many of them --

MR. SPRUNG: Or burst rupture under thermal load.

VICE CHAIRMAN WYMER:: And many of them were in steam environments as well.

DR. GARRICK: Have you taken whatever data you can find on particle fines and particle distribution and performed a parametric analysis of what this means in terms of dose calculations? In other words, how sensitive is a dose calculation going to be to these kinds of changes that are going to affect the source term?

MR. SPRUNG: In 6672, using traditional aerosol physics, we assumed that 99 percent of the particles at 10 microns or just below would be filtered out by passage through the particle beds. So that is a one hundred-fold reduction in the source term. That is significant.

Whether the change in the size distribution of the released particles below 10 microns, you know, the respirable range, would have a significant effect we did look at.

DR. GARRICK: Yes. See, what I am getting at is, so what? If you do get a considerable distribution of fines and particle sizes, what does that really mean in terms of what we are concerned about; namely, the doses?

MR. SPRUNG: The thing we are trying to confirm is that hundred-fold reduction that we assumed, based on bed filtration. We believe that is real, but is it really a hundred-fold? Is it tenfold? Is it a thousand-fold? Without some real data for a spent fuel rod with its shrunken gap and crack network, without knowing something about maybe how real pellets fracture for the real pellet tests, we are really trying to confirm that traditional aerosol physics gets us well in the ball park for the reductions in what gets out of the rod due to the bed formation and filtering, not trying to confirm with great precision the size distribution.

DR. GARRICK: Yes, and I think it is pretty clear, the more I read and study this, that what you are talking about here is not going to contribute much to a better calculation of the risk; that you are going to learn something about the thresholds at which these things fail, and at which you might get a rupture of the cask, and at which you might get some redistribution of material within the fuel elements, but as far as a risk calculation, a transportation risk, I am not very optimistic about this program helping you very much.

MR. SPRUNG: Let me try one more. I think we don't know for sure very cleanly. We have a computational result for the strains at which the rods would fail with small tears. If, for example, we would discover that, due to rod flexing, you know, the ability to bend, that the failure speed for tears and cracks was substantially higher than we assumed, we might actually decrease things quite substantially based on what we would learn from the impact test.

I mean, at the moment right now we really don't know, other than by computation and by judgment, again, the speed at which a rod might fail and what the failure might look like.

DR. GARRICK: Yes, but my point is very simple: that the risk is not dependent upon the kind of events you are testing. That is my point. Because those events are going to be so rare and so much in the 10 to the minus 11, 10 to the minus 12, 10 to the minus 10 category, that they are not even going to be a visible contributor to the risk.

So, as we discussed in Sandia, from the science standpoint you are going to learn something, but from the risk of transportation I don't think you're going to learn much of anything. I suspect that if we did a real comprehensive risk assessment with uncertainties, that you would barely see anything in the distribution curves, if anything. That is my suspicion because you're outside the envelope. You're outside of the risk domain.

MR. SORENSON: Except that one point to add to that, though, is you may get fuel failure at lower speeds. Now you won't necessarily get closure opening and source term release, but --

DR. LEVENSON: But fuel failure does not generate any risk or --

MR. SORENSON: I agree.

DR. LEVENSON: You have to get canister failure, which you're completely ignoring, and you have to get --

MR. SORENSON: If the containment is sound, you won't --

DR. LEVENSON: You have to have an expelling mechanism to distribute it and, unlike reactor accidents, there's not much in the way of stored energy inside a cask for a dispersal mechanism. So the release from the fuel pin per se would not lead to dose.

MR. SORENSON: I agree. It has to have a way to get out.

DR. LEVENSON: Well, the canister, out through the cask, and there has to be a mechanism to disperse it. A hole isn't enough.

CHAIRMAN HORNBERGER: Another way to look at it is, suppose your filtration factor were 10 instead of 100, would it affect your risk? Our suspicion is no. So doing the experiments to learn whether it's 10, 100, or 1,000 doesn't make any difference to risk.

MR. SPRUNG: If I go back to 6672, increase all my source terms by a factor of 10, then my risks will all go up by a factor of 10. If I add a canister in there, then I suspect my risks go to zero because I suspect -- you know, we didn't have a canister in that study, and we don't see a very good way to fail a canister. That's one of the reasons, of course, that the NRC thinks we should be looking at canisterized casks in the Package Performance Study.

CHAIRMAN HORNBERGER: Right.

MR. SPRUNG: Whether it's obvious in advance of doing any testing that you can't fail a canister --

CHAIRMAN HORNBERGER: But suppose your risk does go up by -- suppose it is linear. Suppose it goes up by a factor of 10. Does that tell you that it is unsafe? I mean, you went down, what, two orders of magnitude or three orders of magnitude from your Modal Study, but the Modal Study didn't suggest that it was unsafe. Now you're saying, "Oh, now we'll go back up by a factor," and who cares?

MR. SPRUNG: I think the question of whether you try to show it is that your best current ability to analyze shows that it is still lower, whether that is worth doing is a choice I think NRC has to make, not the technical person.

CHAIRMAN HORNBERGER: But it's not based

on risk.

DR. GARRICK: Yes. See, it's another example of where the risk-informed perspective is not dominating the decisionmaking process.

DR. LEVENSON: Okay, Ray, questions?

VICE CHAIRMAN WYMER:: I wouldn't touch any of this.

(Laughter.)

DR. LEVENSON: John?

DR. GARRICK: No, I think I'm finished.

DR. LEVENSON: John?

DR. GARRICK: No, fine.

DR. LEVENSON: Okay. Well, I want to thank both you guys for coming, and getting from Albuquerque to here is no easier than getting from here to Albuquerque. We've done that.

MR. SORENSON: You did it last week.

(Laughter.)

DR. LEVENSON: So thank you very much.

MR. SORENSON: Thank you for your attention.

MR. SPRUNG: Yes.

DR. LEVENSON: I turn this back over to you, George.

CHAIRMAN HORNBERGER: Yes, my thanks as

well. That was very good.

MR. SORENSON: Thank you.

CHAIRMAN HORNBERGER: Excellent.

MR. MAYFIELD: Mr. Chairman, if I might?

CHAIRMAN HORNBERGER: Oh, I'm sorry.

MR. MAYFIELD: I'm the Director of the Division of Engineering Technology and Research, and the Package Performance Study is being managed out of my Division. There were a couple of points we wanted to make sure didn't get lost with the Committee or in the record.

We wanted to re-stress the point that Ken had made that the protocols are going to be published for public comment. They are going to be out late this month, and will be out through September. It is a 90-day public comment period.

We are looking specifically for input on things like choice of cask to be tested, impact speeds, the fire test parameters. We are then going to hold some public meetings in both Nevada and here to seek public comment on this.

As Ken pointed out, the test protocols are an initial proposal. We are keenly interested in stakeholder input on the nature of the tests and the specifics and the protocols. Once we get that public comment, then we will finalize the test plan and move forward, but we did want to make sure that everyone understood that this is an initial proposal that is going to be put out for public comment.

DR. GARRICK: Yes, one of the concerns that the Committee has, I know, about this is that we don't want to find ourselves engaged in a program that results in a high likelihood of a ratcheting phenomena. In other words, it would be unfortunate if out of this came a requirement for changing the regulations, increasing the tests, and doing something that made transportation risk and outlier from a risk-informed regulatory point of view from other activities that you regulate.

MR. MAYFIELD: I understand.

DR. GARRICK: And you know, when you're dealing with the public and you talk enough about something, there's a tendency to think that that something should be the basis for the rules. I think we have to be very careful about that. I think that if we are going to do that, it has to be appropriately characterized. That's why we made the distinction in our discussion between something for the purpose of better understanding the risk and something for the purpose of better understanding the science.

MR. MAYFIELD: I think that is an important point, and it was the second thing I wanted to emphasize. There was a lot of interesting dialog about the fuel piece of this and the risk considerations. The test we have asked Sandia, the primary focus for the structural interest, the structural test goes to being able to provide some validation for the computer codes that are used in analyzing the casks and to take that beyond the linear elastic regime, where I think everyone is convinced the computer codes work just fine.

There are a lot of us convinced the computer codes will work just fine beyond that, but the fact is we don't have the large-scale demonstration tests using modern-sized casks to demonstrate that fact. That was the driving interest in going into these tests, as opposed to evaluating any specific cask design or any particular beyond-design-basis, or they call it extra-regulatory conditions. It is to get enough velocity, enough energy into the cask so that you do, in fact, take it beyond the linear elastic regime.

DR. LEVENSON: The question I have is, if in the real world no accident, no case is going to take it there, why do we need to increase our understanding of it?

MR. MAYFIELD: Well, I think that Ken pointed out you begin to be out in the tails of the distributions, and I'm not sure you can say with absolute certainty that no accident will take you beyond those --

DR. LEVENSON: No, but we have a basic philosophy that says, somewhere out on the tail there's a cutoff and we'll quit worrying about it.

MR. MAYFIELD: And the issue is to evaluate the computer codes, to make sure that as we're evaluating other designs and other conditions, that those computer codes have an experimental basis, that we can demonstrate our ability to do those calculations.

DR. LEVENSON: Why don't we do a cask test at 250 miles an hour?

CHAIRMAN HORNBERGER: It's too far out on the tail.

(Laughter.)

MR. MAYFIELD: It's too far out on the tail.

DR. LEVENSON: No, but that's my whole point: How far out on the tail? It seems to me that --

CHAIRMAN HORNBERGER: I knew that was your point.

DR. LEVENSON: -- this is kind of an arbitrary --

CHAIRMAN HORNBERGER: I knew that was your point. You made your point very well.

(Laughter.)

MR. MAYFIELD: Well, again, I think that's part of your point, is why we're seeking public comment on the test protocols and stakeholder input, and, obviously, input from this Committee will be of interest to us.

MR. SORENSON: If I may interject real briefly, one example, Milt, to answer your question, is there's been some discussion about looking at accidents that do not involve the limiters, a back-breaker accident, if you will, where the cask is impacted in the middle of the cask, and a non-limiters example is a bridge abutment. If we can go to the point where we do this test and we can demonstrate that we can capture the response in the elastic-plastic regime for one case, we can say, you know, we can analyze that and we're confident that we can get the response of that cask analytically; we don't have to do a test for every scenario that you can think of that might cause plastic deformation of the cask body.

DR. LEVENSON: But I guess, with the matter of how sensitive is this as a public issue, it seems to me that you could do the same thing by making a test vehicle that would be substantially cheaper than a commercial cask and one that you can design specifically to maximize the data you're going to get to validate a code. My guess is that an actual cask is not your first choice for a test vehicle, if primarily what you want to do is validate the code.

MR. MAYFIELD: If I could, coming from a research and large-scale experimental background, I can assure you I could design a test vehicle that would answer the question. However, the public interest is not being addressed by that kind of test vehicle, and that becomes a very important consideration.

DR. LEVENSON: But the public issue is answered by testing up to maximum probable conditions. When you go way beyond, that is not answering the public question.

MR. MAYFIELD: Well, I think the characterization of "way beyond" is what we're looking for some feedback on, and I think there is a range of views about how far is too far.

DR. LEVENSON: Well, you know, some of the tests, preliminary test protocols for fuel go up to 150 miles per hour, and that's pretty far beyond.

MR. MAYFIELD: Again, that is why we are seeking some stakeholder input.

(Laughter.)

CHAIRMAN HORNBERGER: I said, tongue-in-cheek, to my colleagues, I guess over lunch, that I really am glad that you folks weren't in charge of designing the Verrazano-Narrows Bridge.

(Laughter.)

Any other comments?

(No response.)

Okay, we're going to break here. We'll go off. We don't need to be on the record any longer. Let's take a 10-minute break and reconvene. We'll talk about some letters.

(Whereupon, the foregoing matter went off the record at 5:20 p.m.)

CERTIFICATE

This is to certify that the attached proceedings before the United States Nuclear Regulatory Commission in the matter of:

Name of Proceeding: Advisory Committee on Nuclear Waste (135th Meeting)

Docket Number: N/A

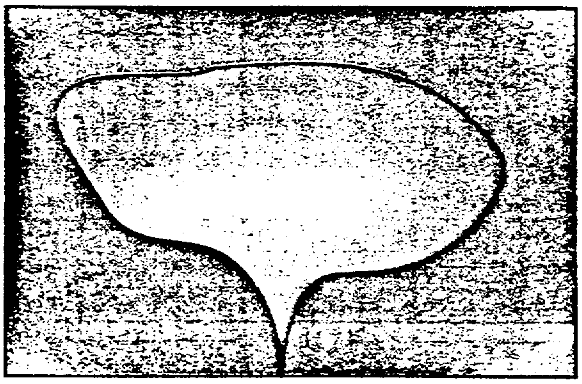
Location: Rockville, Maryland

were held as herein appears, and that this is the original transcript thereof for the file of the United States Nuclear Regulatory Commission taken by me and, thereafter reduced to typewriting by me or under the direction of the court reporting company, and that the transcript is a true and accurate record of the foregoing proceedings.

Rebecca Davis

Rebecca Davis
Official Reporter
Neal R. Gross & Co., Inc.

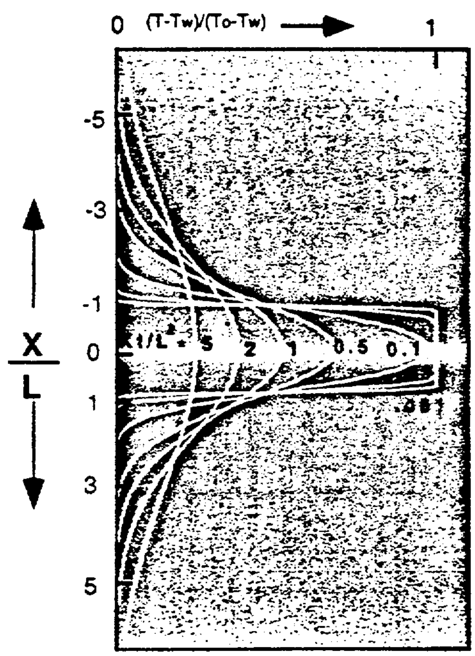
1. Initially Crystal Free (Superheated?)

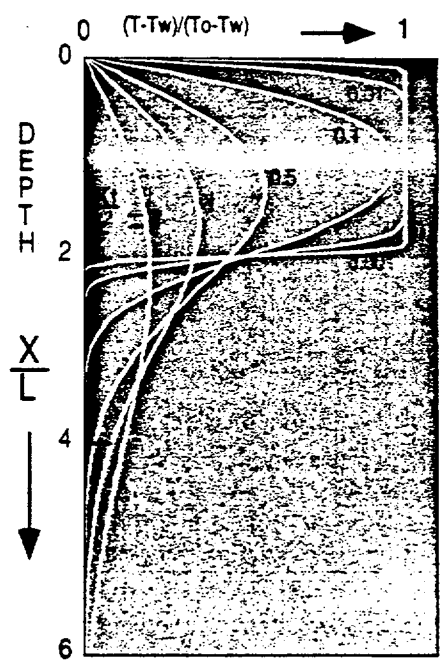


Not in Magma made of Lava

Perhaps only in Impact Sheets

2. Cooling Mainly from Roof





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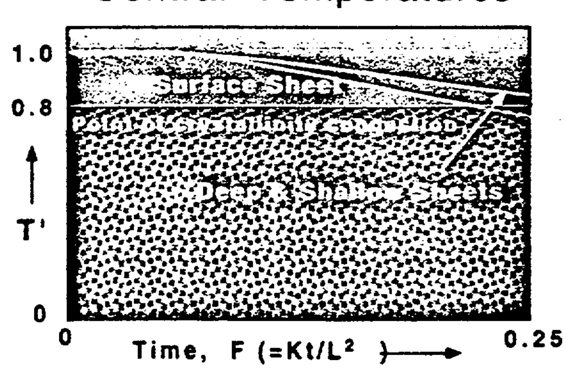
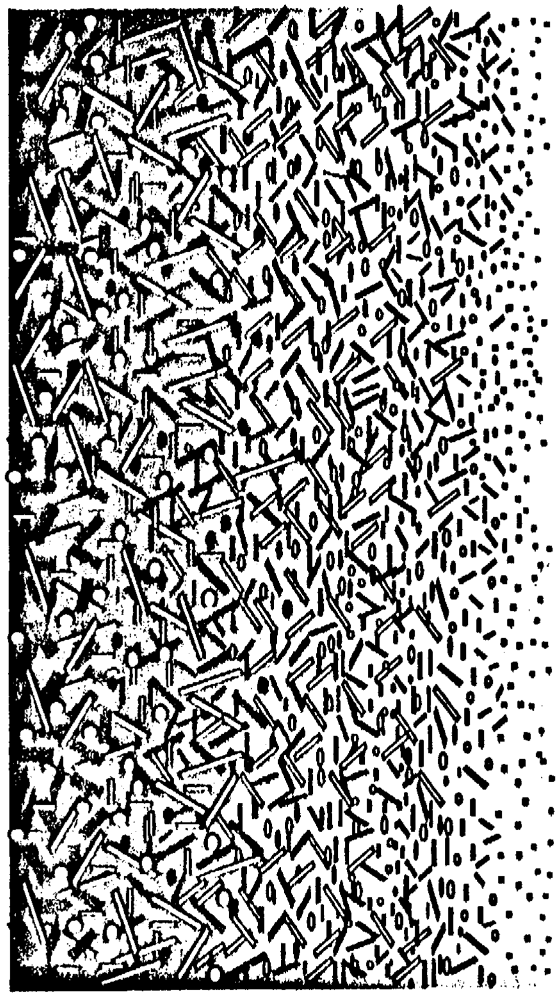
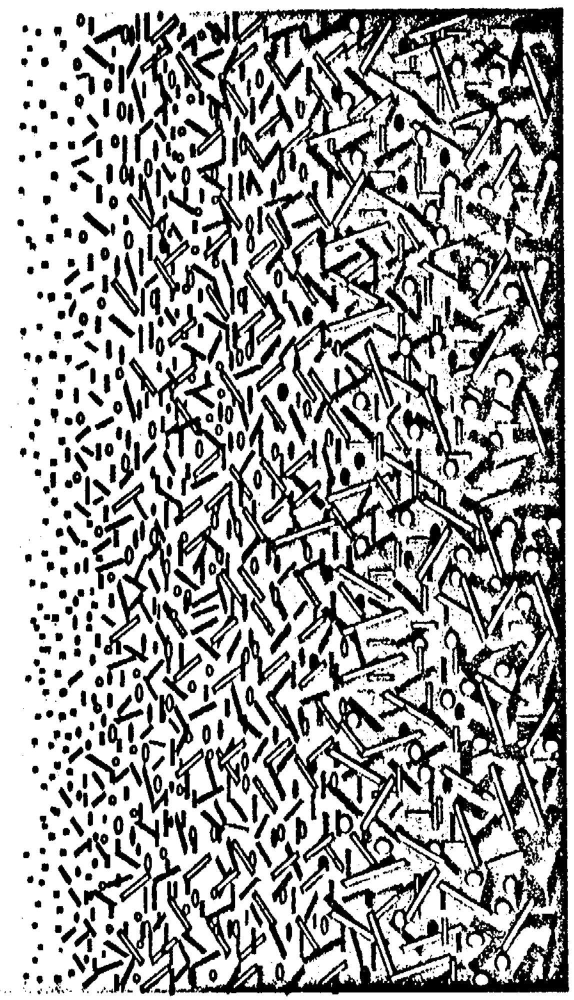
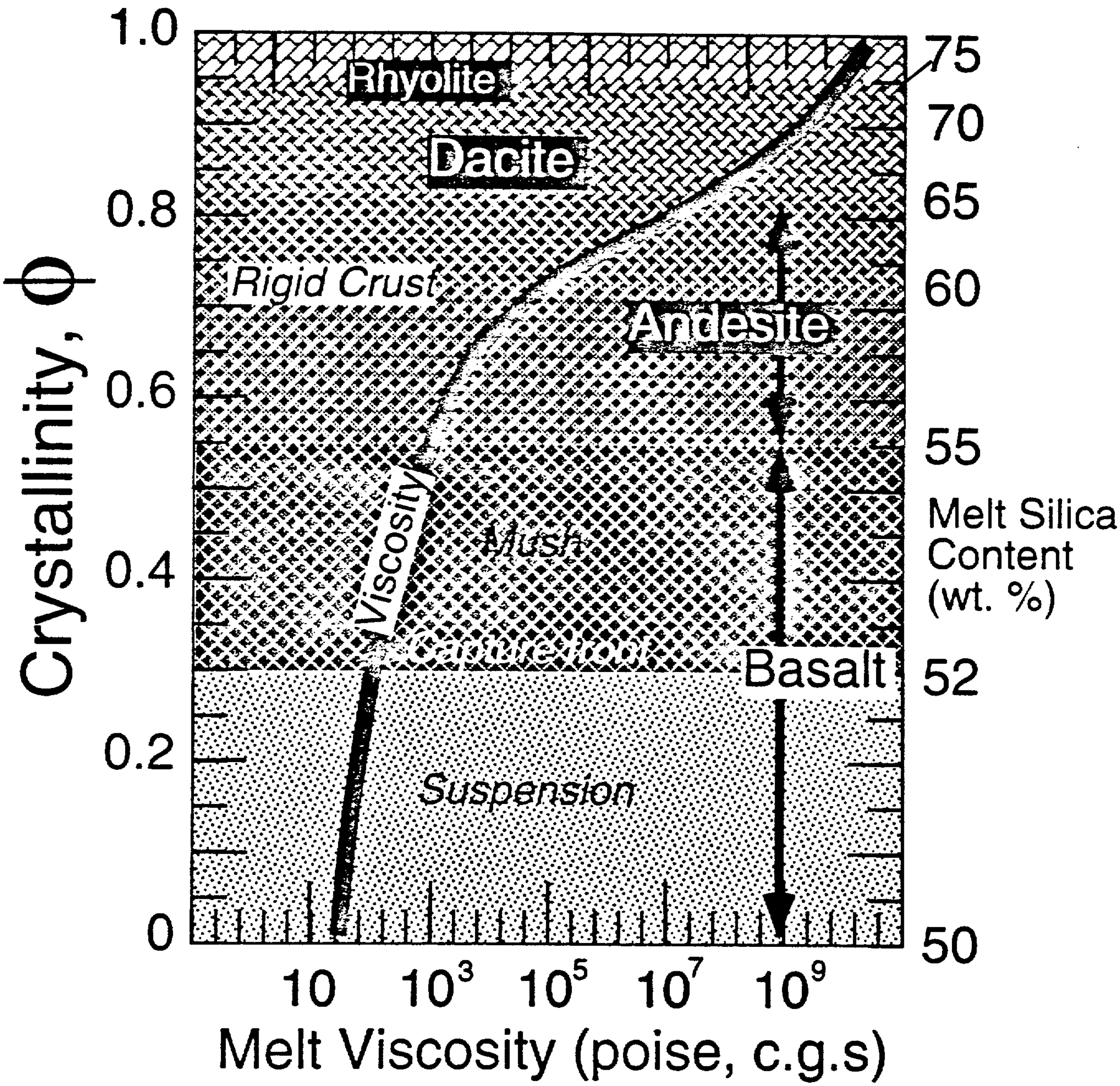


B. Marsh
135th ACNW Mtg






Rhyolite
Dacite
Rigid Crust
Andesite
Viscosity
Mush
Basalt
Suspension
1.0
0.8
0.6
0.4
0.2
0
Crystallinity, Φ
75
70
65
60
55
52
50
Melt Silica Content (wt. %)
10
10^3
10^5
10^7
10^9
Melt Viscosity (poise, c.g.s)

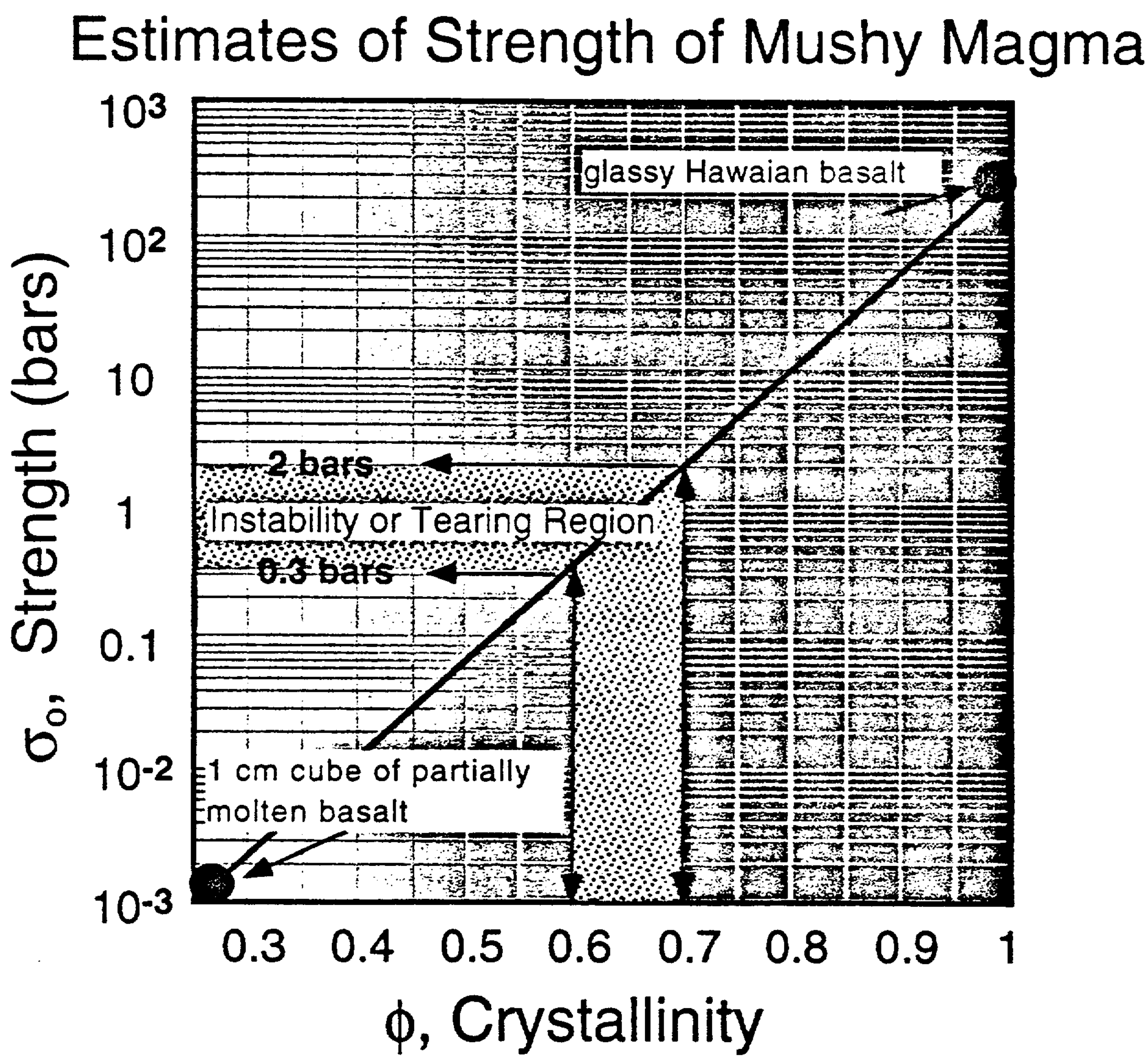
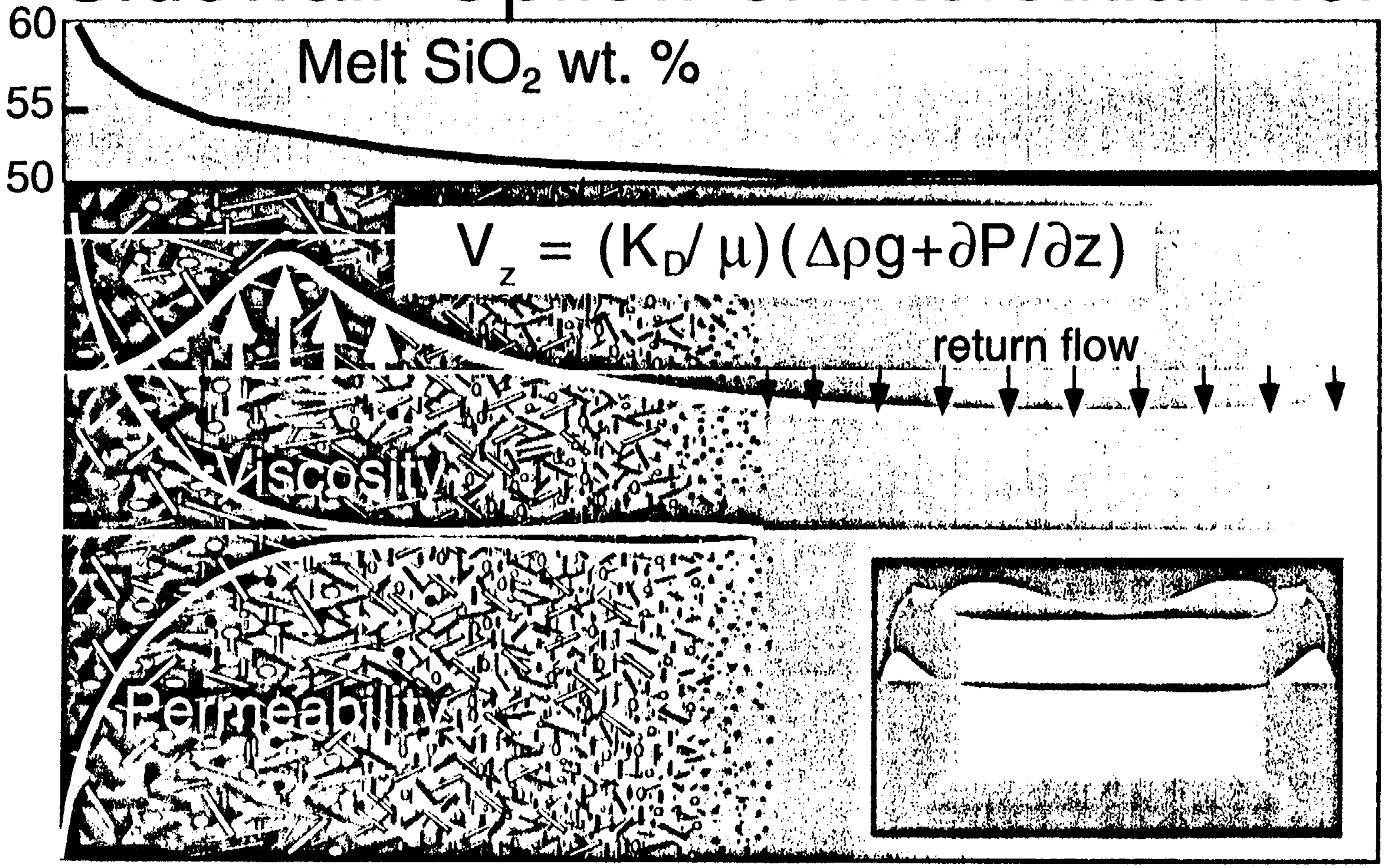
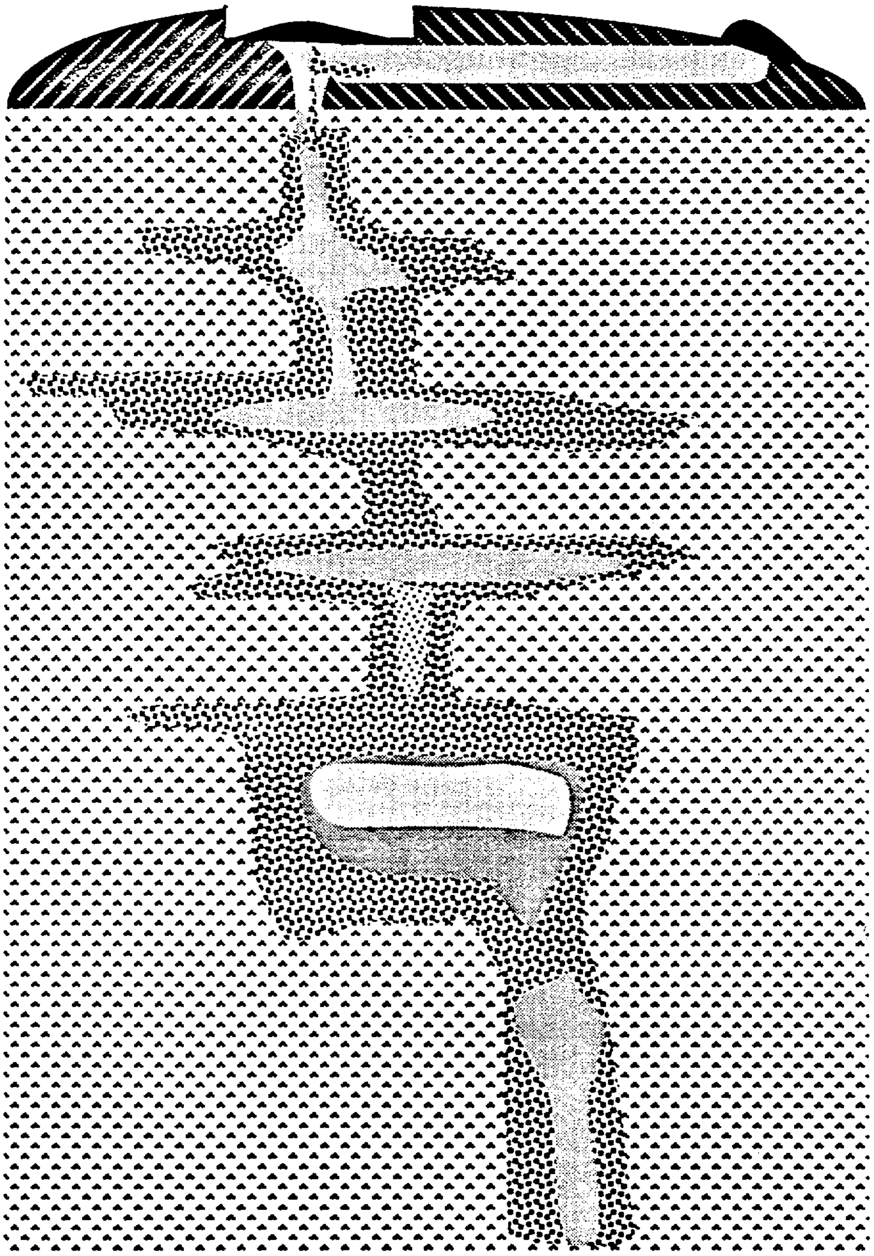


Figure 6: Estimates of the strength of partially molten rock through the crystallization interval. The three regions where something is known of the strength are indicated, and the log-linear line through the diagram is largely hypothetical.

Sidewall Upflow of Interstitial Melt



MUSH COLUMN



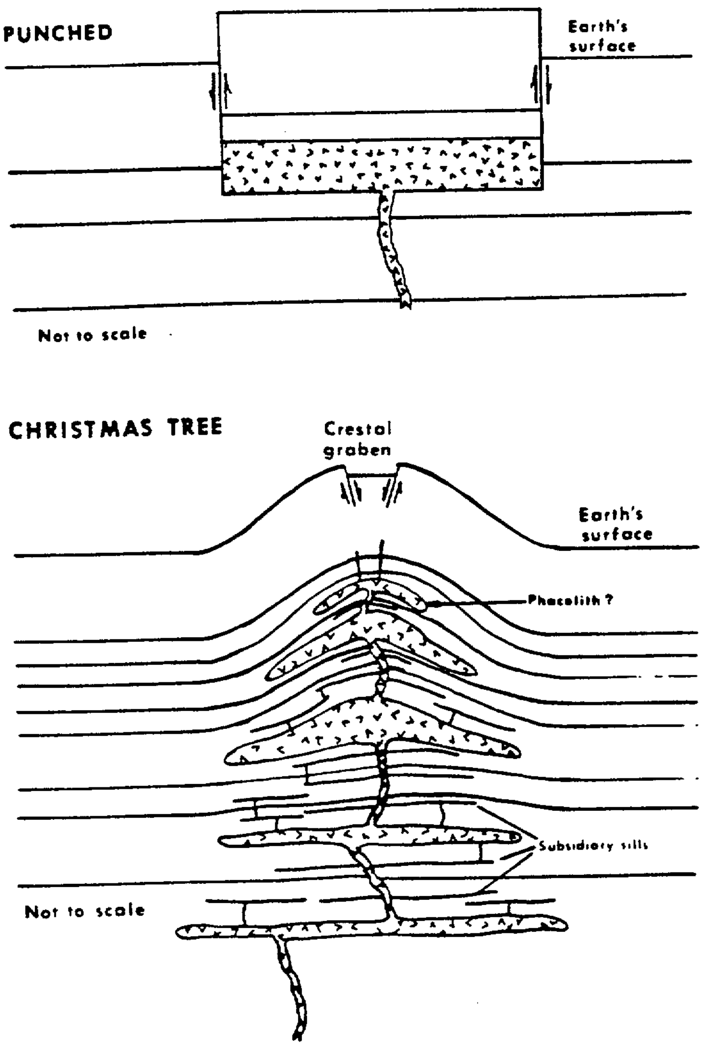


Figure 8. Punched and Christmas-tree laccoliths.

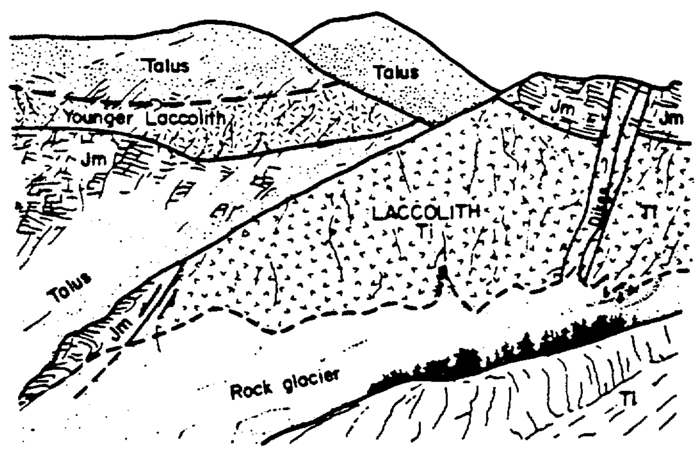
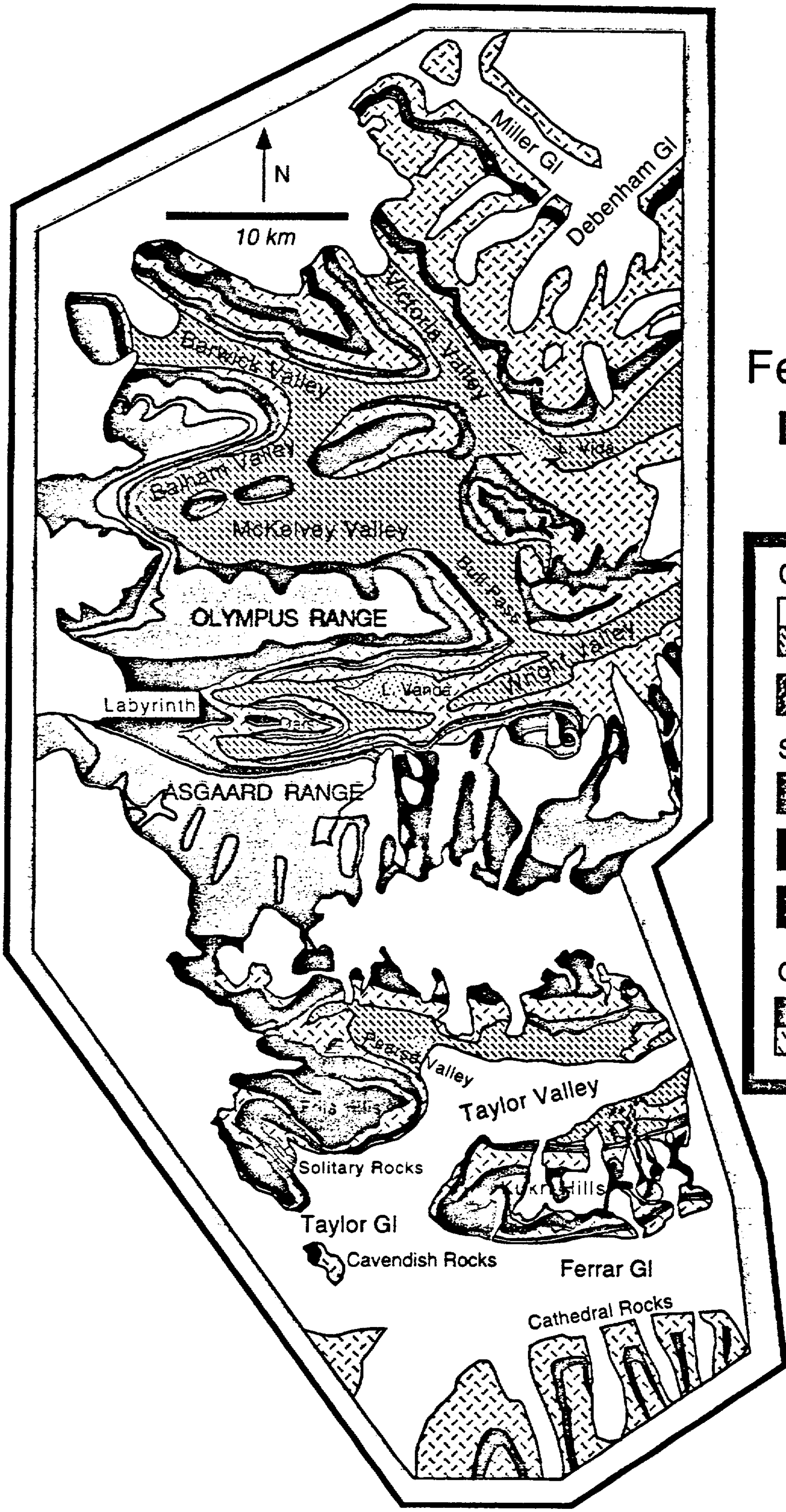


Figure 9. The Mount Peale–Mount Tukuhnikivatz laccolith at the head of Brumley Creek above Gold Basin in the La Sal Mountains, Utah, is an example of a punched laccolith. The small laccolith exposed in the ridge to the left postdates the Mount Peale–Mount Tukuhnikivatz laccolith and bends upward as it approaches the larger, earlier laccolith. View is looking northeast from the north flank of Mount Tukuhnikivatz.

uous series of possible shapes between two distinct end members: punched and Christmas-tree laccoliths (Fig. 8). Gilbert's ideal laccolith (Fig. 1) falls between these two end members.

Punched laccoliths are characterized by small deformation of the overburden beyond the periphery and the development of large-scale shear fractures (slip planes) at, or near, the periphery. The concept was first expressed by Paige (1913, p. 544). Punched laccoliths are associated with elastic-plastic rock behavior, and such rheology is usually only found in the epizone. In the field, punched laccoliths are recognizable by their flat tops, peripheral faults, and steep sides. One example of a punched laccolith is the Mount Peale–Mount Tukuhnikivatz laccolith (Fig. 9) in the La Sal Mountains, Utah. Punched laccoliths are often referred to in the literature as bysmaliths. Unfortunately, the term bysmalith is also associated with an invalid hypothesis regarding the role of magma viscosity in the mechanical deformation of the roof, and I favor abandoning the term.

Christmas-tree laccoliths are characterized as domes with no peripheral faults, and the beds overlying the intrusion are continuous across the laccolith. If doming has continued far enough, a crestal graben may have formed. Otherwise, the extension over the dome has been accommodated entirely by ductile deformation of the beds. A mechanical model for the formation of Christmas-tree laccoliths within the epizone is presented. However, plastic rheology within the mesozone favors formation of Christmas-tree laccoliths. An excellent example of the smooth dome associated with a Christmas-tree laccolith is Green Mountain near Sundance, Wyoming (Fig. 10). The igneous intrusion is



Preliminary
Geologic map

Ferrar Dolerites
Dry Valleys, Antarctica

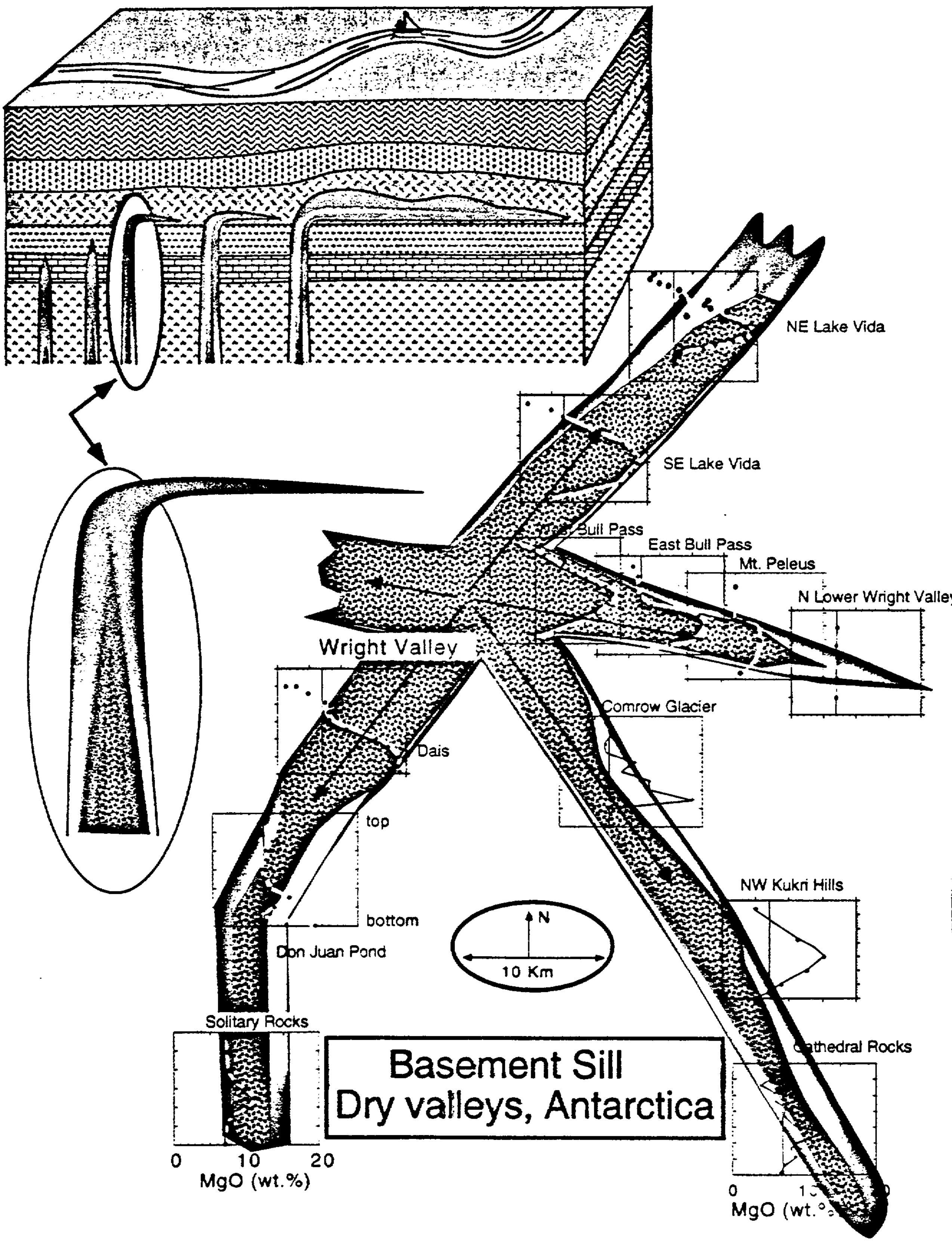
Cover
- Ice
- Rock
- Young basalts

Sills
- Upper Sills
- Labyrinth Sill
  Peneplain Sill
- Basement Sill

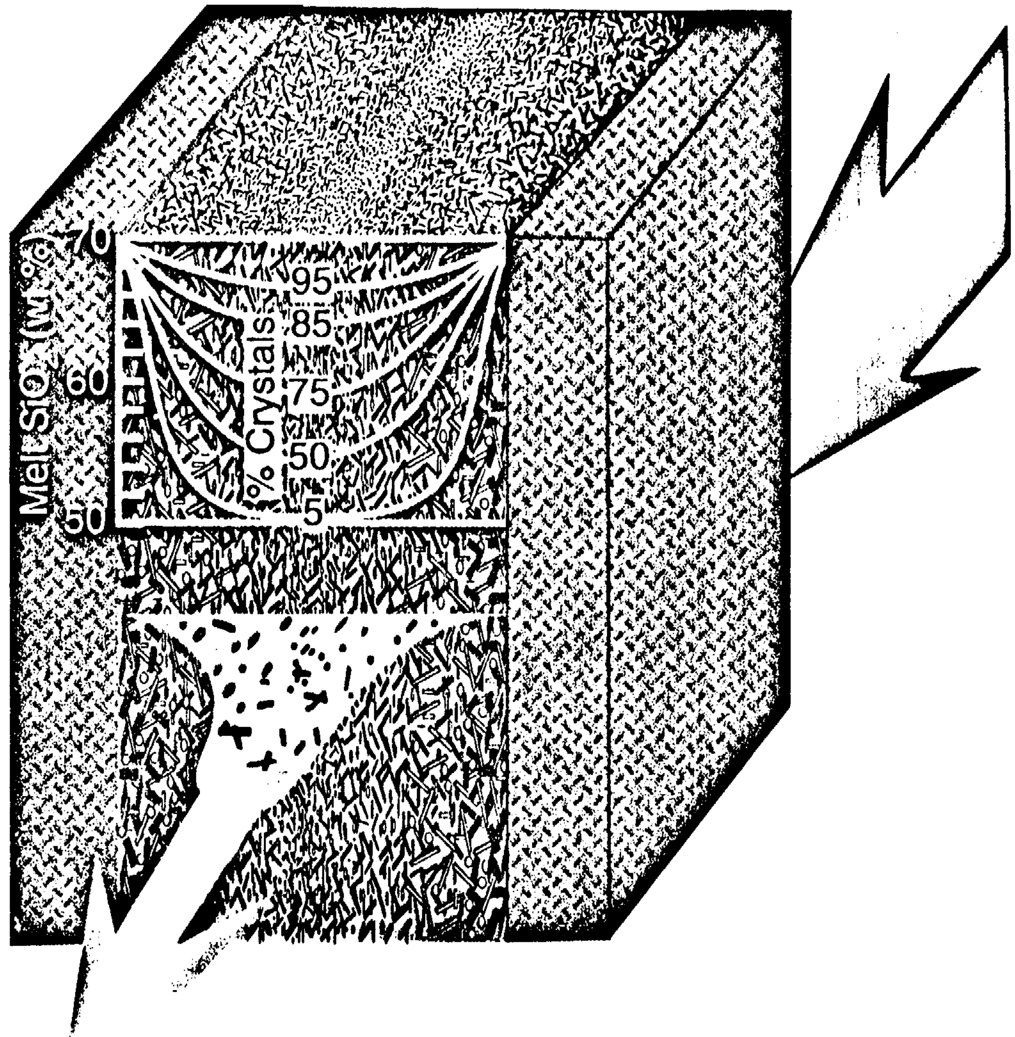
Country Rock
- Beacon Sandstones
- 'Granite' & Dikes

B. D. Marsh & M. J. Zieg
Dept. Earth & Planetary Sciences
Johns Hopkins University
Baltimore, Maryland 21030

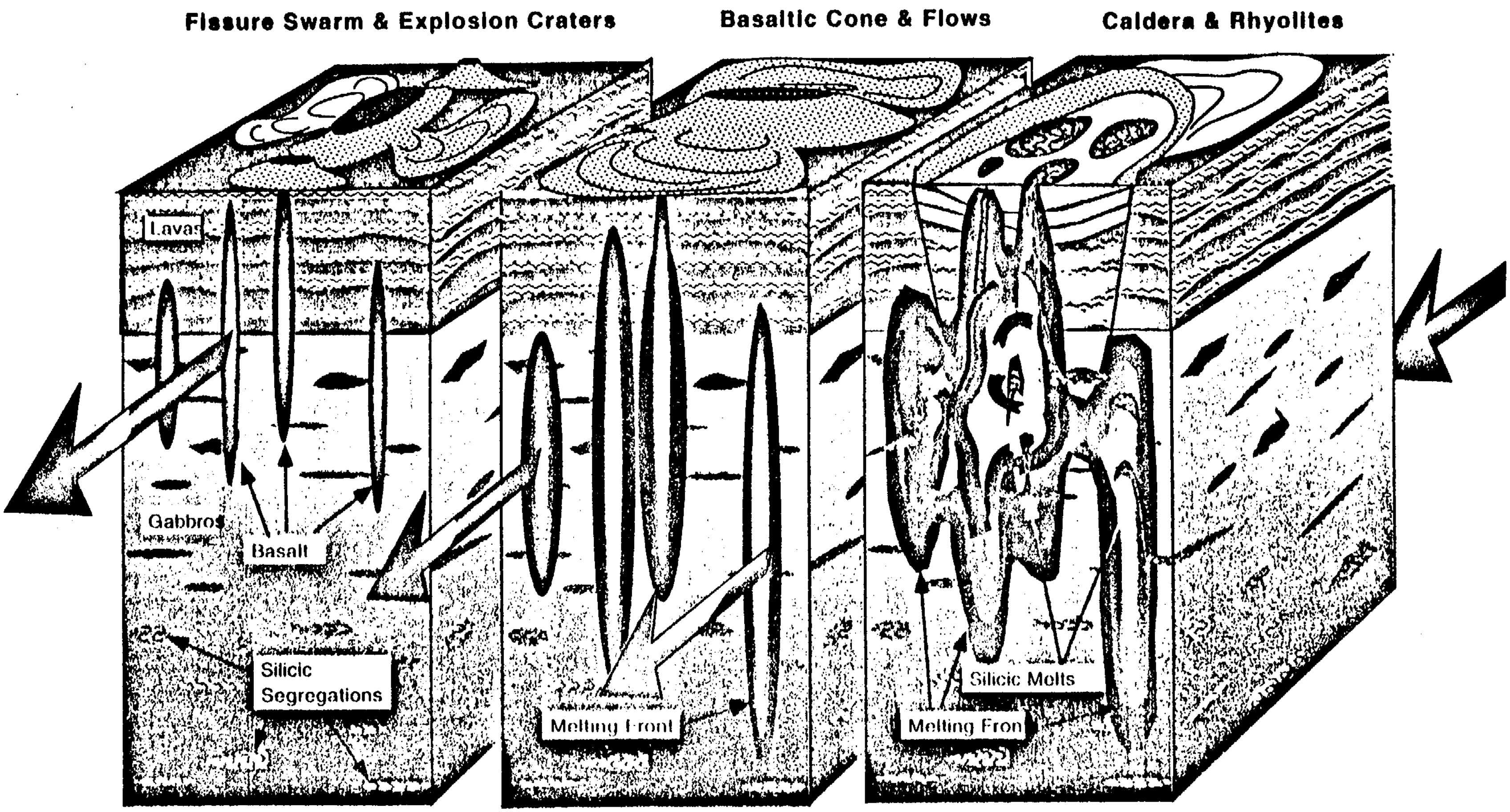
1999


NE Lake Vida
SE Lake Vida
East Bull Pass
Mt. Peleus
N Lower Wright Valley
Wright Valley
Comrow Glacier
Dais
top
bottom
Don Juan Pond
NW Kukri Hills
N
10 Km
Solitary Rocks
Cathedral Rocks
0
10
20
MgO (wt.%)
Basement Sill
Dry valleys, Antarctica

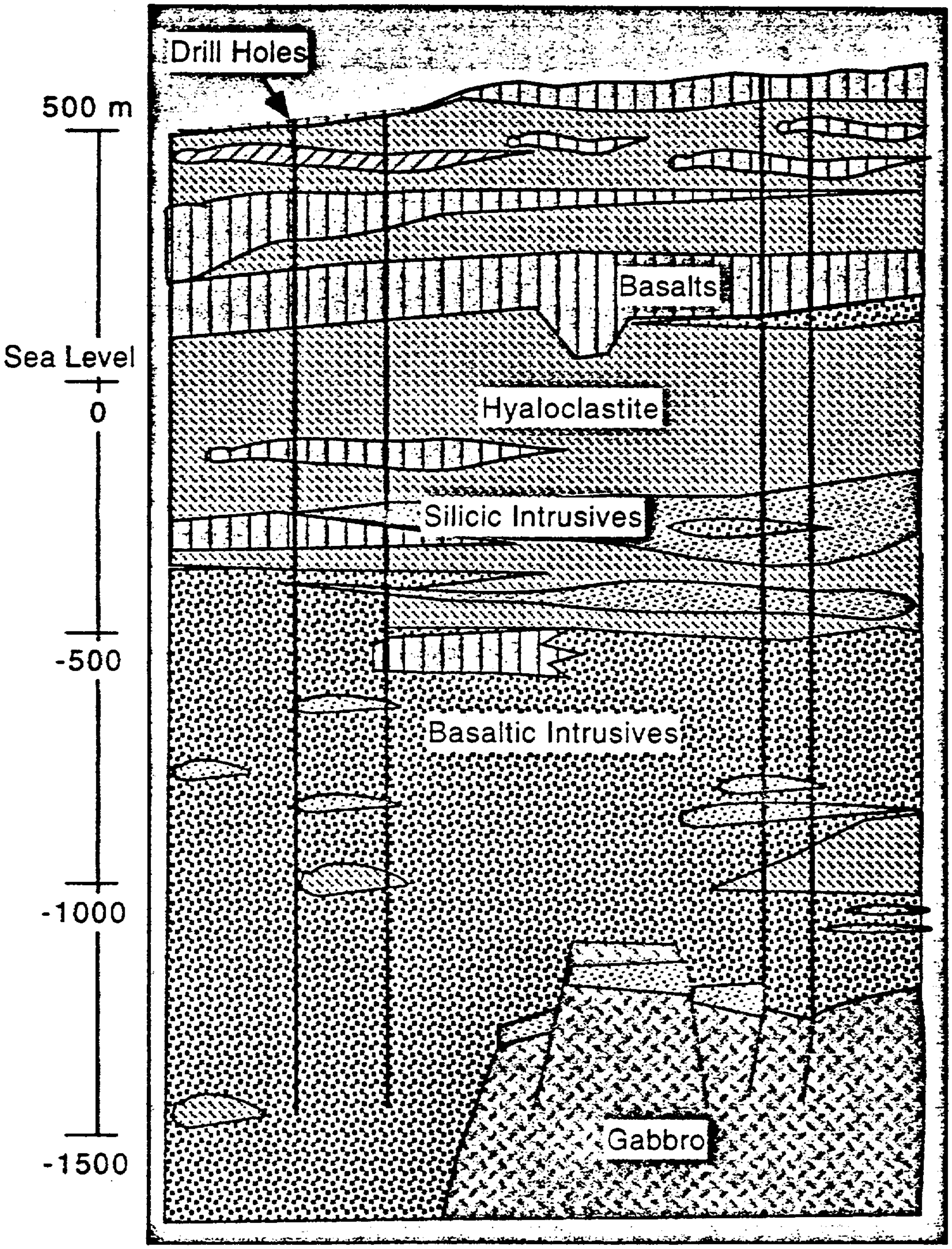
Interstitial Melt Flushing by Fresh magma



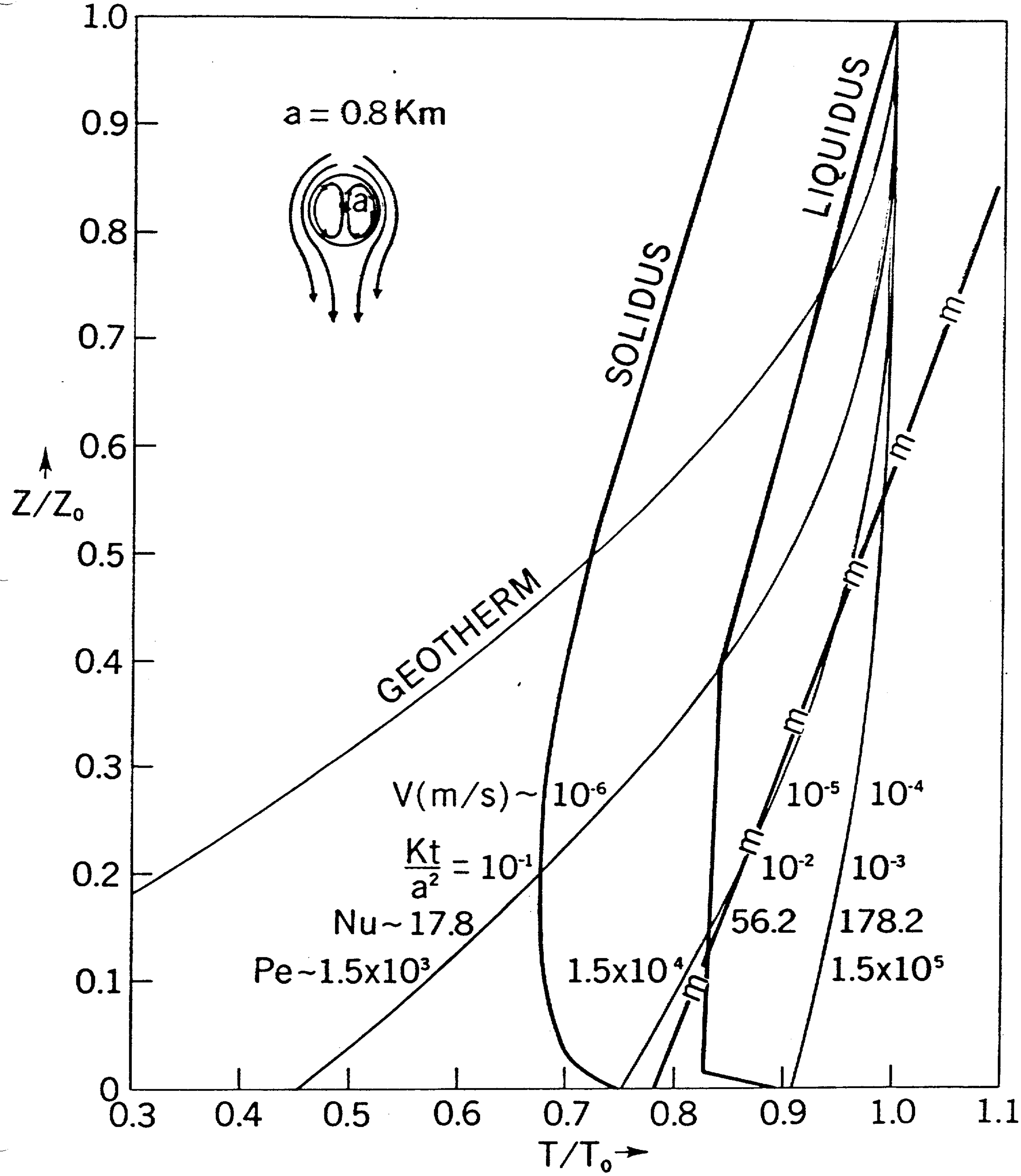
Generation of Rhyolitic Magma in Iceland Through Reprocessing of Older Crust



Iceland Crust



Leirbotnar - Suδurhliδar (Krafla) Region
(H. Armannsson et al., 1987, Jokull, no. 37, p 13)


a = 0.8 Km
a
SOLIDUS
LIQUIDUS
GEOTHERM
V(m/s) ~ 10-6
10-5
10-4
Kt/a2 = 10-1
10-2
10-3
Nu ~ 17.8
56.2
178.2
Pe ~ 1.5x10³
1.5x10⁴
1.5x10⁵
m
Z/Z₀
T/T₀
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1

Shock Wave Models & Igneous Activity

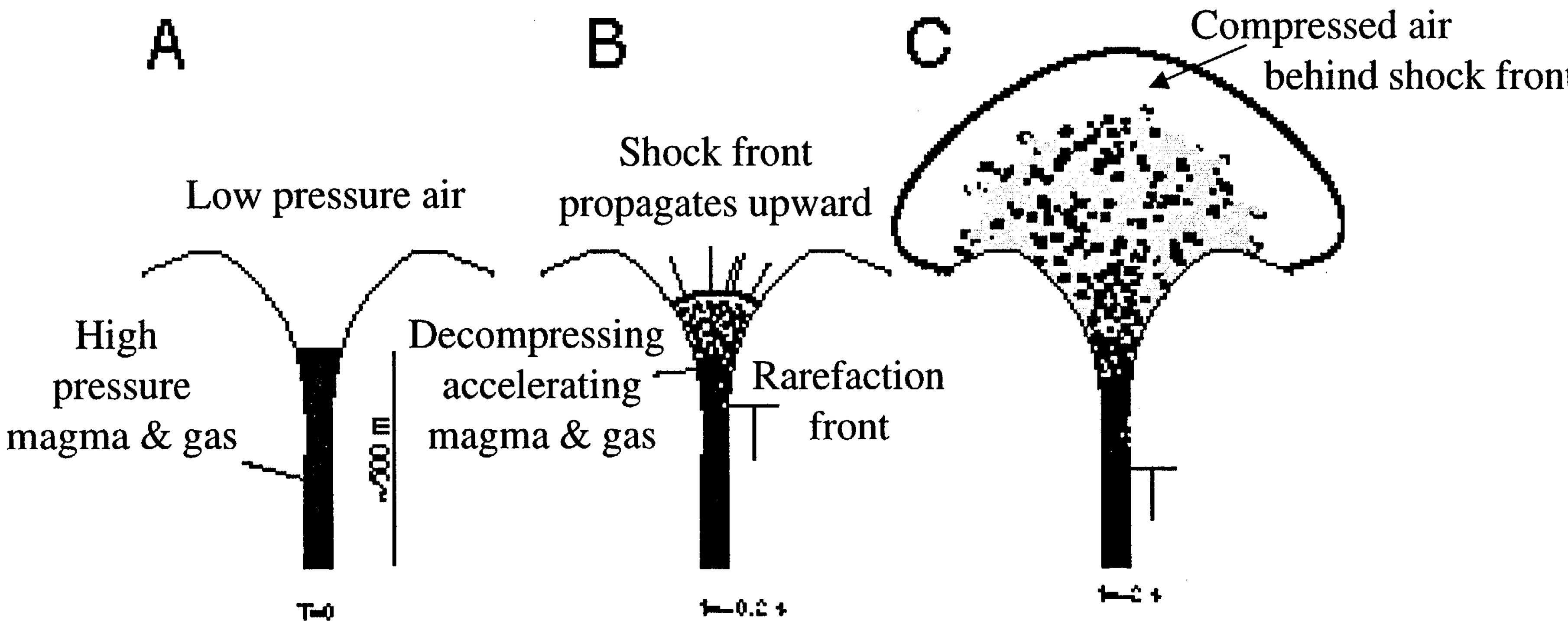
Meghan Morrissey

135th ACNW Meeting

June 18-20, 2002

- Shock waves in volcanic environments
- Shock tube mechanics
- Review of Bokhove and Woods model
- Comments and recommendations

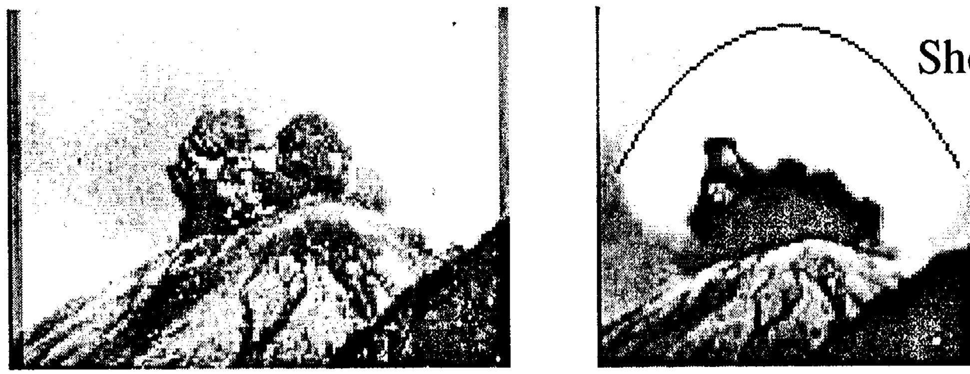
Shock waves in volcanic environments



Examples

Ngauruhoe Volcano, NZ 1975
time lapse 0.5 sec

1975
@
Ngauruhoe, NZ



1995
@
Ruapehu, NZ

Examples of recorded air shocks.

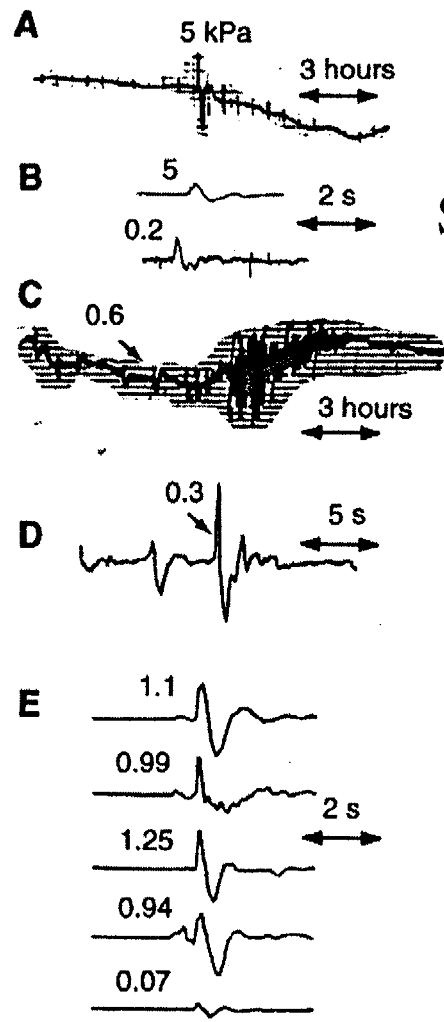
Mount St. Helens 1980

Sakurajima, Japan 1989

Mount Pinatubo 1991

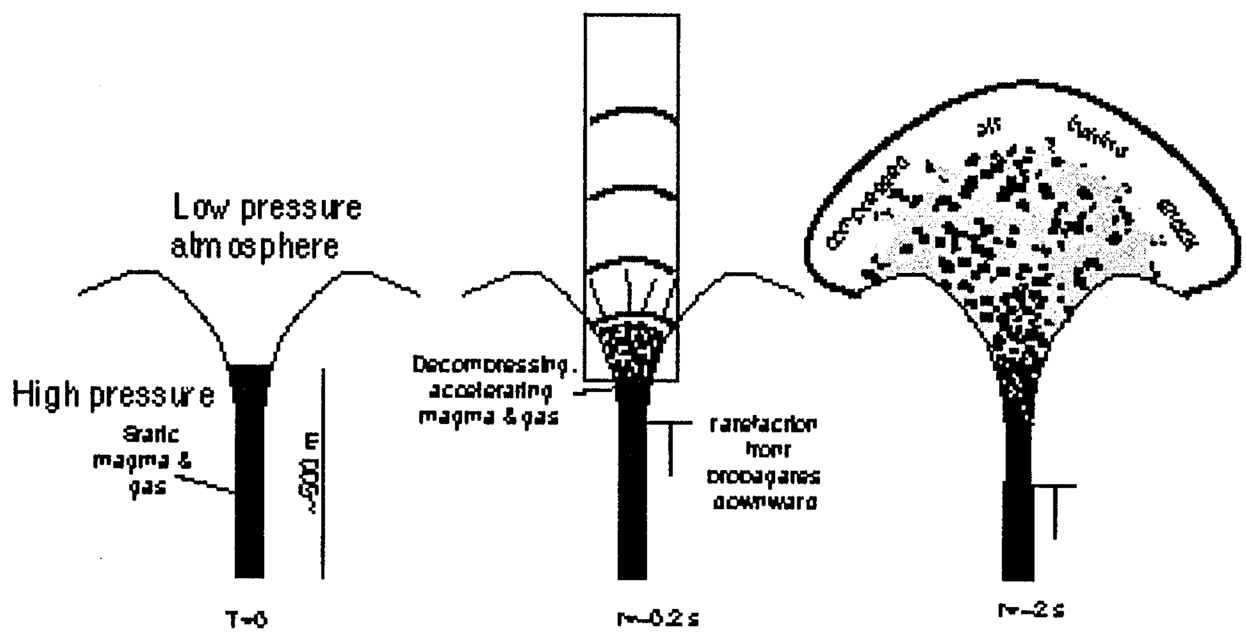
Ruapehu, NZ 1995

Mount Tokachi, Japan 1988

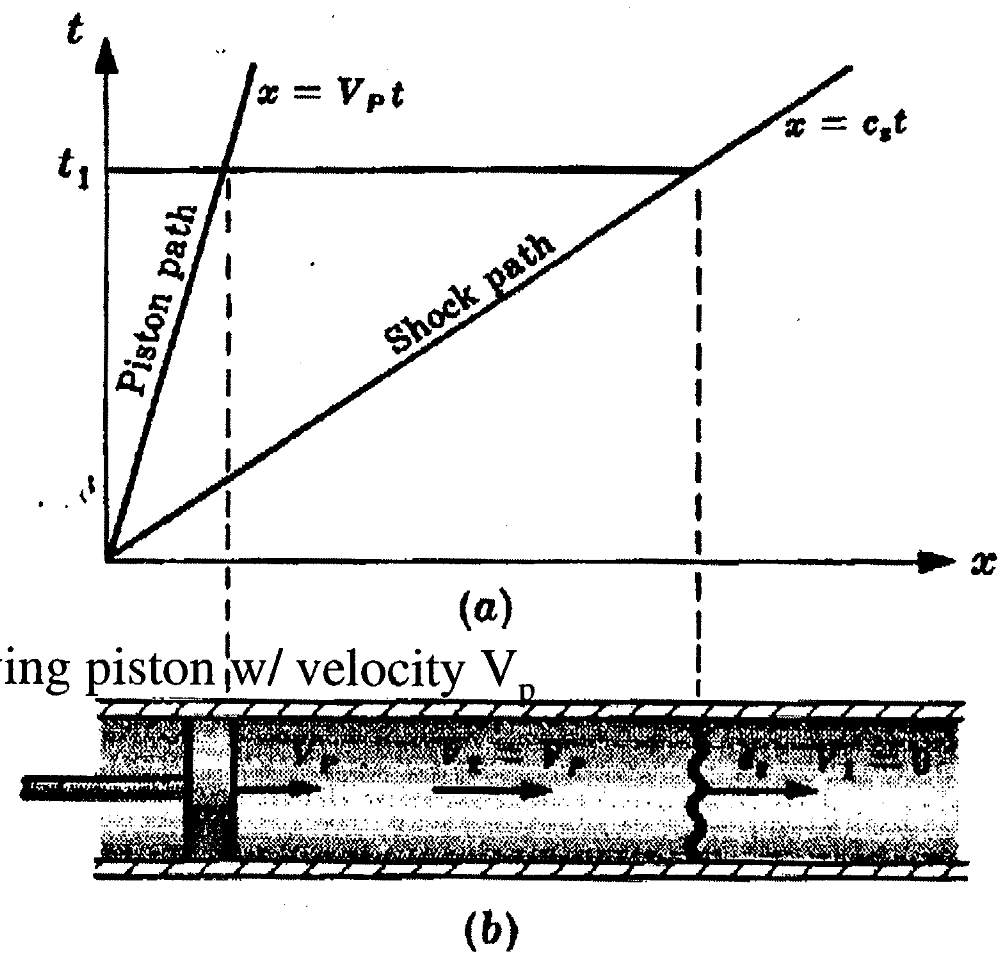


Bokhove and Woods Model

Trap air shock inside a tunnel or tube.



Shock tube mechanics 1-D



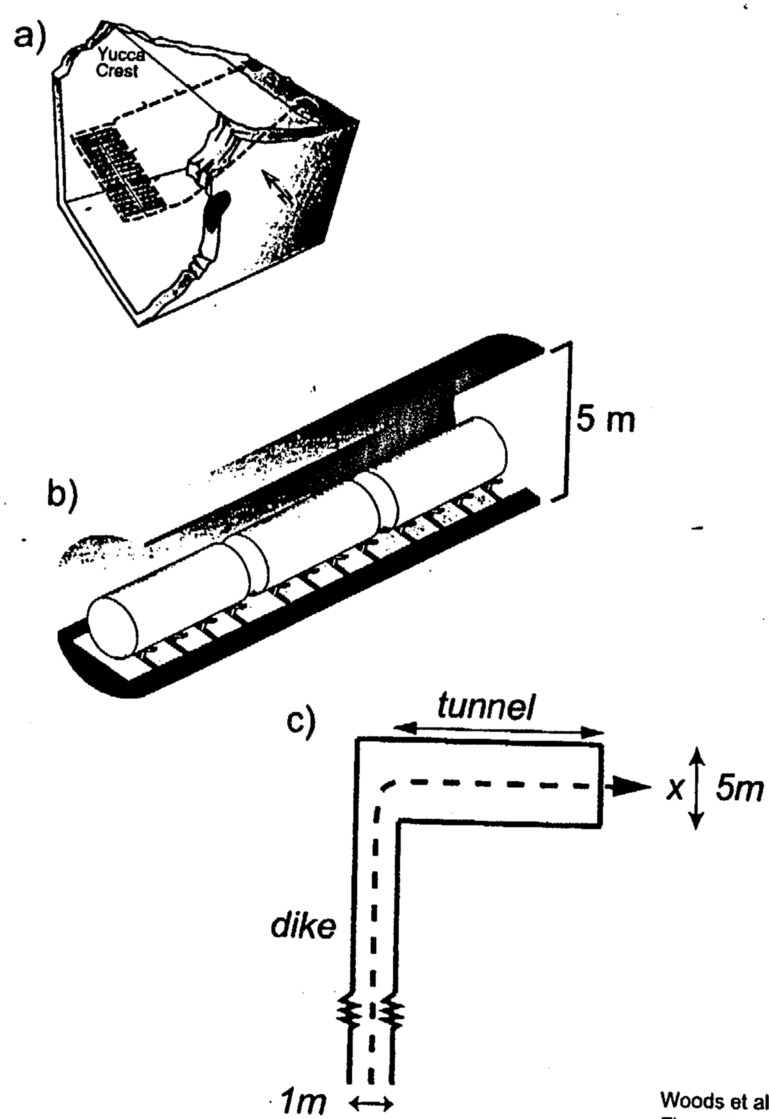
Driving piston w/ velocity V_p

Shock pressure, $P_{shk} = \dfrac{\text{driving force}}{\text{x-area of tube}}$

Wave velocity depends on P_{shk}-P_{atm}, T_{atm}.

Boundary condition:
Reflected energy depends on rigidity of the wall.

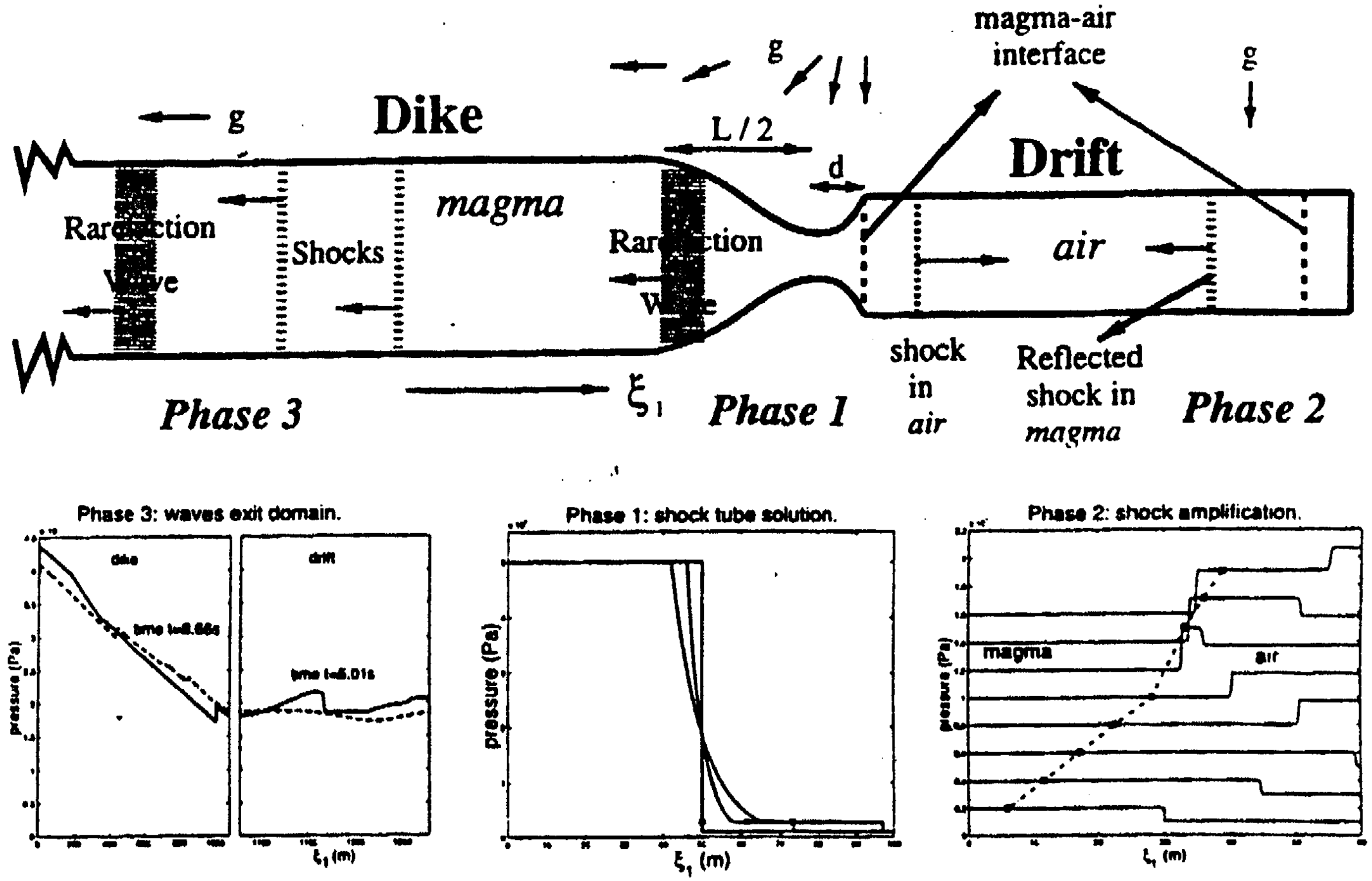
Bokhove and Woods Model



Woods et al., Figure 2

Assumptions

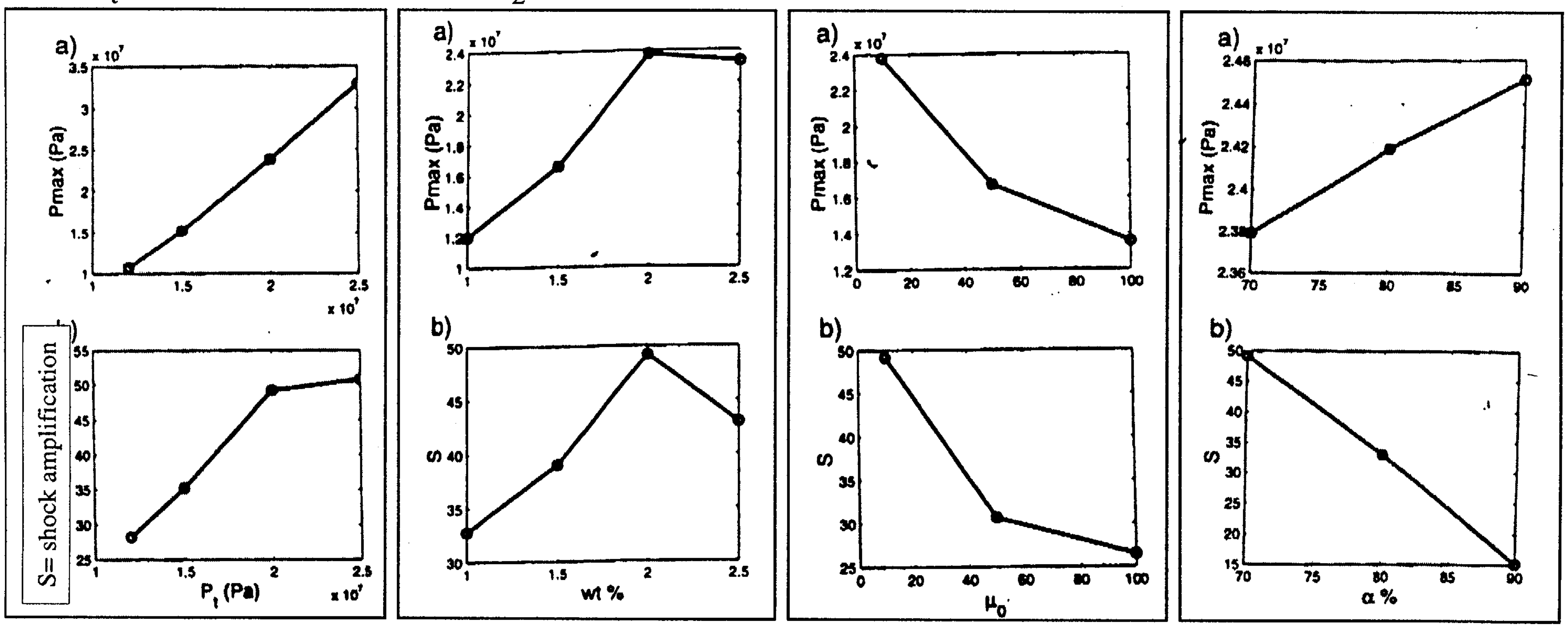
- 1-D shock tube with gravity accounting for turn at intersection.
- Magma enters drift as foam, contains 1-2.5 wt% H_2O and void fraction < fragmentation level.
- Neglects presence of waste packages.
- Dike geometry is fixed or prescribed.
- Magma enters drift at 20 MPa and 1000 K.
- Viscous effects accounted for by frictional term.



- Rarefaction or expansion wave acts to lower the pressure of magmatic fluid.
- Shock wave acts to raise the pressure of air.
- Reflected shock waves increase the pressure inside tunnel. Boundary conditions determine the magnitude: wall: no energy is transmitted ; magma/air interface: energy is transmitted into magma depending on its thermomechanical state. In the model, P max is 15-50 times the initial pressure.

Parametric study of boundary conditions @ magma-air interface

P_t : 12-25 MPa | H_2O : 1-2.5 % | Friction | Foam Void %



Pt, H_2O: less reflective energy absorbed.

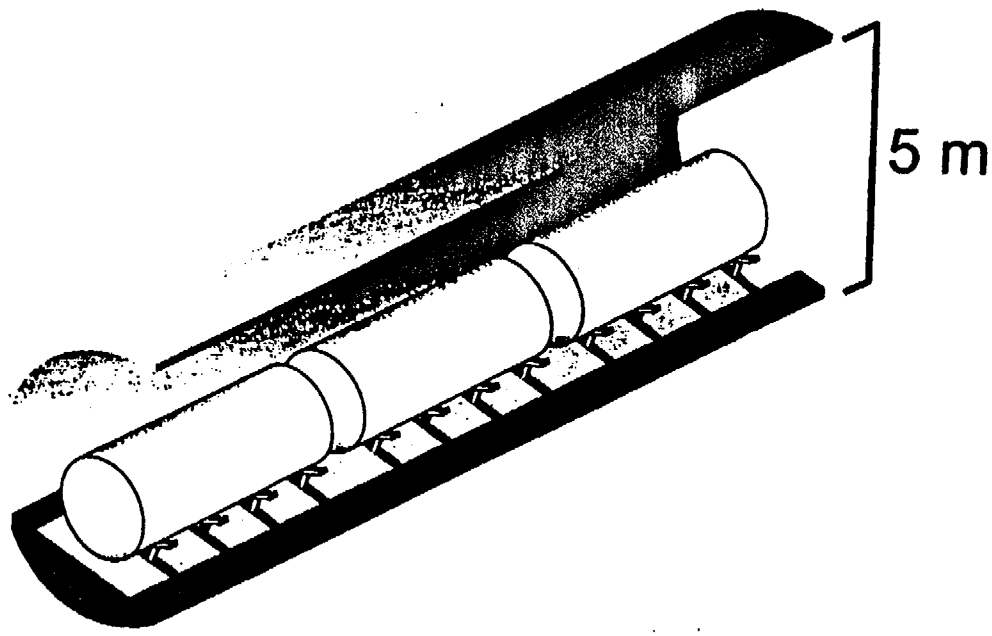
Friction, Void% (viscosity): more reflective energy absorbed.

Assumptions

1. 1-D shock tube with gravity accounting for turn at intersection.
2. Magma enters drift as foam, contains 1-2.5 wt% H_2O and void fraction < fragmentation level and steady flow behavior.
3. Neglects presence of waste packages.
4. Dike geometry is fixed or prescribed.
5. Magma enters drift at 20 MPa.
6. Rigid wall at end of tunnel.
7. Air in tunnel remains clean, no entrainment of sand/silt considered.
8. Temperature inside tunnel at 25° C.

Oversights of model

1. Shock wave may reflect off side walls of tunnel producing a series of reflecting shocks down the tunnel.
2. Maybe more vesicular or a gas-ash mixture; effects magma flow behavior.
3. To be discussed.
4. Dike tip geometry likely to change as magma enters tunnel. Magma flow behavior may change.
5. Pressure too high.
6. Fill material is not rigid and will absorb more energy.
7. Entrainment of sand/silt into moving air will lower sound speed and magnitude of shock wave.
8. Air temperature determines sound speed @25° C, ss=340 m/s @150° C, 415 m/s.

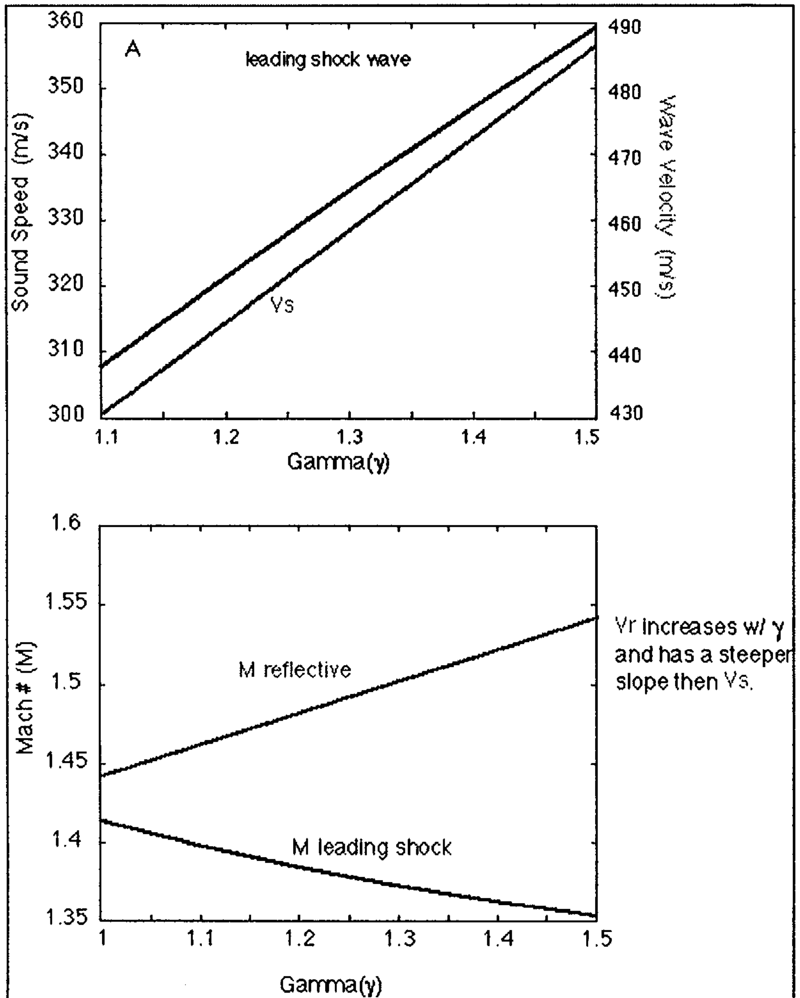


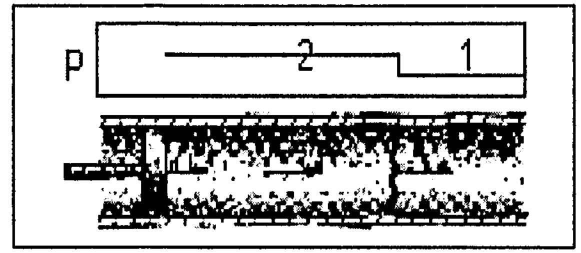
B&W's shock tube scenario with packages in tunnel

- Shock wave will propagate around packages assuming spacing is small. The shock wave will pressurize the tunnel and packages.
- Localized reflections (package may experience hammering).
- Passage of shock wave in a dusty atmosphere will abrade packages.

Reducing the wave velocity and pressure: dust and temperature

Normal shock relations for a moving shock wave (ref. Modern compressible flow, Anderson,1990).





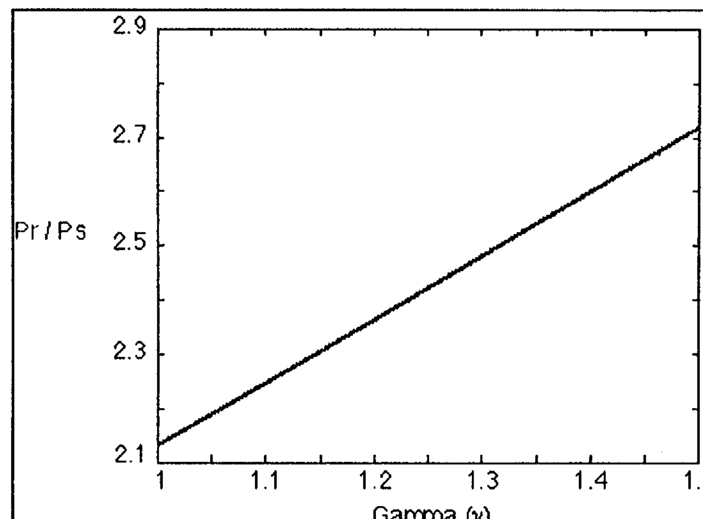
$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_s^2 - 1) \quad (7.12)$$

Solving Eq. (7.12) for M_s,

$$M_s = \sqrt{\frac{\gamma + 1}{2\gamma}\left(\frac{p_2}{p_1} - 1\right) + 1} \quad (7.13)$$

However, since $M_s = \mathbf{V}/a_1$, Eq. (7.13) yields

$$\mathbf{V} = a_1\sqrt{\frac{\gamma + 1}{2\gamma}\left(\frac{p_2}{p_1} - 1\right) + 1} \quad (7.14)$$



How realistic is the model?

• It's fairly realistic. If a magma intrudes into the tunnel, it will likely generate a leading shock wave. B&W's model demonstrates how the shock wave may develop in the tunnel. The magnitude of the shock wave depends on the driving force of the magmatic fluid, mechanical properties of the magmatic fluid and wall, and the initial thermodynamic state of air inside tunnel.

Uncertainties of the model?

- Behavior of ascending magma: will it be rich in volatiles and ready to explosively expand when it reaches the tunnel or will it behave as a partially degassed foam and passively enter the tunnel or move steadily into tunnel or will it be a mixture of ash and gas?
- The boundary conditions at end of tunnel.
- Entrainment of sand/silt.

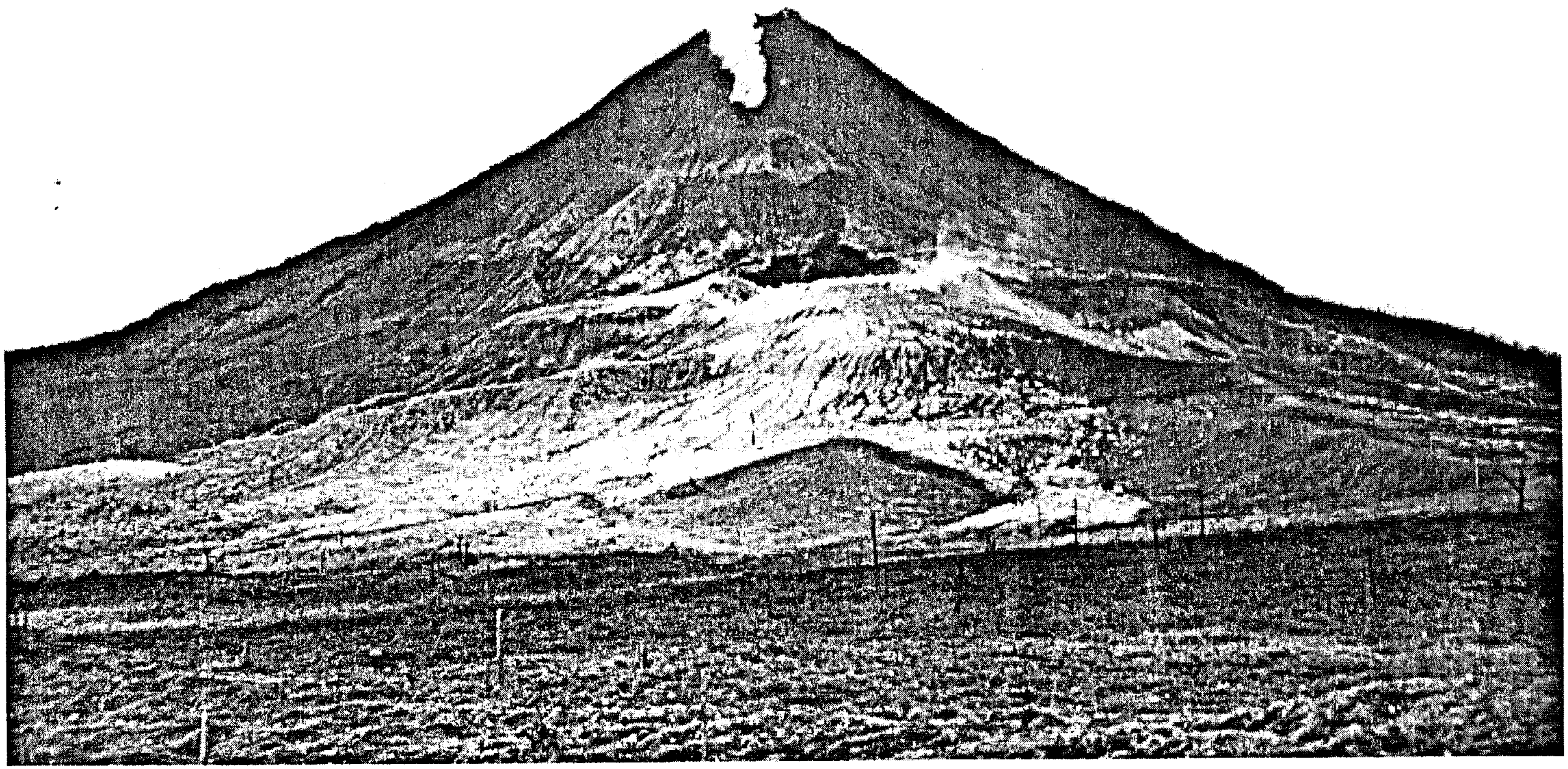
How to engineer tunnel for shock waves

- Enable walls to absorb or transmit energy.
- Pressurize and cool tunnel.
- Strength packages and mounts to withstand pressurization and abrasion from reflected shock waves.

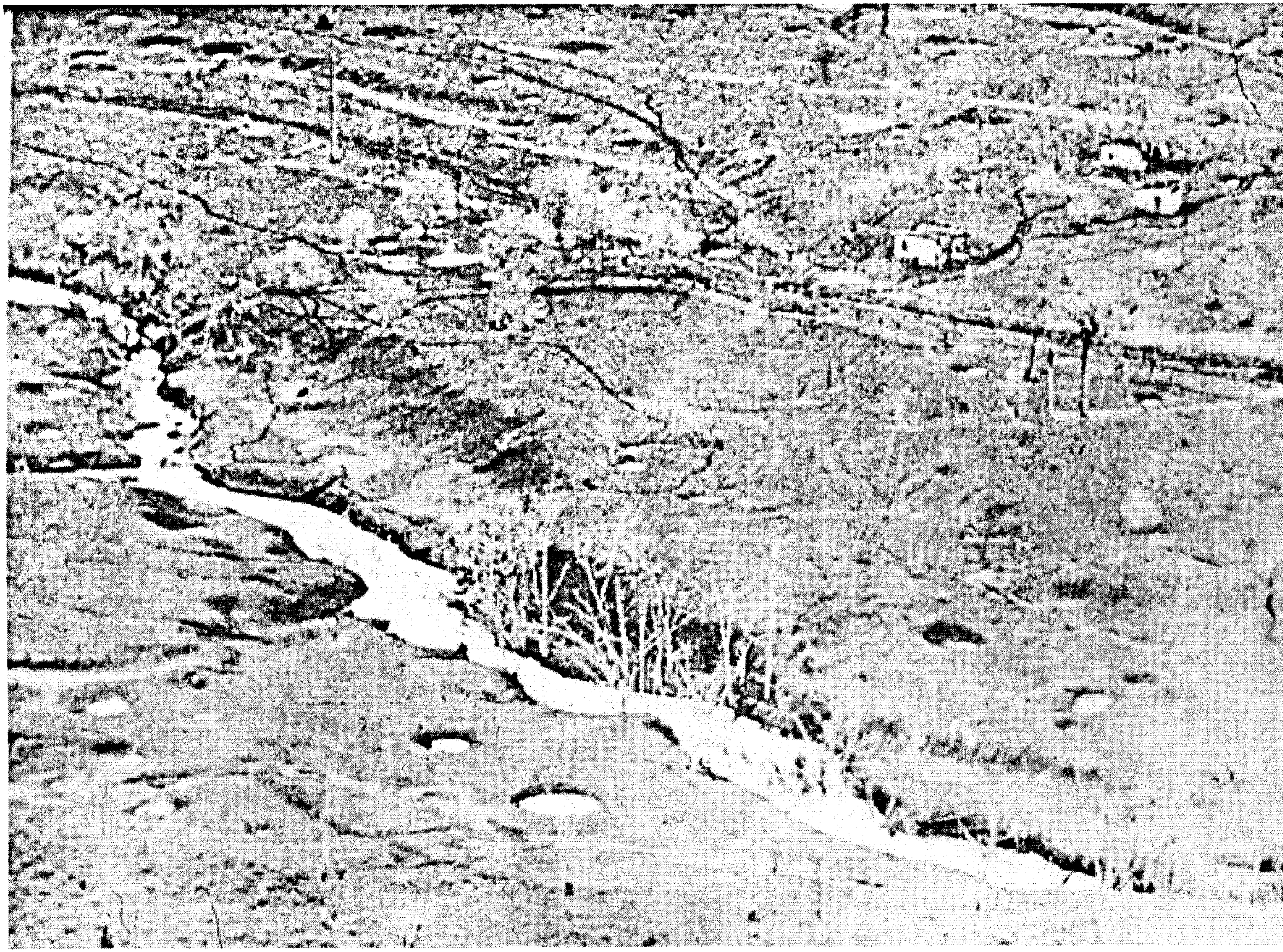
Yucca Mountain Dike Intrusion Consequence Analysis: What More Do We Need To Do

William G. Melson

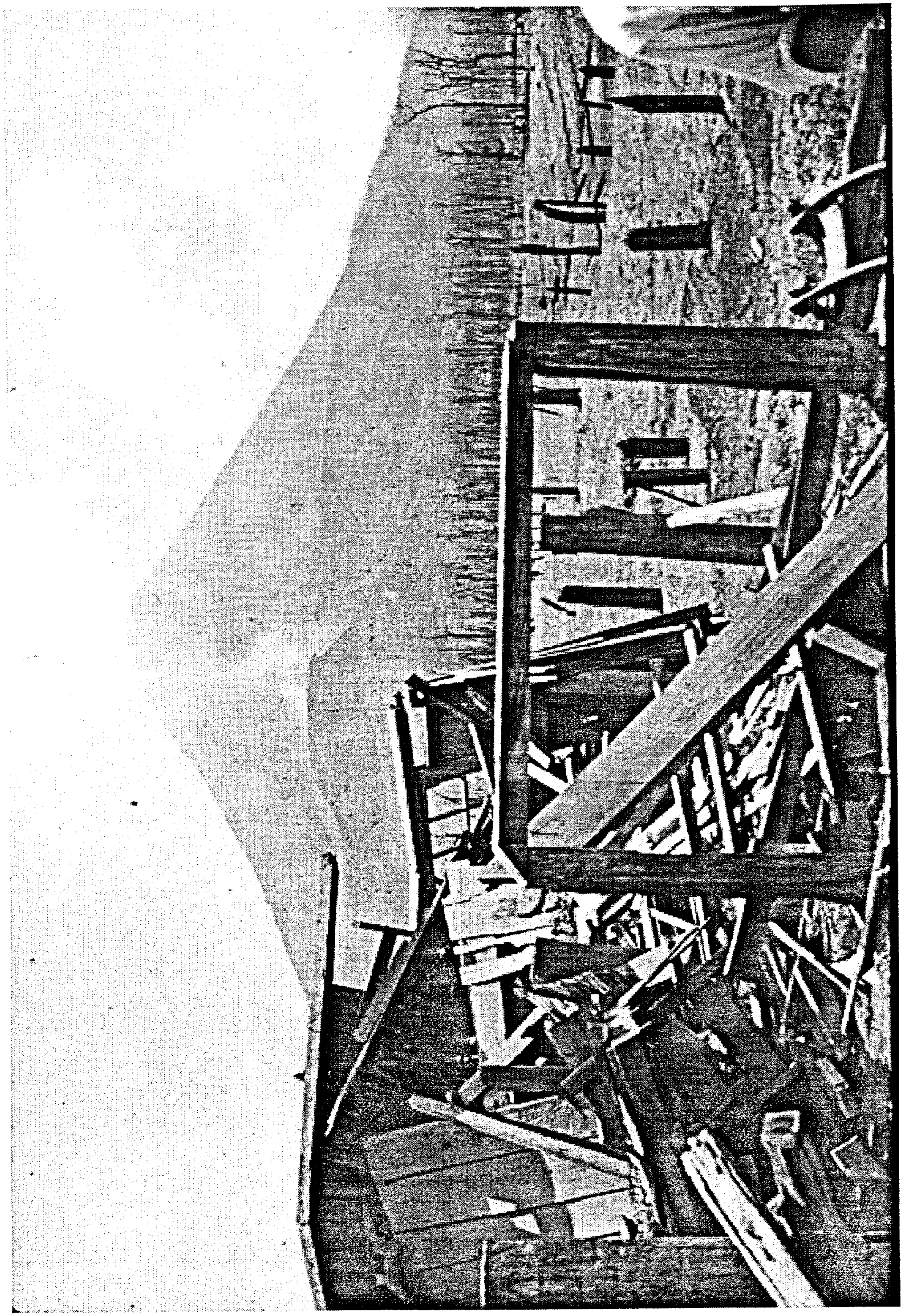
Consultant to the NWTRB and Senior Scientist, Division Petrology and Volcanology, Smithsonian Institution

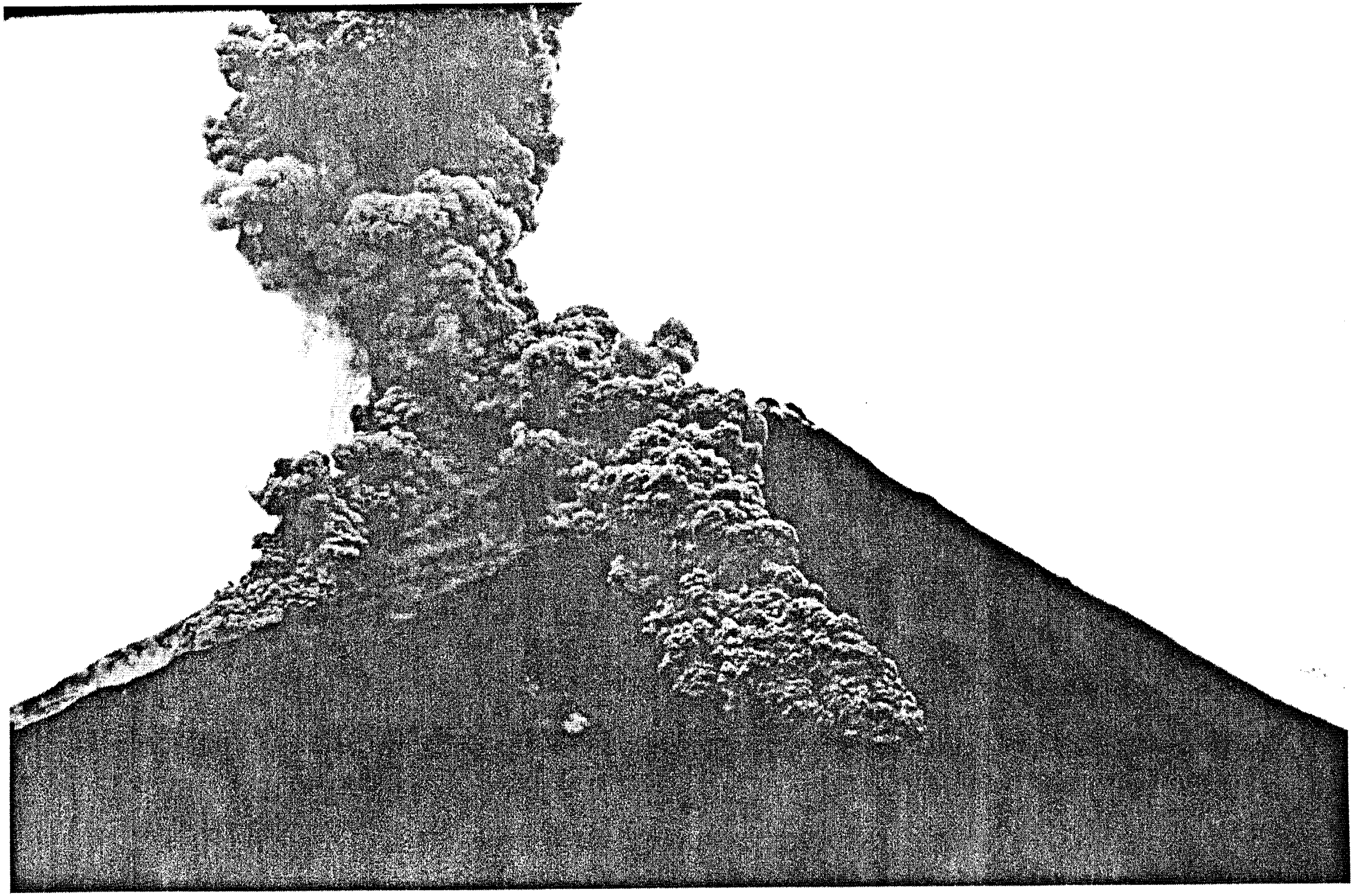


Devastated zone, explosions of July 29-Aug 1, 1968. Arenal Volcano, Costa Rica.

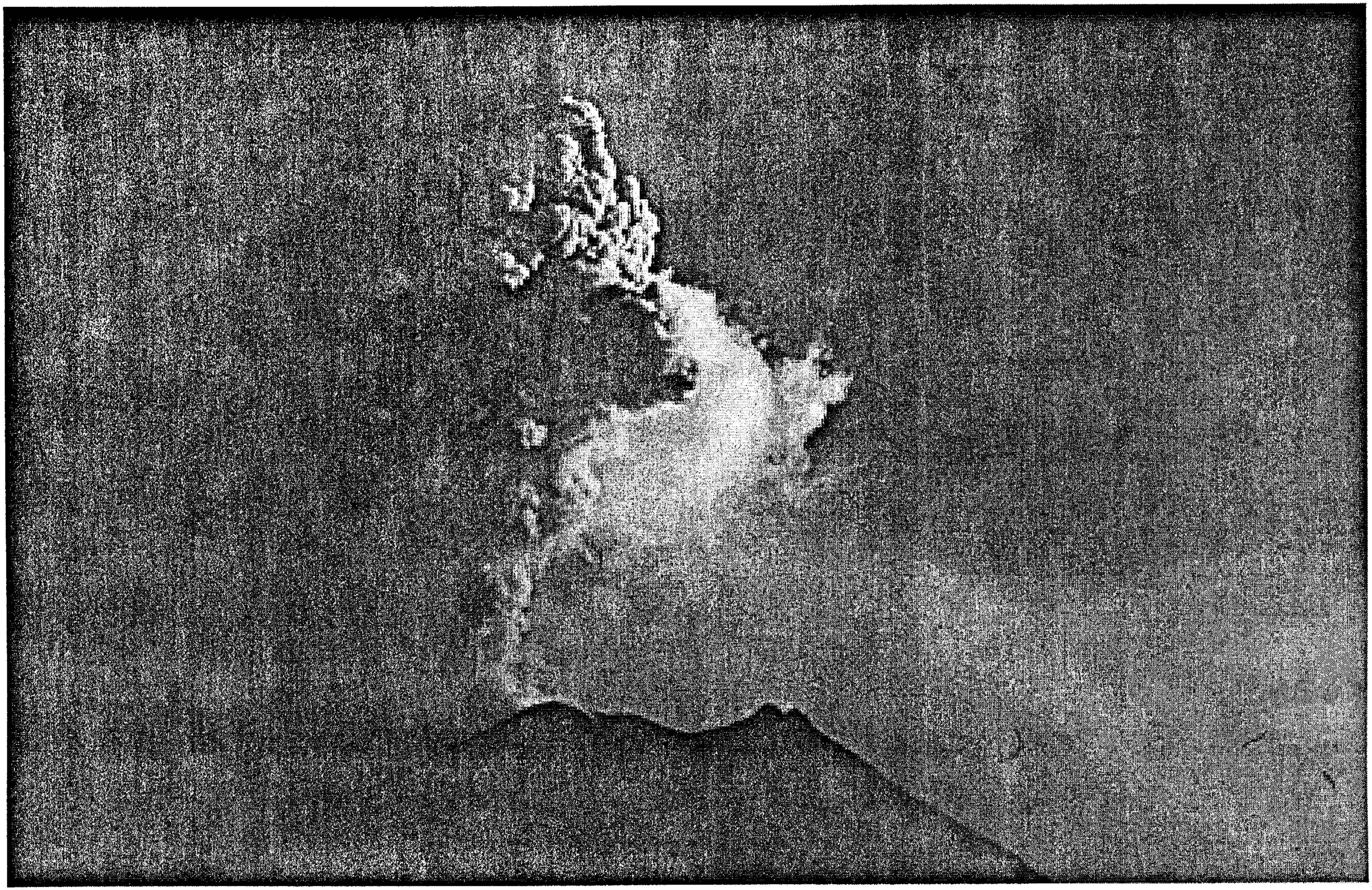


Impact Field, Arenal Volcano, July, 1968

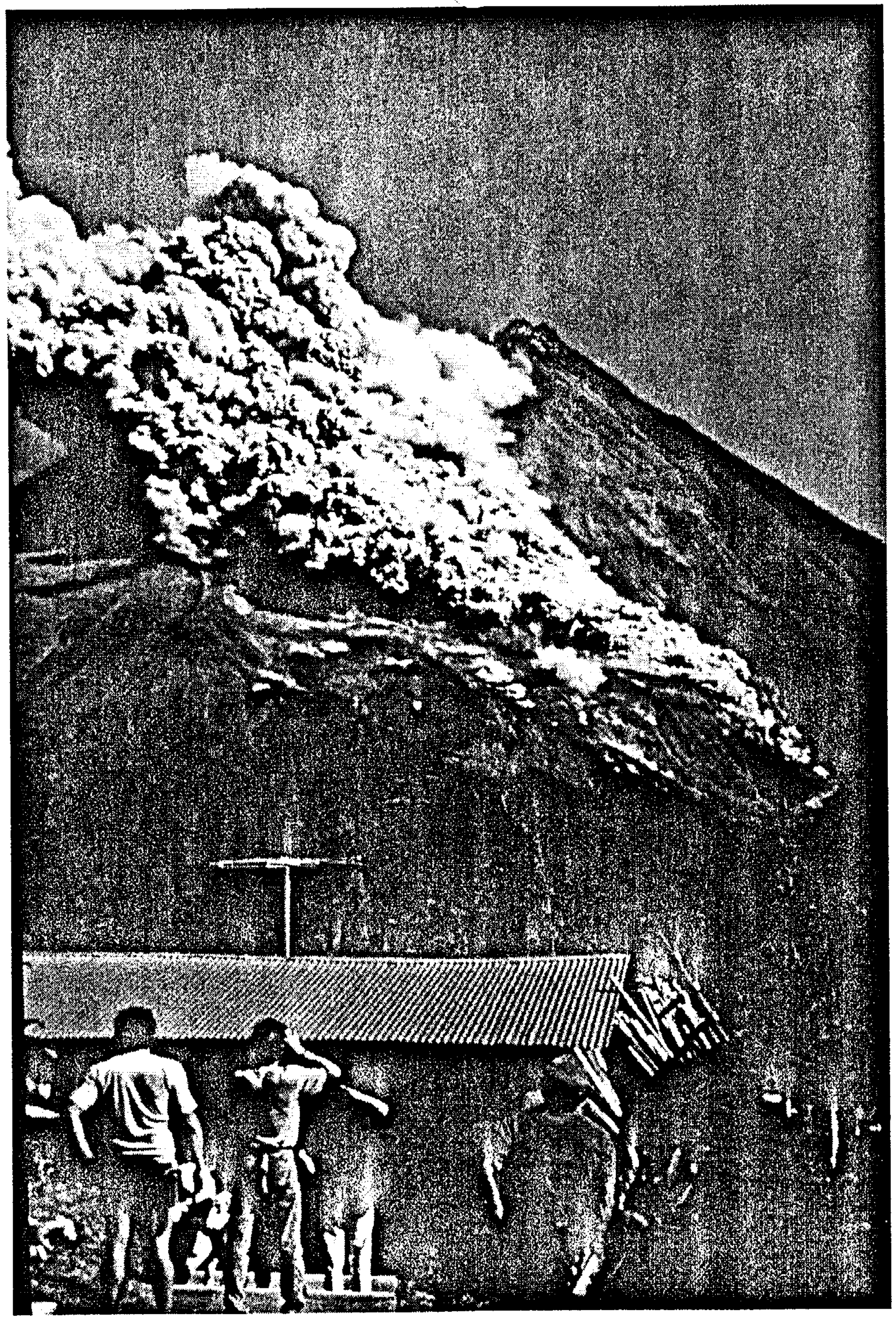




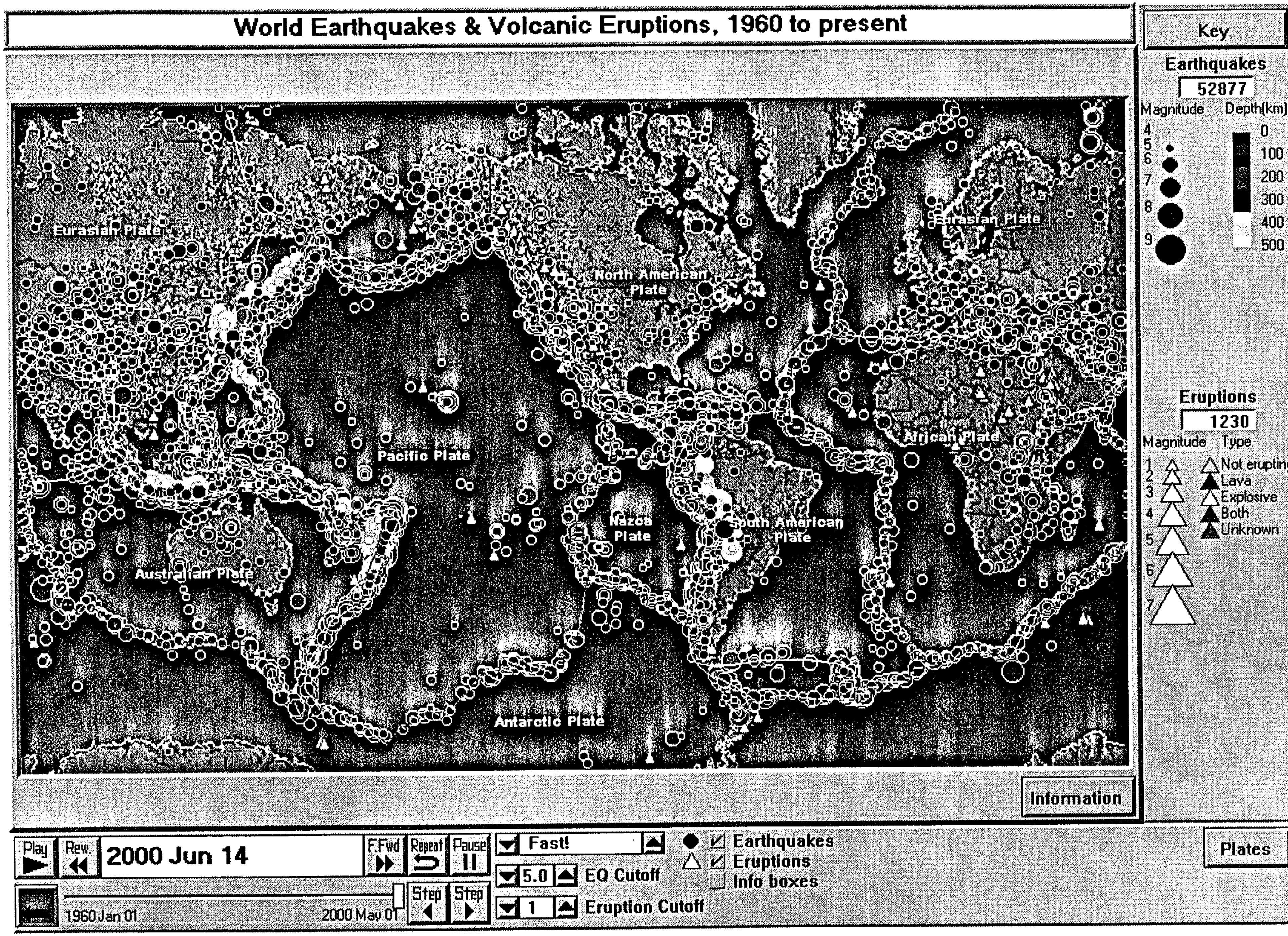
Pyroclastic Flow, Arenal Volcano, Costa Rica, 1987

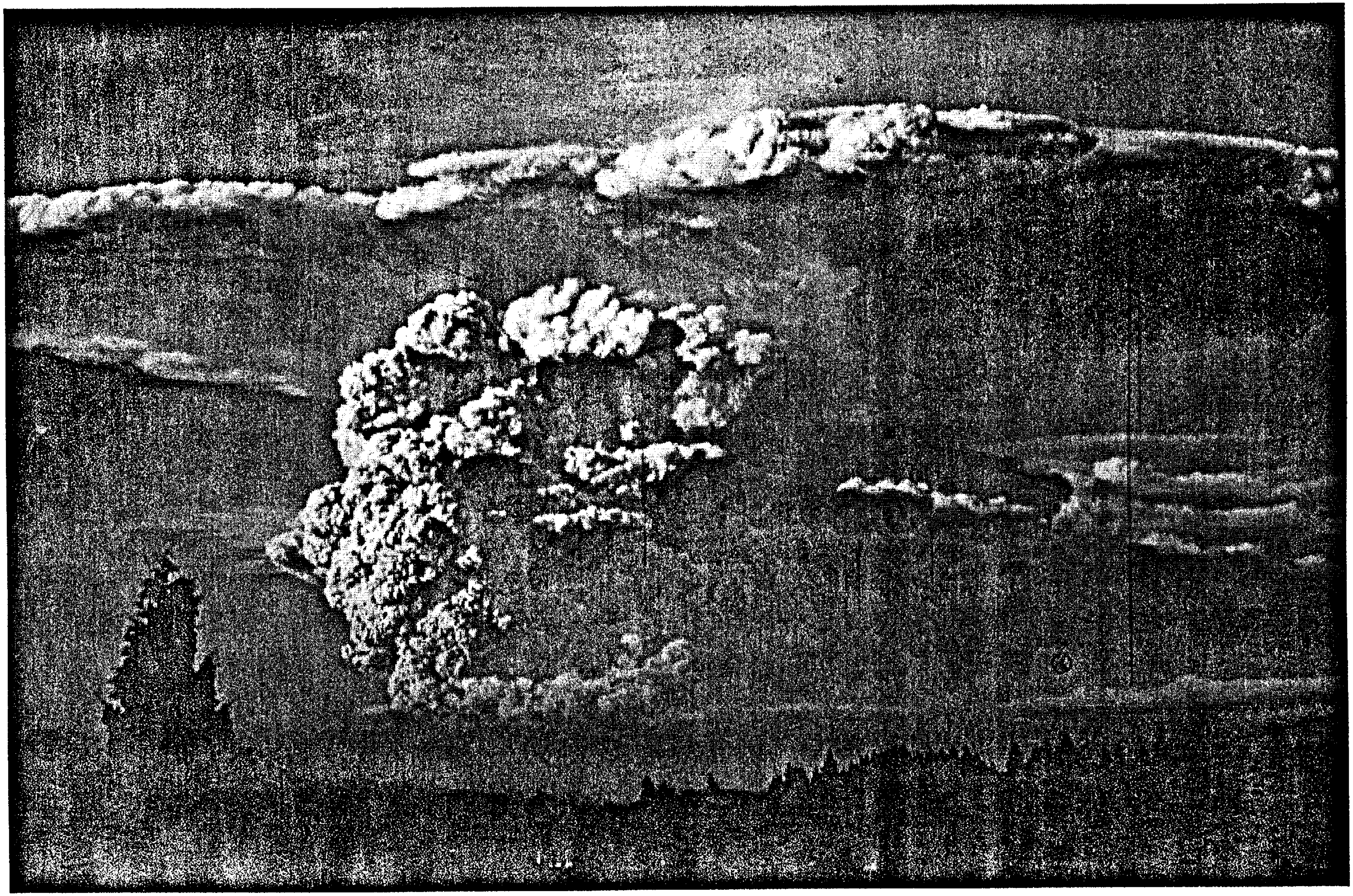


Arenal Volcano, Costa Rica, Explosion in March, 1995

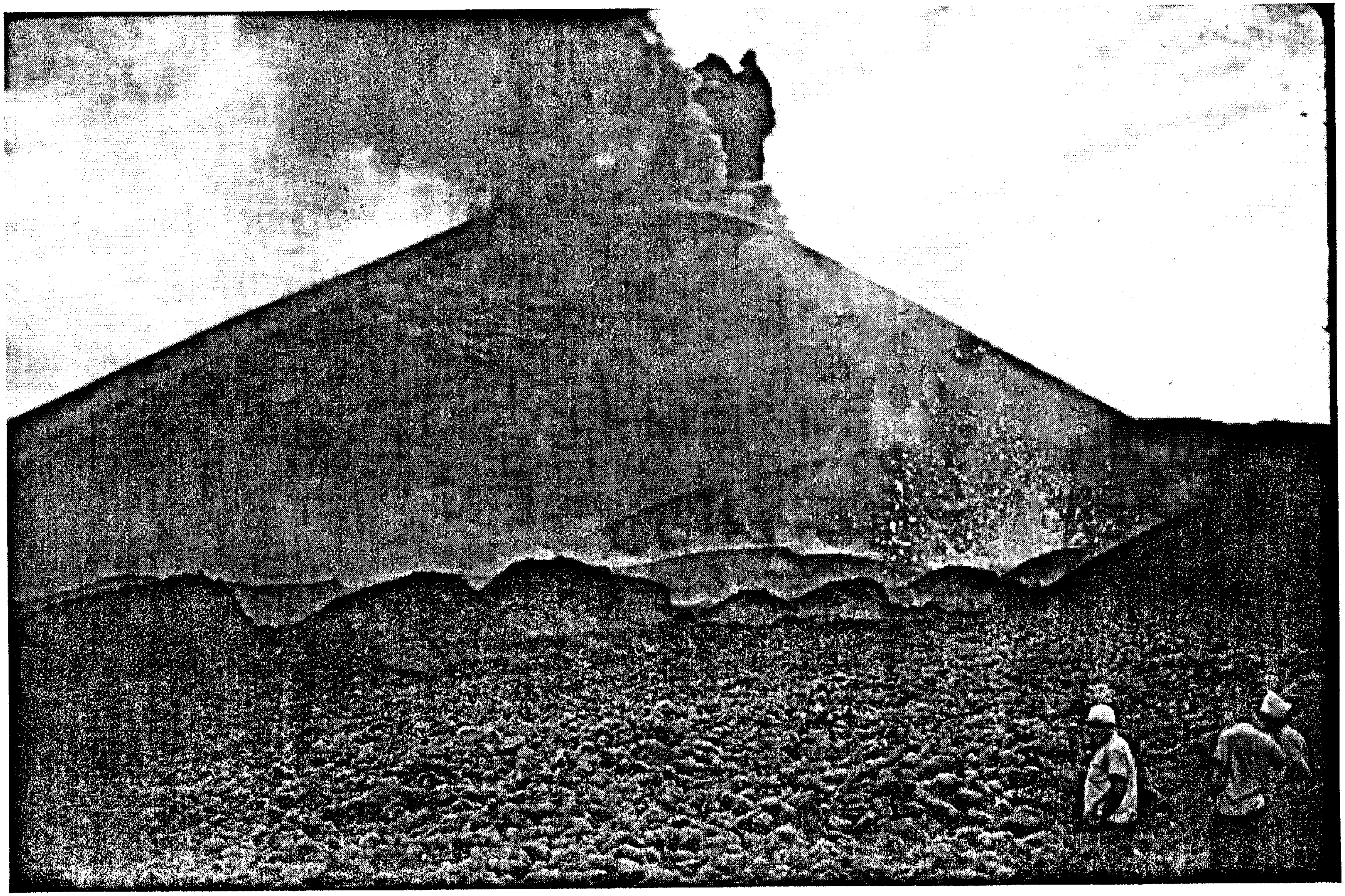


Arenal Volcano,
Costa Rica
1989

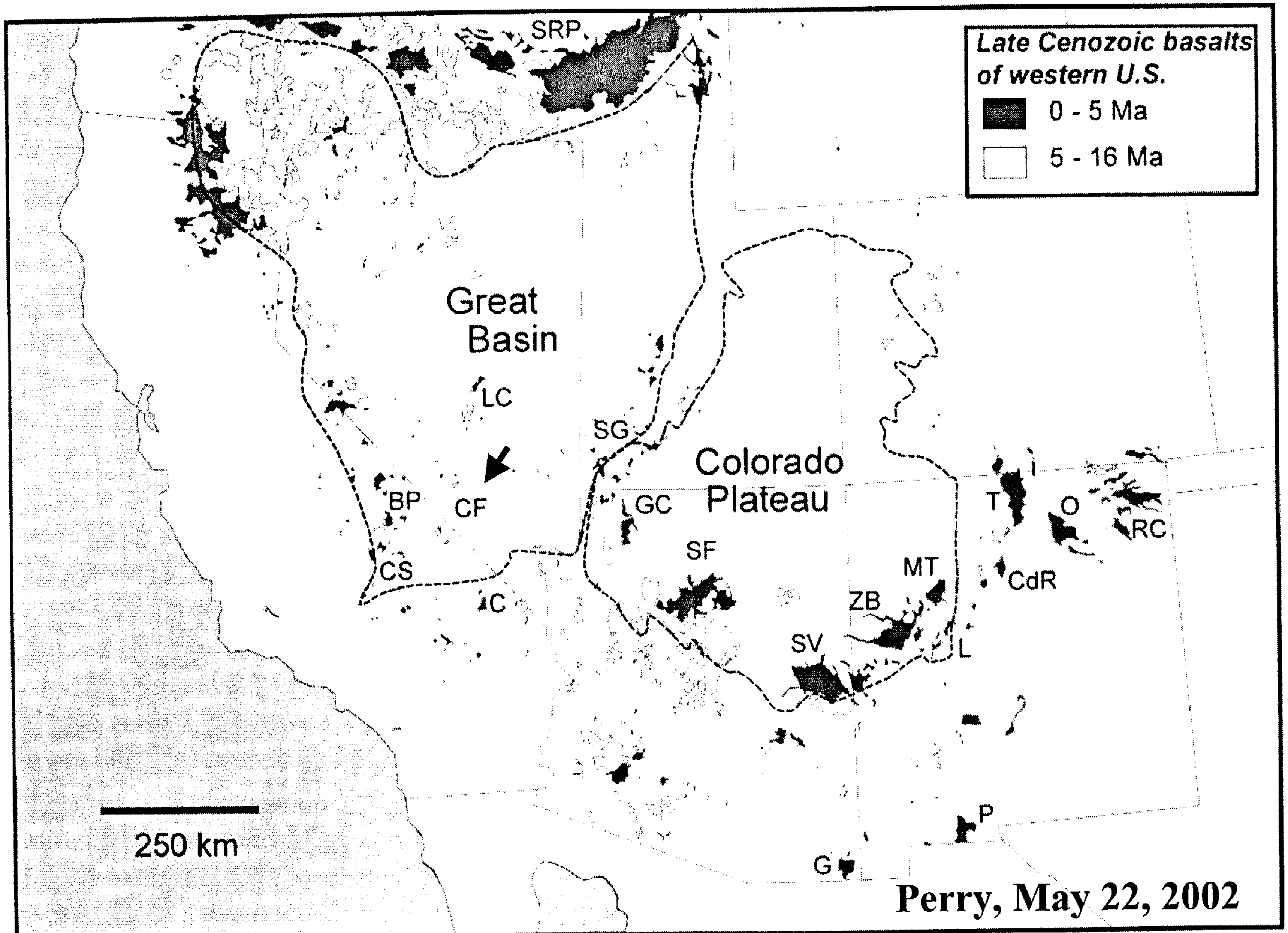

World Earthquakes & Volcanic Eruptions, 1960 to present
Key
Earthquakes
52877
Magnitude
Depth(km)
4
5
6
7
8
9
0
100
200
300
400
500
Eurasian Plate
North American Plate
Eurasian Plate
Pacific Plate
African Plate
Nazca Plate
South American Plate
Australian Plate
Antarctic Plate
Eruptions
1230
Magnitude
Type
1
2
3
4
5
6
7
Not erupting
Lava
Explosive
Both
Unknown
Information
Play
Rew.
2000 Jun 14
F.Fwd
Repeat
Pause
Fast!
Earthquakes
Eruptions
Info boxes
Plates
5.0
EQ Cutoff
1
Eruption Cutoff
Step
Step
1960 Jan 01
2000 May 01



Mt. St. Helens, May 18, 1980. Water-rich (up to 7 wgt %) dacitic magma

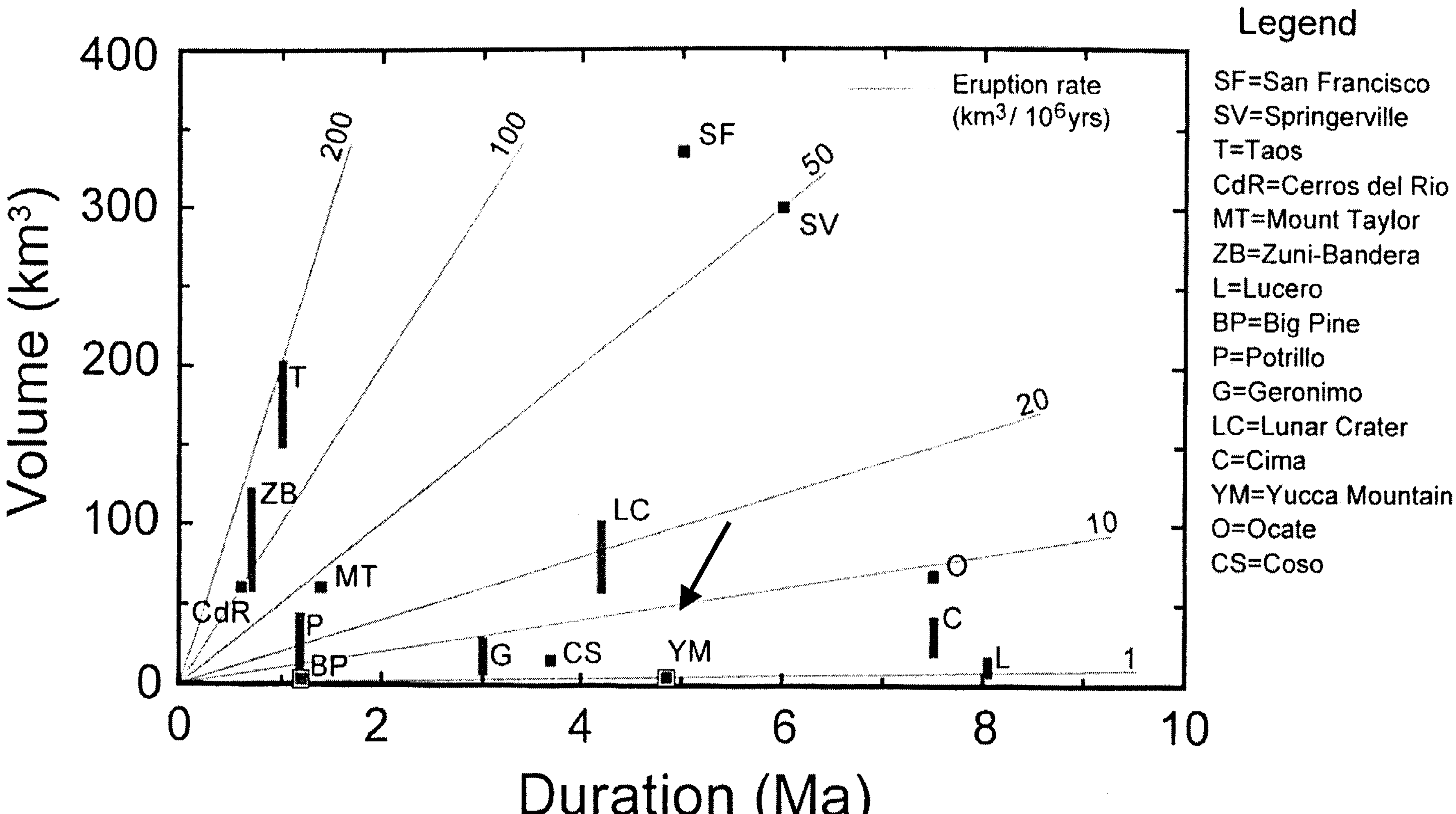


Strombolian Eruptions of Cerro Negro, Nicaragua, 1968



Perry, May 22, 2002

Basaltic volcanic fields of the southwestern U.S.

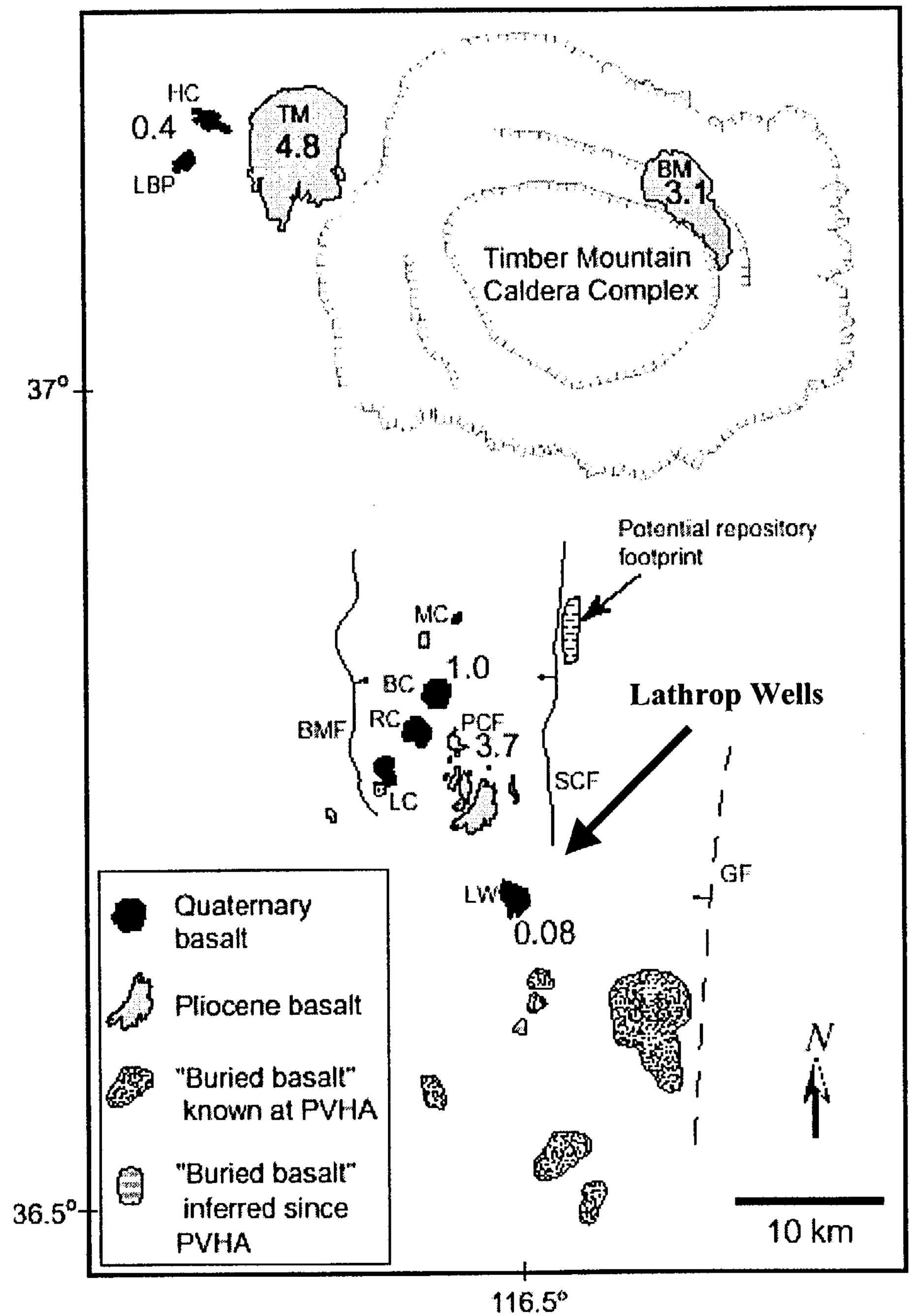


Perry, May 22, 2002

What More is Needed Concerning:

1. Probability of Disruption

2. Consequence of Intrusion and Disruption


HC
0.4
LBP
TM
4.8
BM
3.1
Timber Mountain
Caldera Complex
37°
Potential repository
footprint
MC
1.0
BC
Lathrop Wells
RC
PCF
BMF
3.7
SCF
LC
GF
LW
0.08
Quaternary
basalt
Pliocene basalt
"Buried basalt"
known at PVHA
"Buried basalt"
inferred since
PVHA
N
10 km
36.5°
116.5°

Probability of Disruption Background

• Crater Flat Volcanic Field: small volume basaltic eruptions from monogenetic (single episode) eruptions over the past few million years. Last eruption at Lathrop Wells cone about 75,000 years ago.

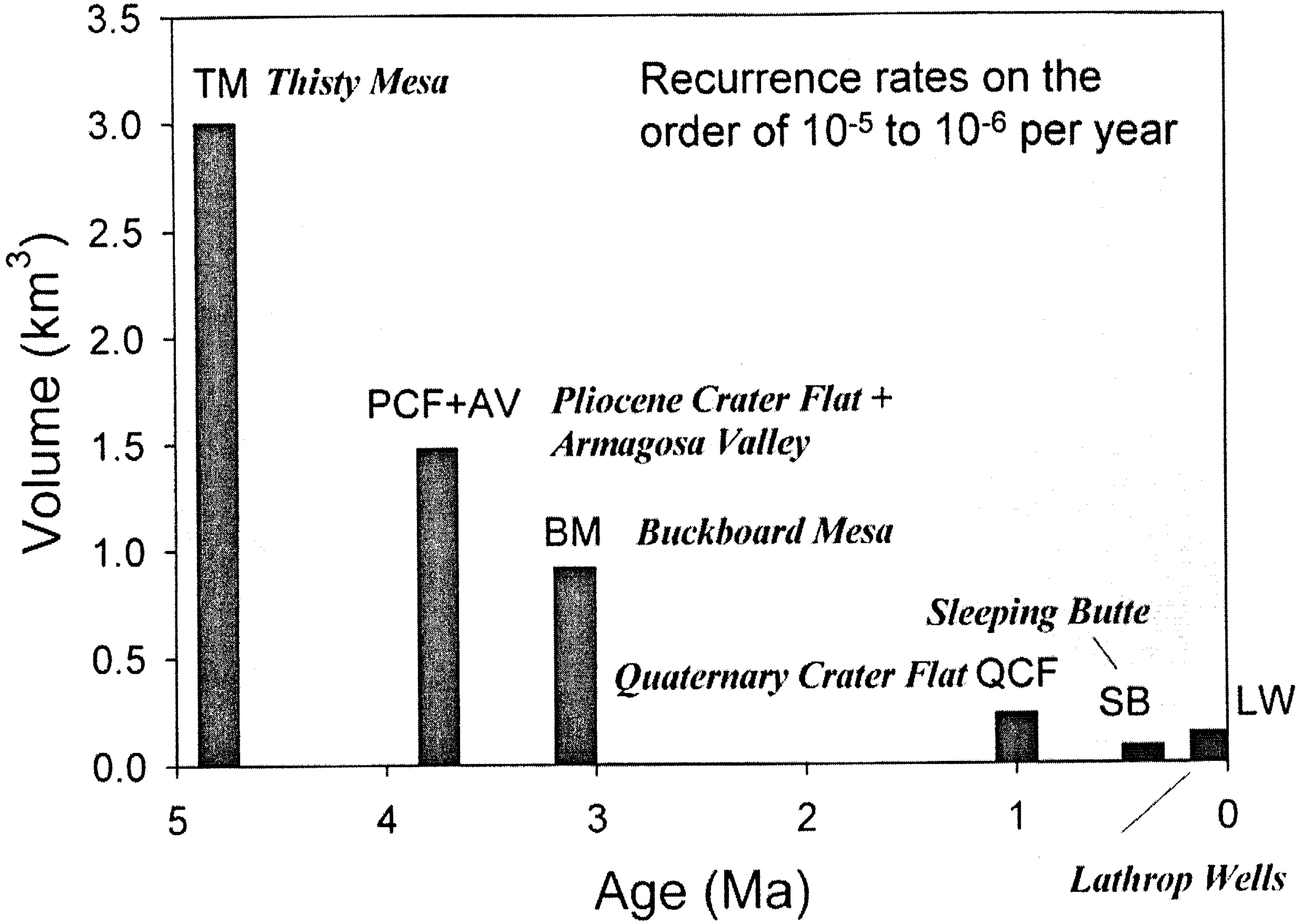
• Quaternary Volcanic centers so far restricted to the rift-valley just west of Yucca Mountain.

•Probabilities of dike intersection estimated around 10^{-8}/a by Bruce Crowe and coworkers in late 80'. Most recent estimates by the Probability Volcanic Hazard Assessment (PVHA) panel are also around ca. 10^{-8}/a; NRC estimates are slightly higher (ca. 10^{-7}/a)

•Point: Likelihood of dike intersection obtained by diverse and meticulous analyses remains extremely small.

Age and volume of basaltic volcanic episodes in the Yucca Mountain region

PERRY, MAY 21,2002



In the simplest sense, how are intersection values of ~10^{-8} per year calculated?

= Recurrence rate (per year) × Conditional disruption probability

= 10^{-5} to 10^{-6} × 10^{-2} to 10^{-3}

Results therefore range from 10^{-7} to 10^{-9} per year

Perry, May 22, 2002

Some Benchmarks In Estimates of Probability of Disruption:

- 1980-90 Crowe's (LANL, DOE) estimates of 10^{-8}/Annum

- @1995 First higher estimates: Conner (CNWRA) Ho and Smith (U Nevada LV).

- **Mid-Nineties: Resolution of poly- or monogenetic origin of Lathrop Wells Cone: monogenetic at about 75,000 yrs (youngest center of Crater Flat Field).**

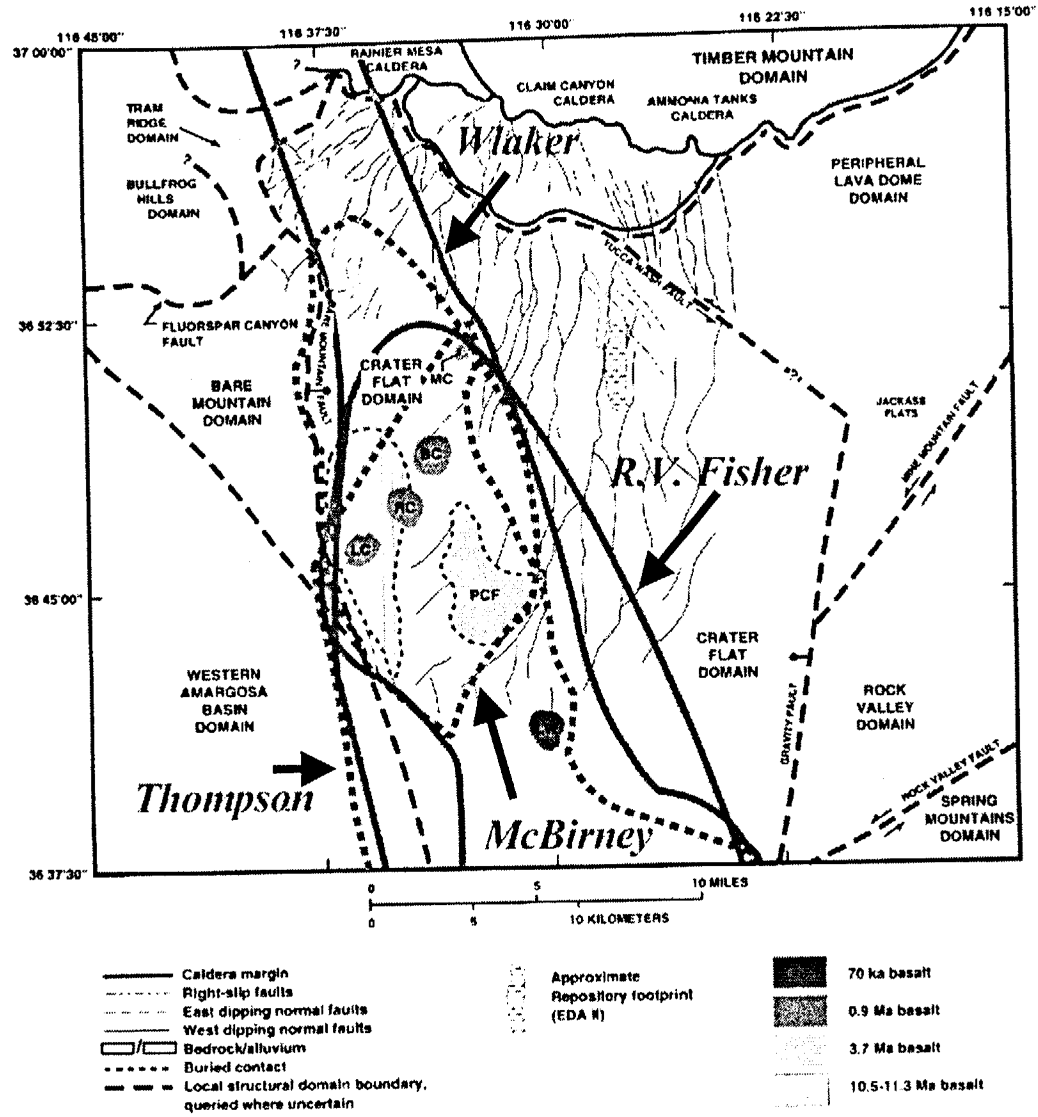
- **1996 PVHA completed**

- **Needs Completion: ID of buried magnetic anomalies**

PVHA Expert Panel

(Completed 1996)

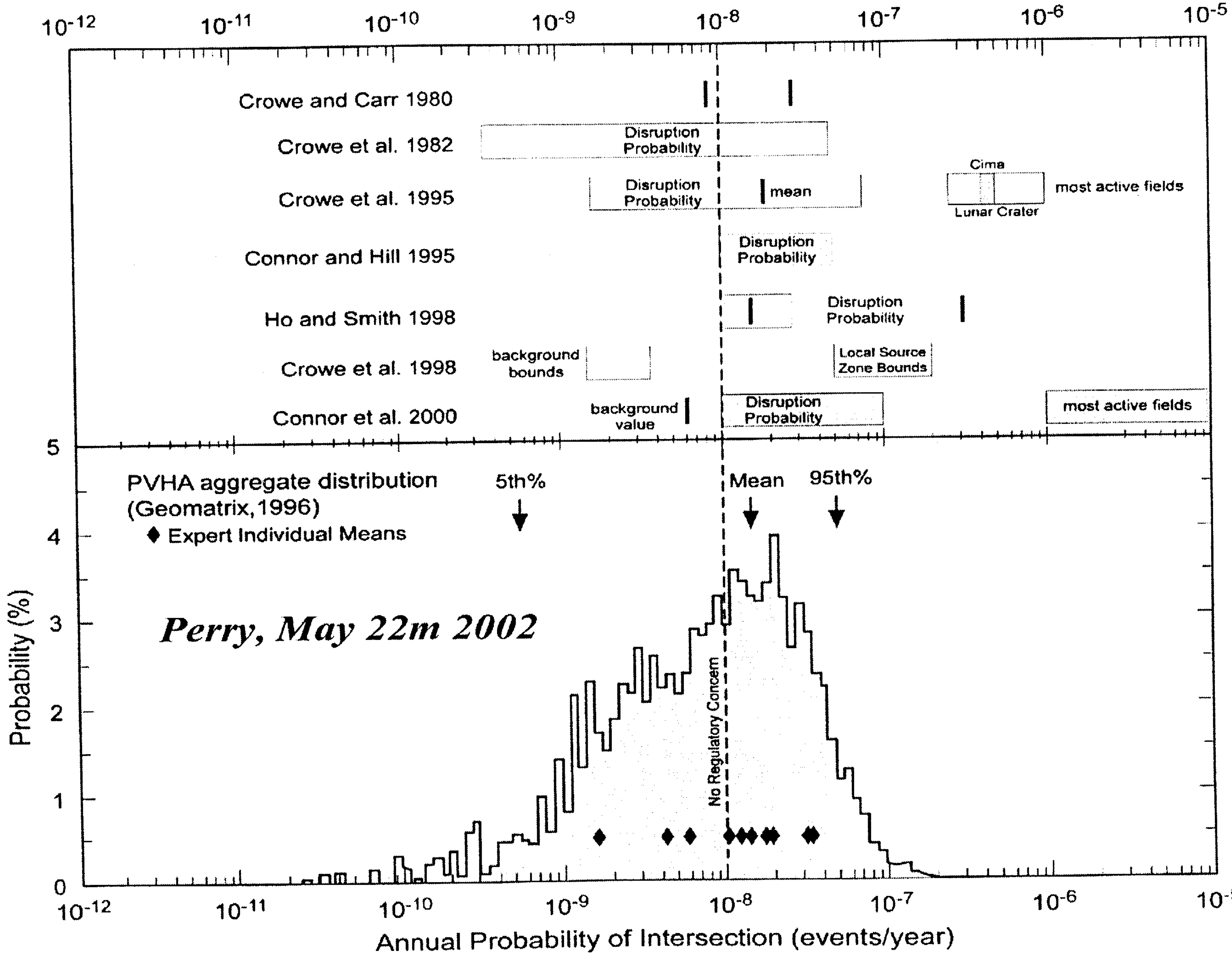
Expert	Affiliation
Dr. Richard W. Carlson	Carnegie Institute of Washington
Dr. Bruce M. Crowe	Los Alamos National Laboratory
Dr. Wendell A. Duffield	USGS, Flagstaff
Dr. Richard V. Fisher	University of California, Santa Barbara
Dr. William R. Hackett	WRH Associates, Salt Lake City
Dr. Mel A. Kuntz	USGS, Denver
Dr. Alexander R. McBirney	University of Oregon
Dr. Michael F. Sheridan	State University of New York, Buffalo
Dr. George A. Thompson	Stanford University
Dr. George P. L. Walker	University of Hawaii, Honolulu



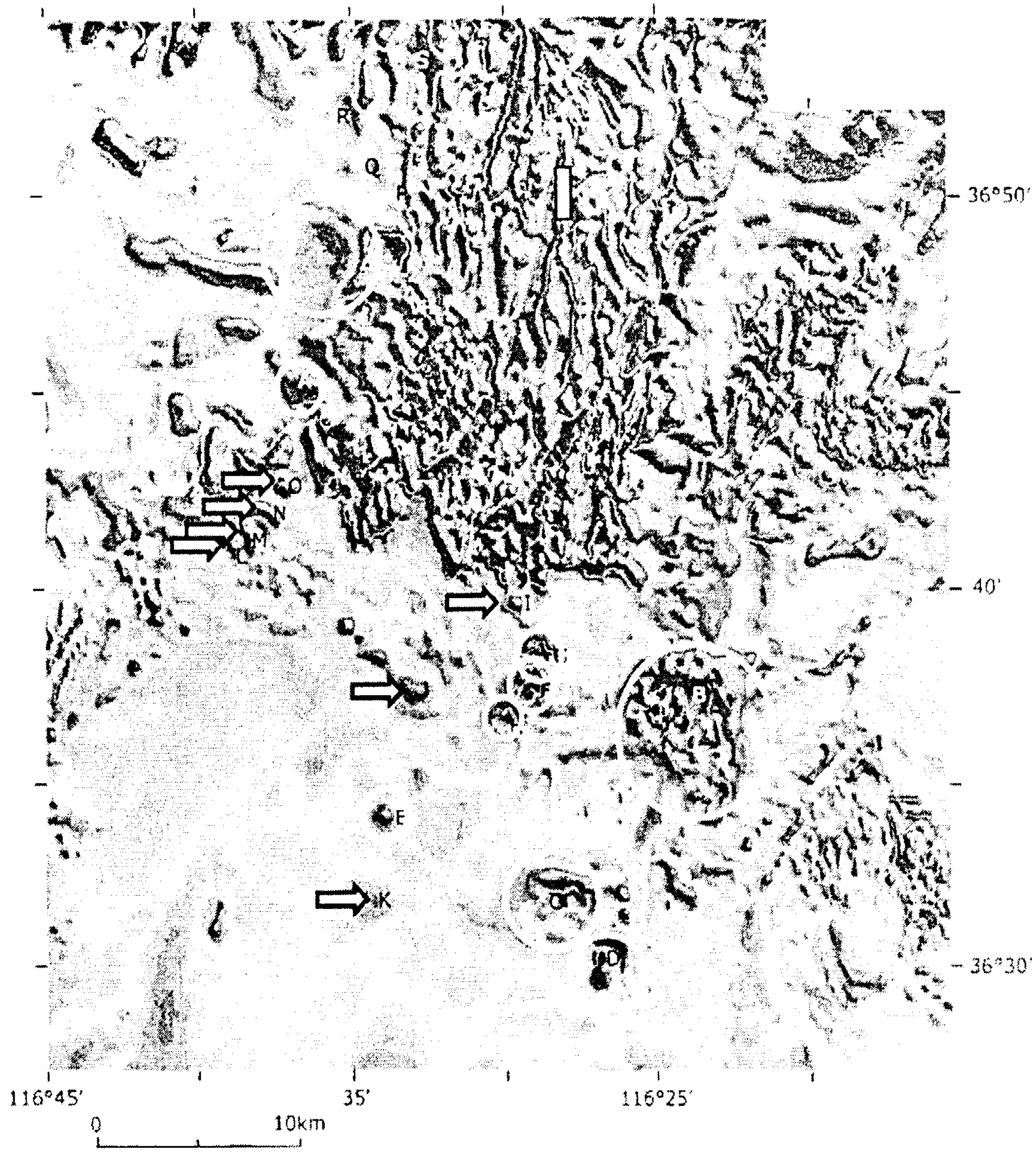
PVHA SOURCE ZONE BOUNDARIES NEAR YUCCA MOUNTAIN THAT ENCLOSE AREAS OF RELATIVELY HIGHER VOLCANIC EVENT FREQUENCY

Fisher — McBirney

Walker — Thompson



10-12
10-11
10-10
10-9
10-8
10-7
10-6
10-5
Crowe and Carr 1980
Crowe et al. 1982
Disruption Probability
Crowe et al. 1995
Disruption Probability
mean
Cima
Lunar Crater
most active fields
Connor and Hill 1995
Disruption Probability
Ho and Smith 1998
Disruption Probability
Crowe et al. 1998
background bounds
Local Source Zone Bounds
Connor et al. 2000
background value
Disruption Probability
most active fields
PVHA aggregate distribution (Geomatrix,1996)
♦ Expert Individual Means
5th%
Mean
95th%
Perry, May 22m 2002
No Regulatory Concern
Probability (%)
Annual Probability of Intersection (events/year)



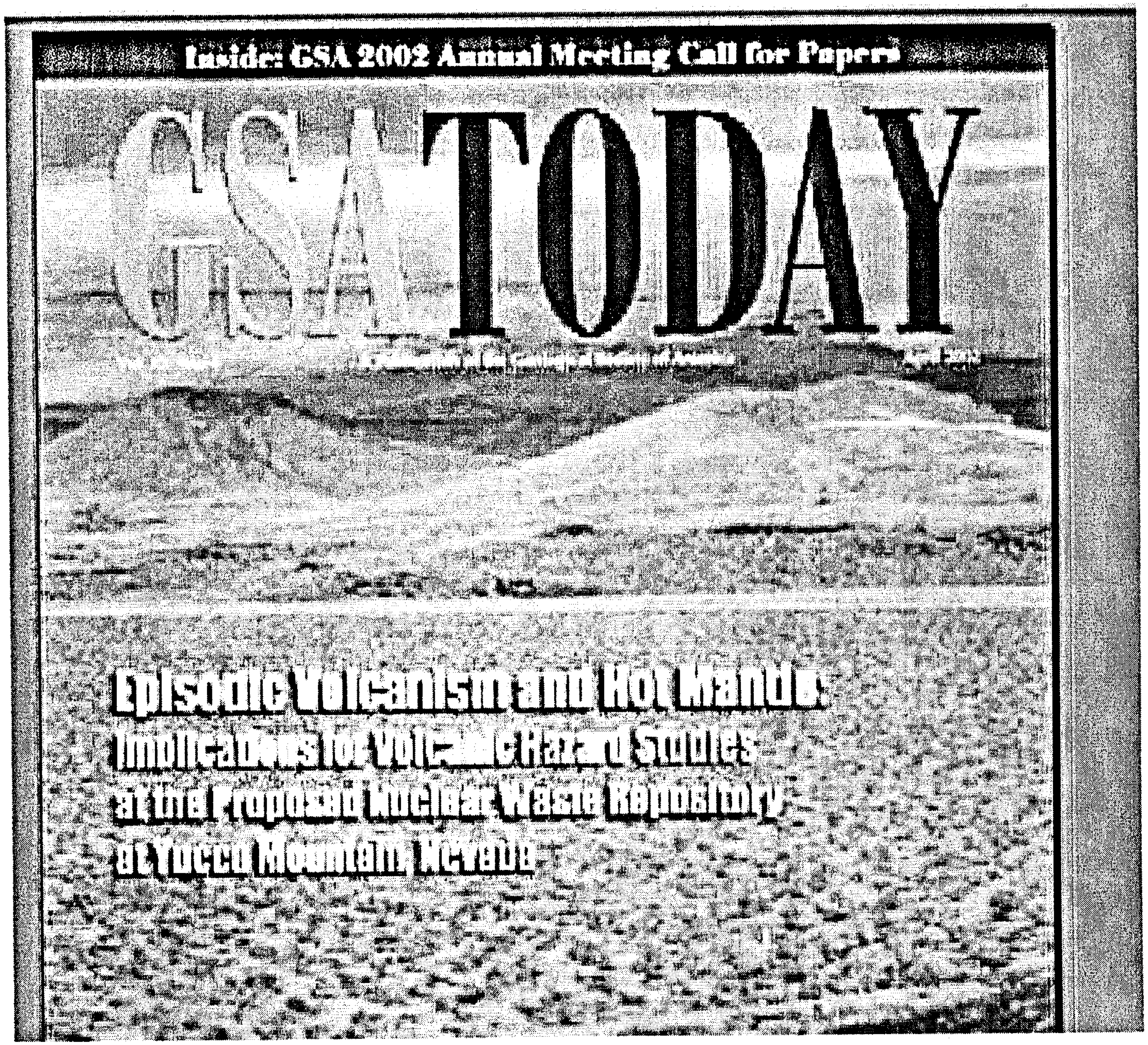
Aeromagnetic anomalies in the Yucca Mountain region

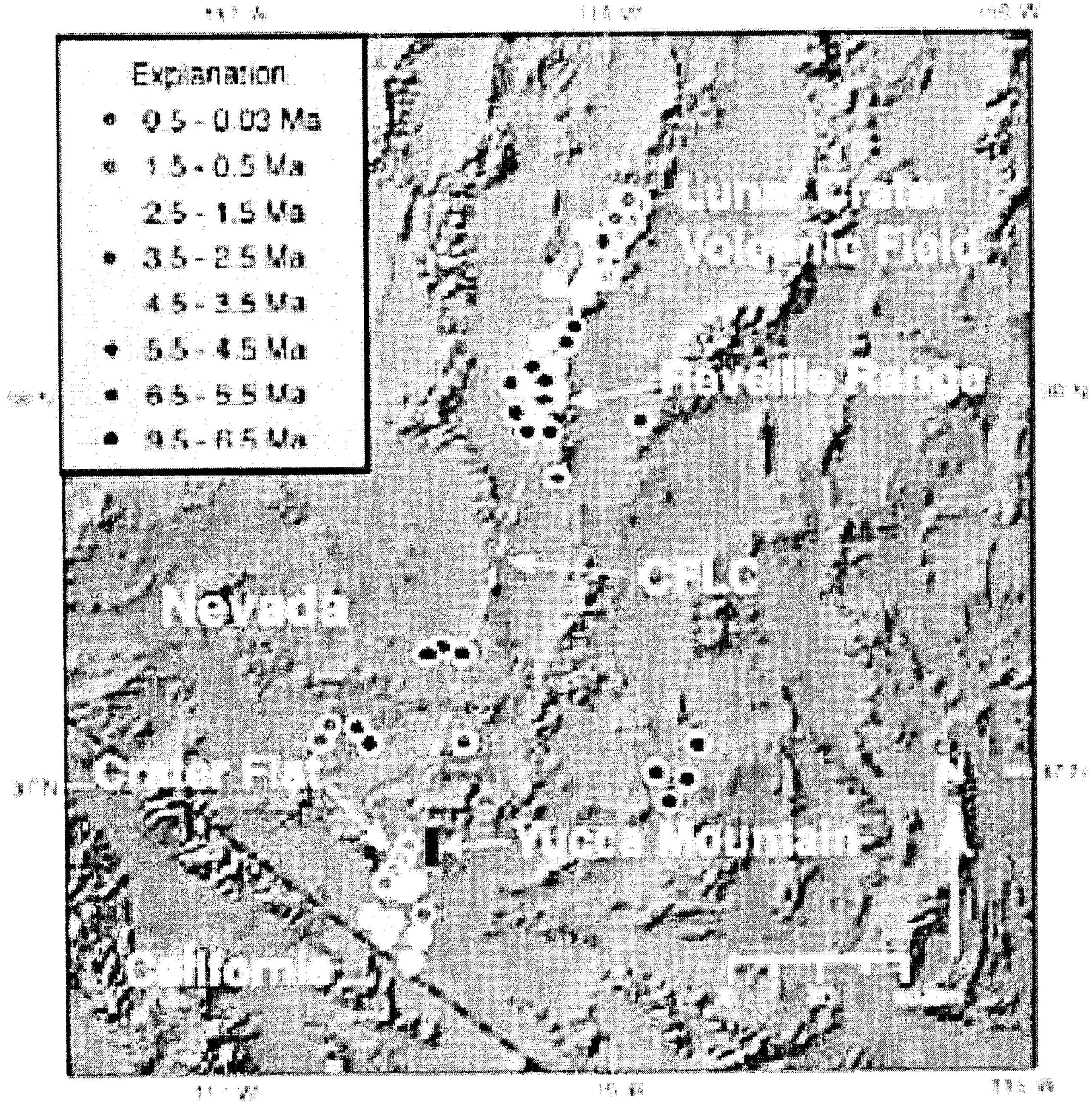
known at time of PVHA

newly recognized

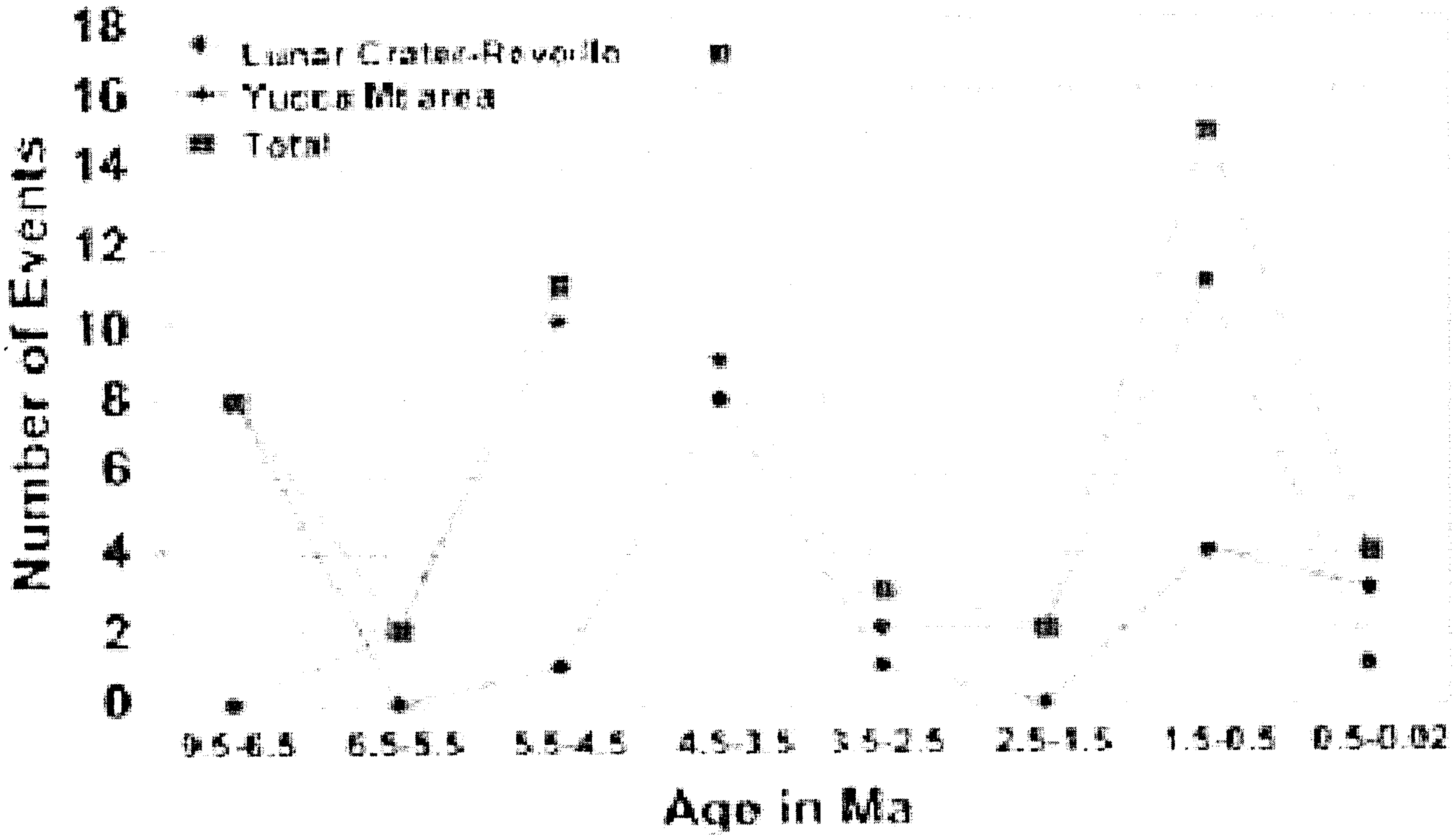
Approximate repository site

Source: O'Leary et al. (2002) USGS Open-File Report 02-020


Inside: GSA 2002 Annual Meeting Call for Papers
GSA TODAY
Episodic Volcanism and Hot Mantle:
Implications for Volcanic Hazard Studies
at the Proposed Nuclear Waste Repository
at Yucca Mountain, Nevada



Explanation
0.5 - 0.03 Ma
1.5 - 0.5 Ma
2.5 - 1.5 Ma
3.5 - 2.5 Ma
4.5 - 3.5 Ma
5.5 - 4.5 Ma
6.5 - 5.5 Ma
9.5 - 6.5 Ma
Lunar Crater
Volcanic Field
Reveille Range
CPLC
Nevada
Crater Flat
Yucca Mountain
California


Lunar Crater-Reveille
Yucca Mt area
Total
Number of Events
0
2
4
6
8
10
12
14
16
18
9.5-6.5
6.5-5.5
5.5-4.5
4.5-3.5
3.5-2.5
2.5-1.5
1.5-0.5
0.5-0.02
Age in Ma

Consequences of Disruption took on new significance when modeling suggested that although disruption was highly improbable it could lead to the highest release of radionuclides to surface via water table and ashfall:

Some Highlights of Consequence Analysis:

- Early 1980s: Lithic contents of eruptives, dike dimensions, hydrovolcanism, etc: Crowe et al., 1983; Link et al., 1982

- Early 1990s: Release-based requirements; DOE began examining began factors governing dike and sill formation, lithic contents of analog volcanoes; assumed backfilled drifts; Terminated about 1/3 complete due to low probability and other programmatic factors

- 1995-98. Transition to dose-based requirements

•1998. New design: large packages in backfilled drifts. Volcanism recognized as possible main contributor to dose during first 10,000 years; documentation restarted, relying on literature and idealized calculations

•2001 - Major reconsideration of work needed for scientific credibility on consequences

•CNWRA consultants model shock processes (consistent with
•DOE results) using steady state, pseudofluid flow into and through drifts.

•2002. Initiation of DOE Peer Review Process of DOE work done and planned on consequence analysis.

•Ongoing resolution of DOE-NRC issues

Proposed analog processes re Yucca Mountain

ELSEVIER

Journal of Volcanology and Geothermal Research 91 (1999) 43–64

Journal of volcanology and geothermal research

www.elsevier.com/locate/jvolgeores

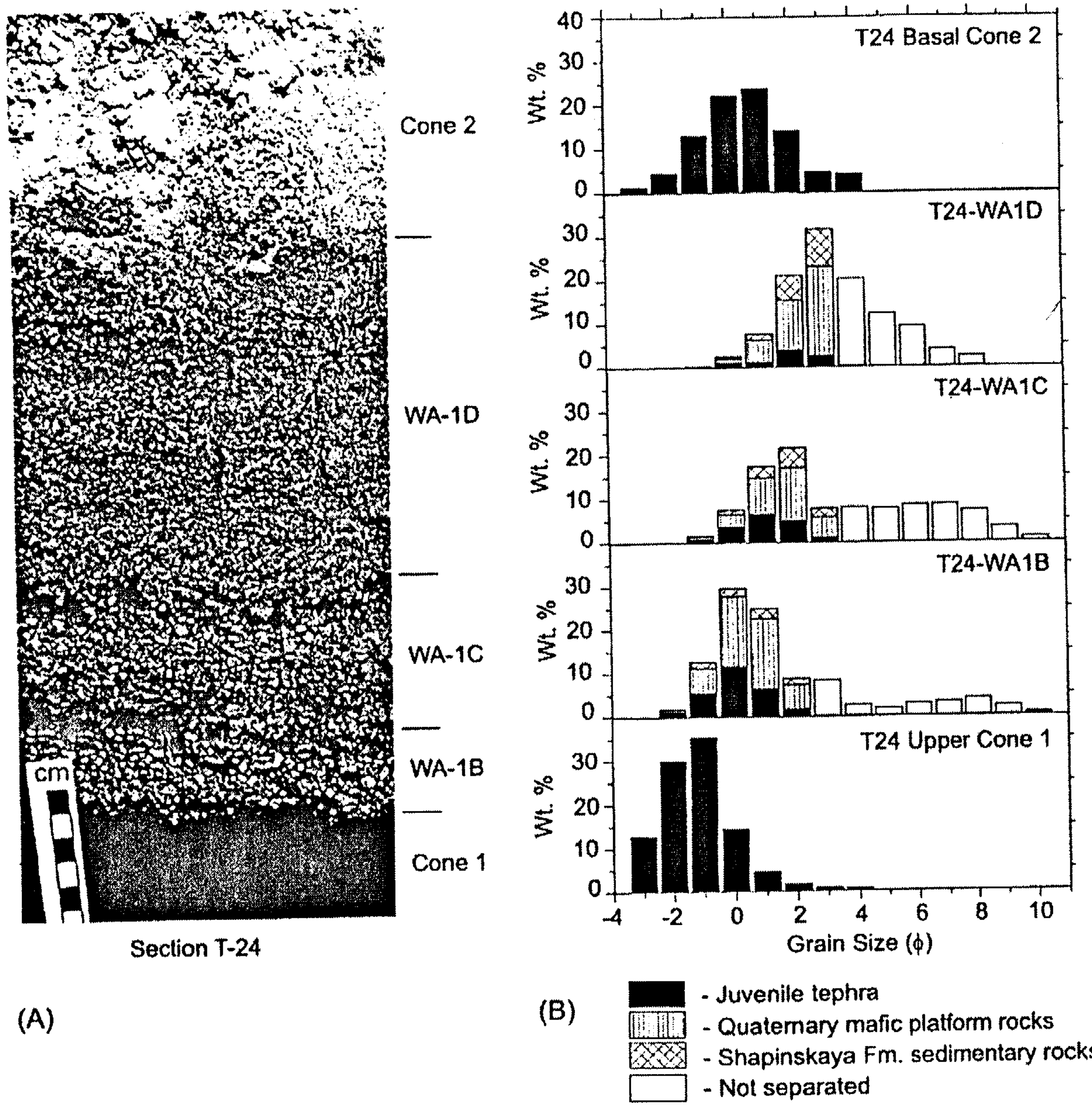
Magmatic and hydromagmatic conduit development during the 1975 Tolbachik Eruption, Kamchatka, with implications for hazards assessment at Yucca Mountain, NV

Philip Doubik [a,1], Brittain E. Hill [b,*]

[a] *Department of Geology, State University of New York, Buffalo, NY 14260, USA*

[b] *Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX 78238-5166, USA*

Accepted 16 April 1999


Cone 2
WA-1D
WA-1C
WA-1B
Cone 1
cm
Section T-24
(A)
T24 Basal Cone 2
T24-WA1D
T24-WA1C
T24-WA1B
T24 Upper Cone 1
Wt. %
Grain Size (ϕ)
(B)
- Juvenile tephra
- Quaternary mafic platform rocks
- Shapinskaya Fm. sedimentary rocks
- Not separated

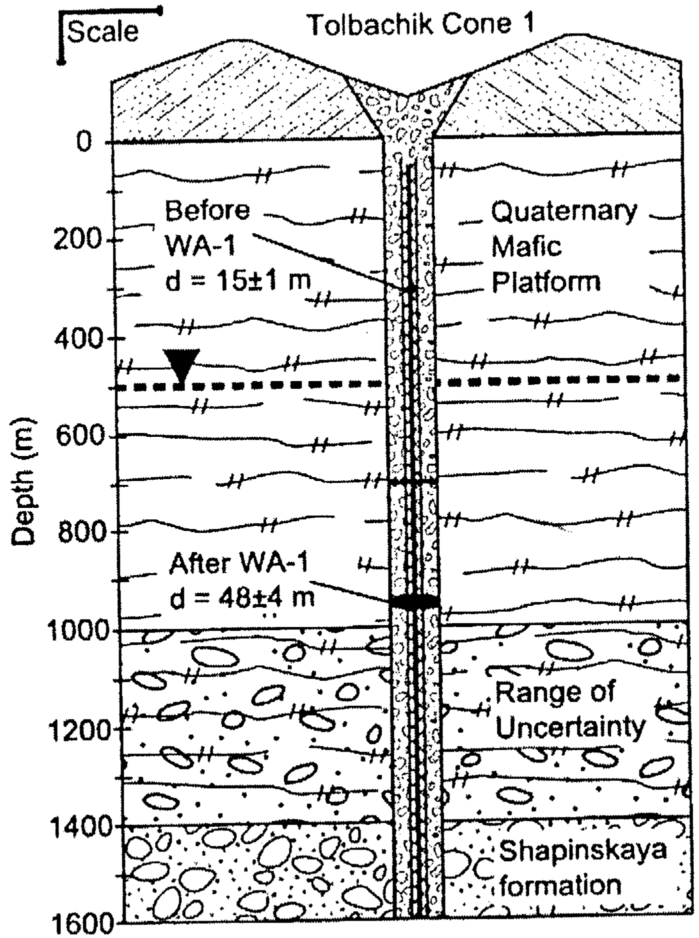
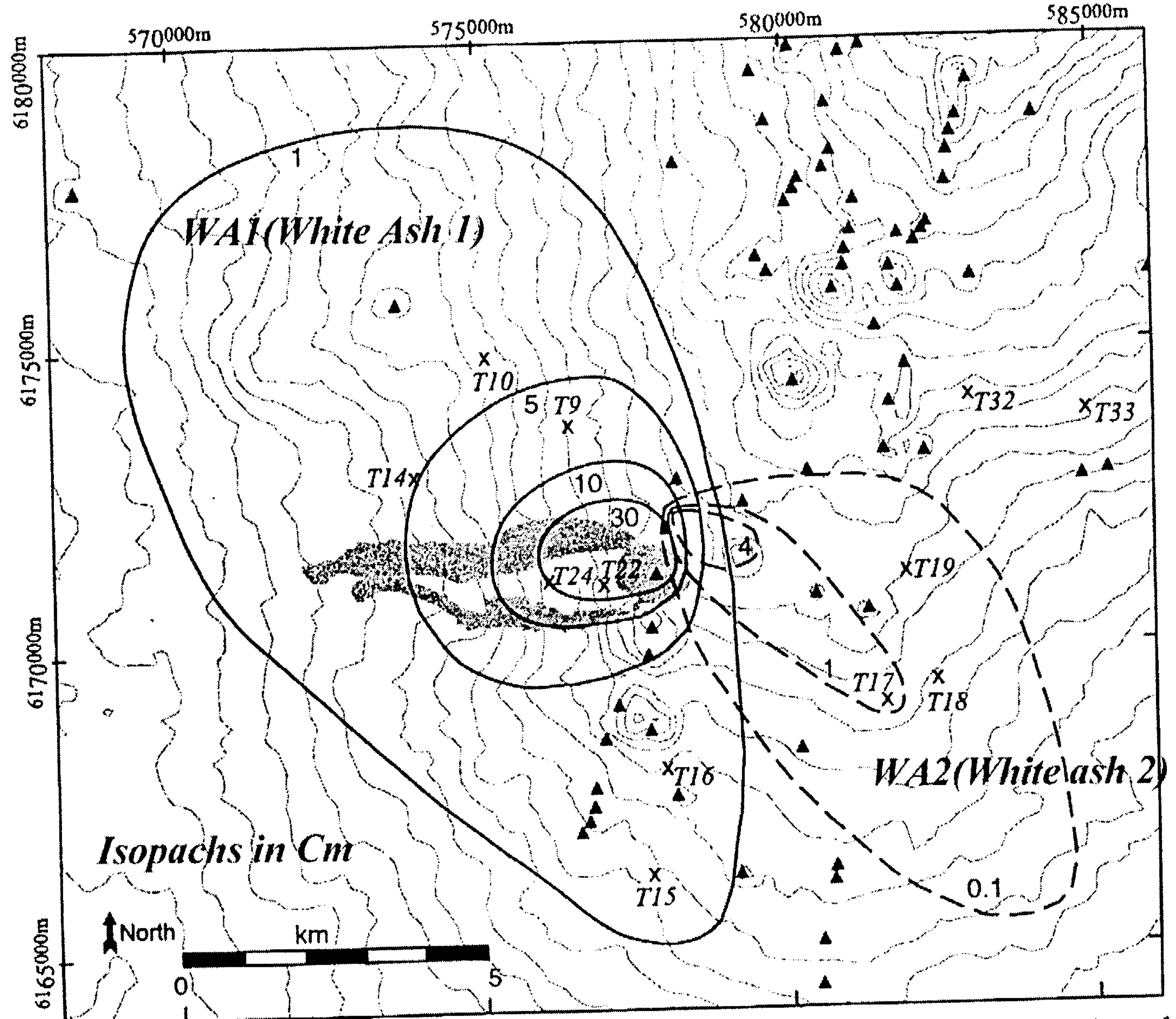


Fig. 11. Cross-section showing scale of subsurface conduit enlargement at Cone 1, relative to other geologic features. Note 2× horizontal exaggeration. Inverted triangle marks depth to water table. Although dimensions of upper breccia zone in crater are speculative, widening of the conduit to 48 ± 4 m does not appear unwarranted for a cinder cone of these dimensions.

Inclusion of More Wall Rock in Specific Episodes

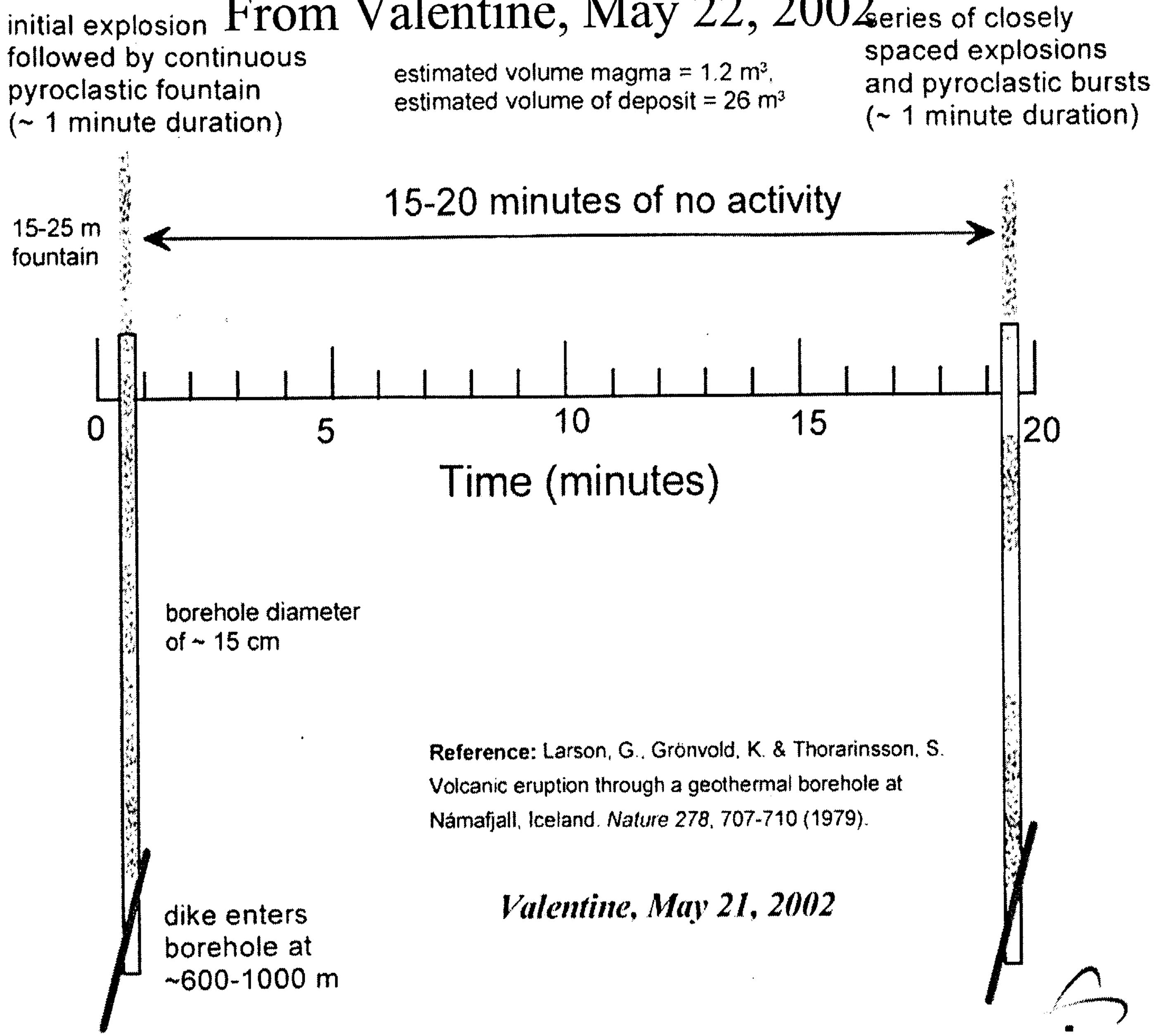


Topographic base from Fig. 1. Isopachs in centimeters for

Distribution of Xenolith-Rich Ash

Iceland borehole eruption, 1977

From Valentine, May 22, 2002



Reference: Larson, G., Grönvold, K. & Thorarinsson, S. Volcanic eruption through a geothermal borehole at Námafjall, Iceland. *Nature 278*, 707-710 (1979).

Valentine, May 21, 2002

Problem with Analog Studies of a Complex Process, such as the Consequences of Igneous Intrusion into Yucca Mountain:

Can give diverse results; there are too few to give statistically significant results: anecdotal evidence

Peer Review Panel Members

Chairperson - Dr. Robert Budnitz, Future Resources Associates, Inc.

Dr. Emmanual M. Detourney, University of Minnesota

Dr. Larry Mastin, U.S. Geological Survey 1990 USGS volcanology water

Dr. Anthony Pearson, Schlumberger Cambridge Research Centre

Dr. Allan Rubin, Princeton University

Dr. Frank Spera, University of California, Santa Barbara

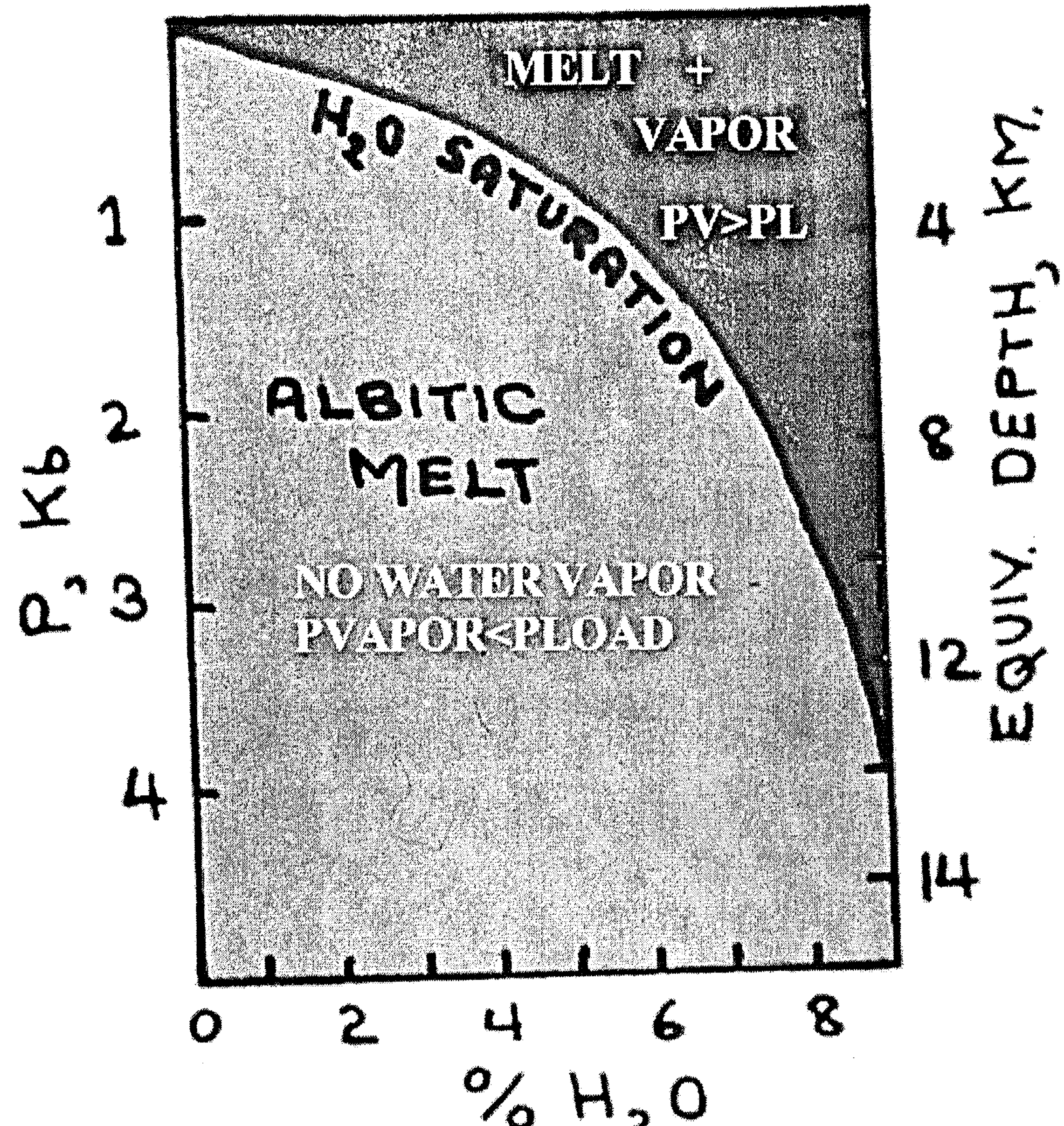
Volatiles, mainly dissolved H_2O, exert the dominant control on the explosivity of magmas: this process is directly relevant to the consequence of dike interesection with the repository

- **The effect of total pressure on the water content of a magma of the composition of albite illustrates some of the general features of explosive magma degassing.**

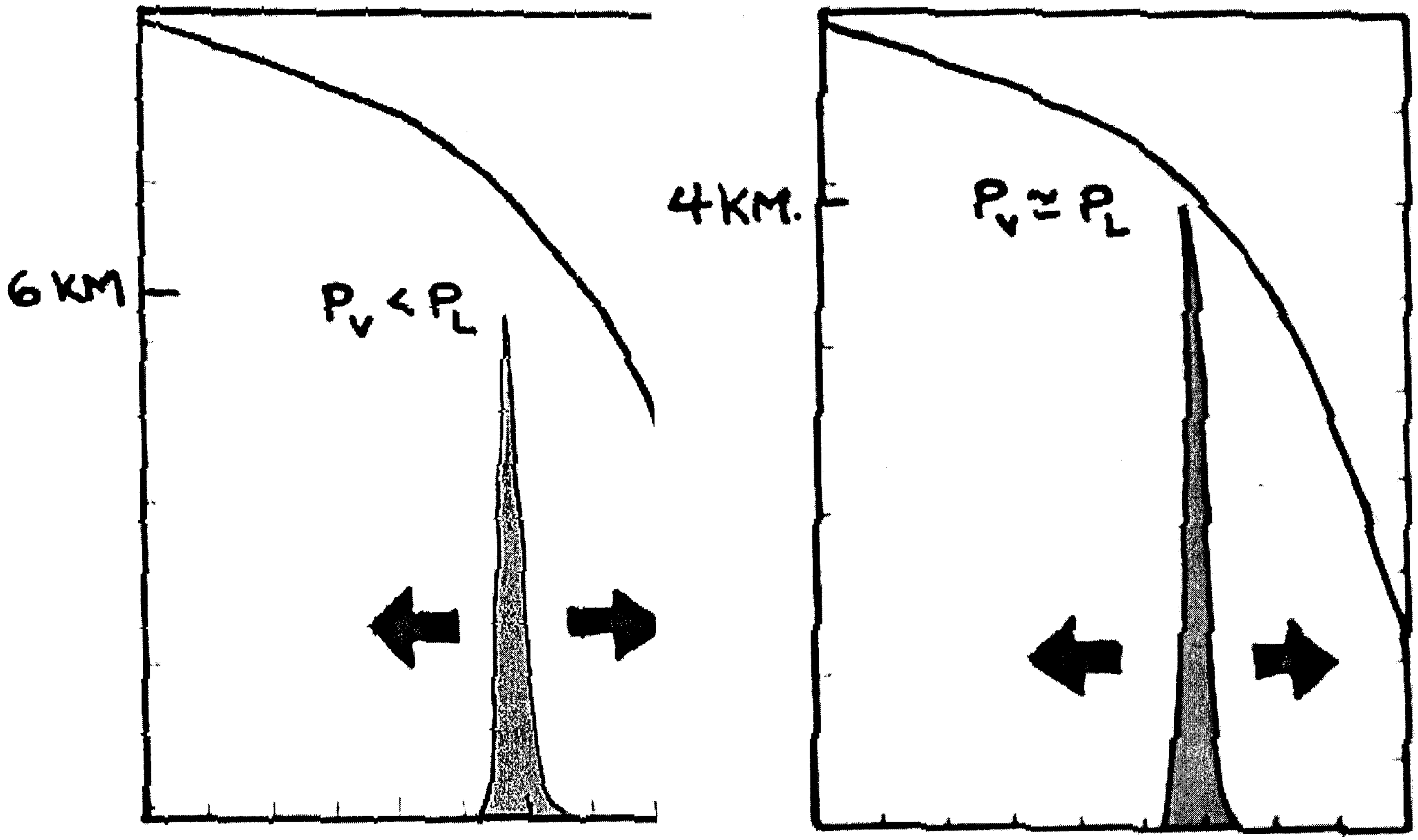
- **Cerro Negro, 1968, Nicaragua, illustrates sequence of increasingly degassesd magmas**

Volatiles, mainly dissolved H_2O, exert the dominant control on the explosivity of magmas: this process is directly relevant to the consequence of dike intersection with the repository

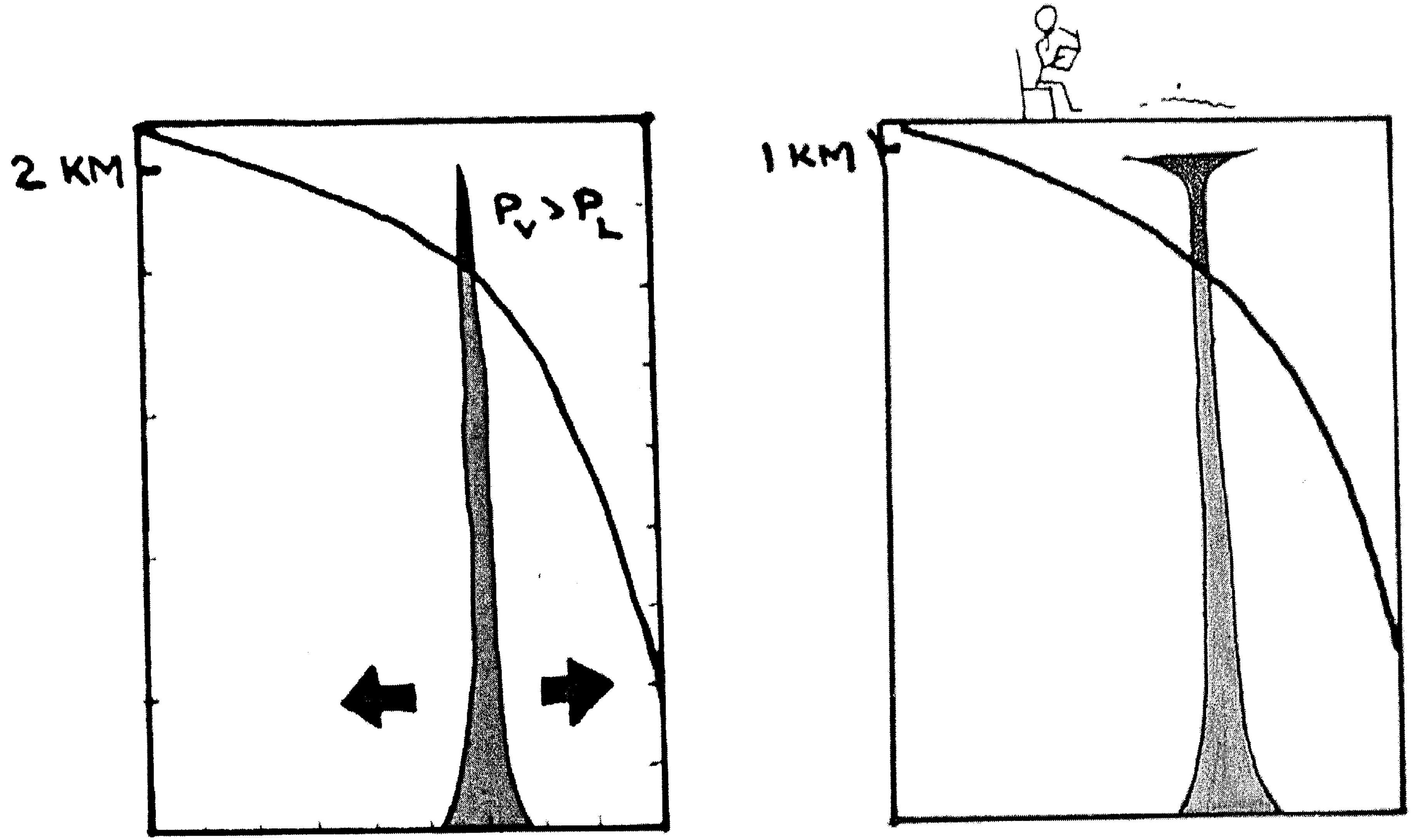
- **The effect of total pressure on a water-saturated magma of the composition of albite illustrates some of the general features of explosive magma degassing.**

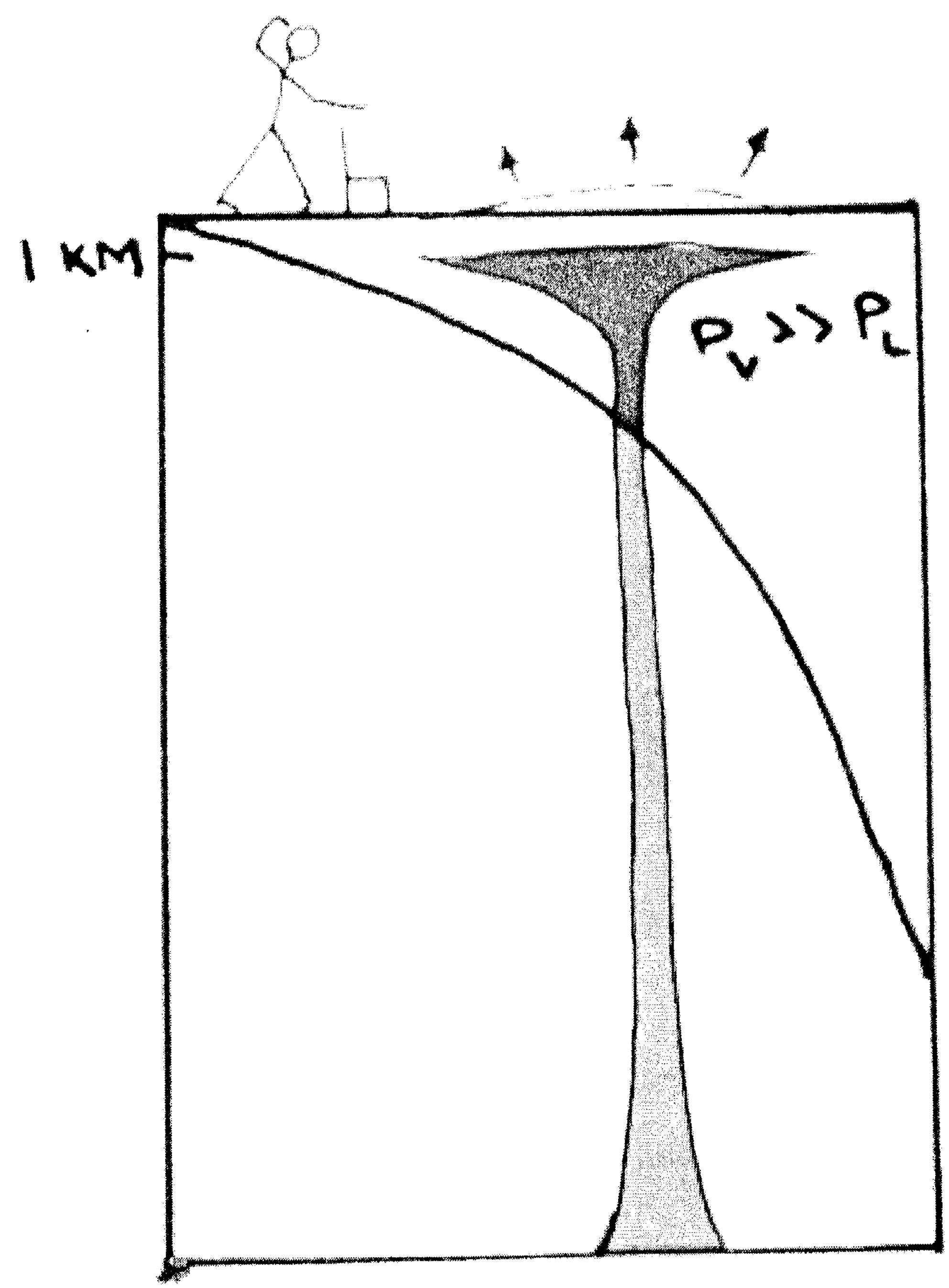


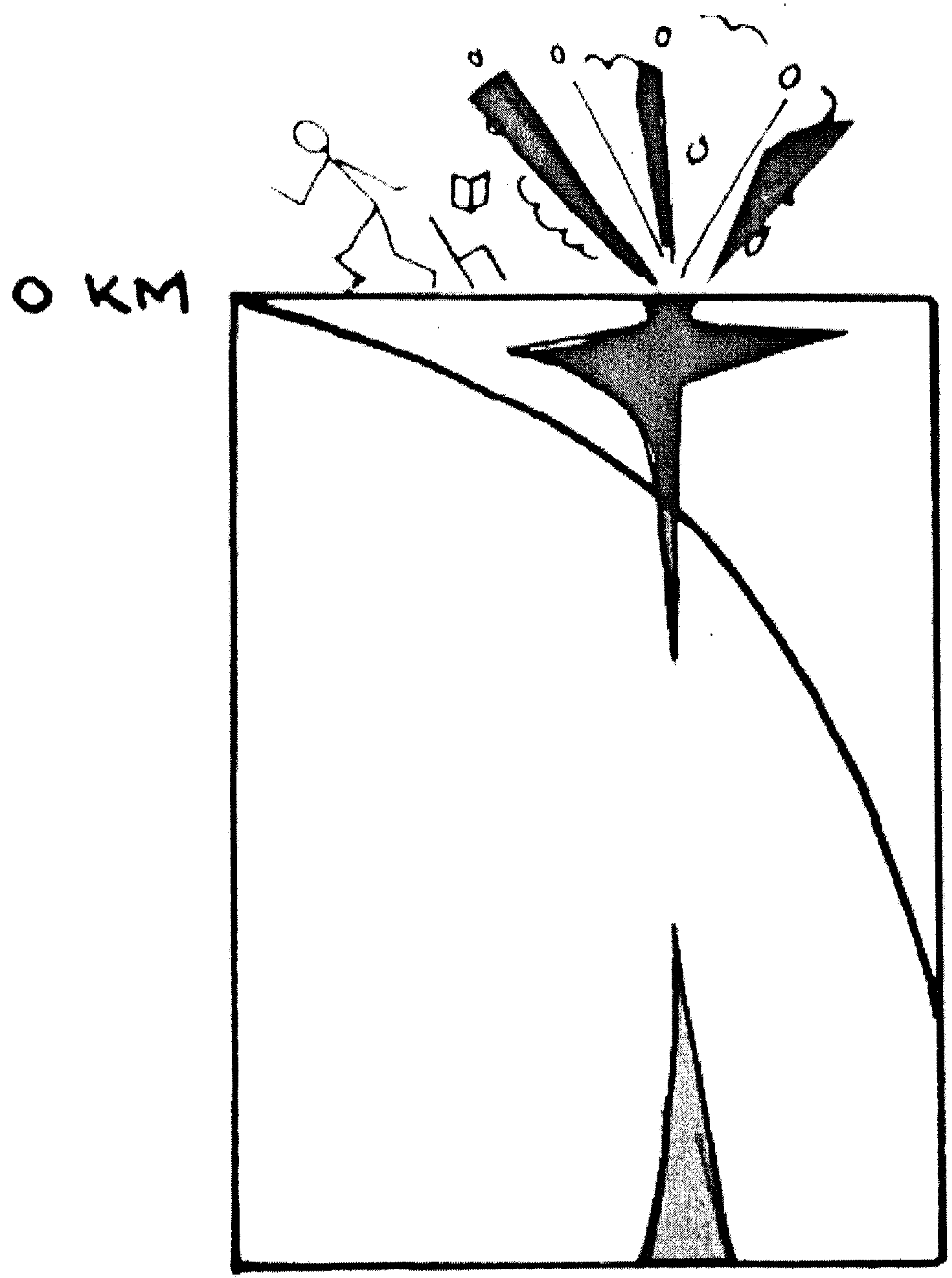
Phase Diagram: Albite + Water



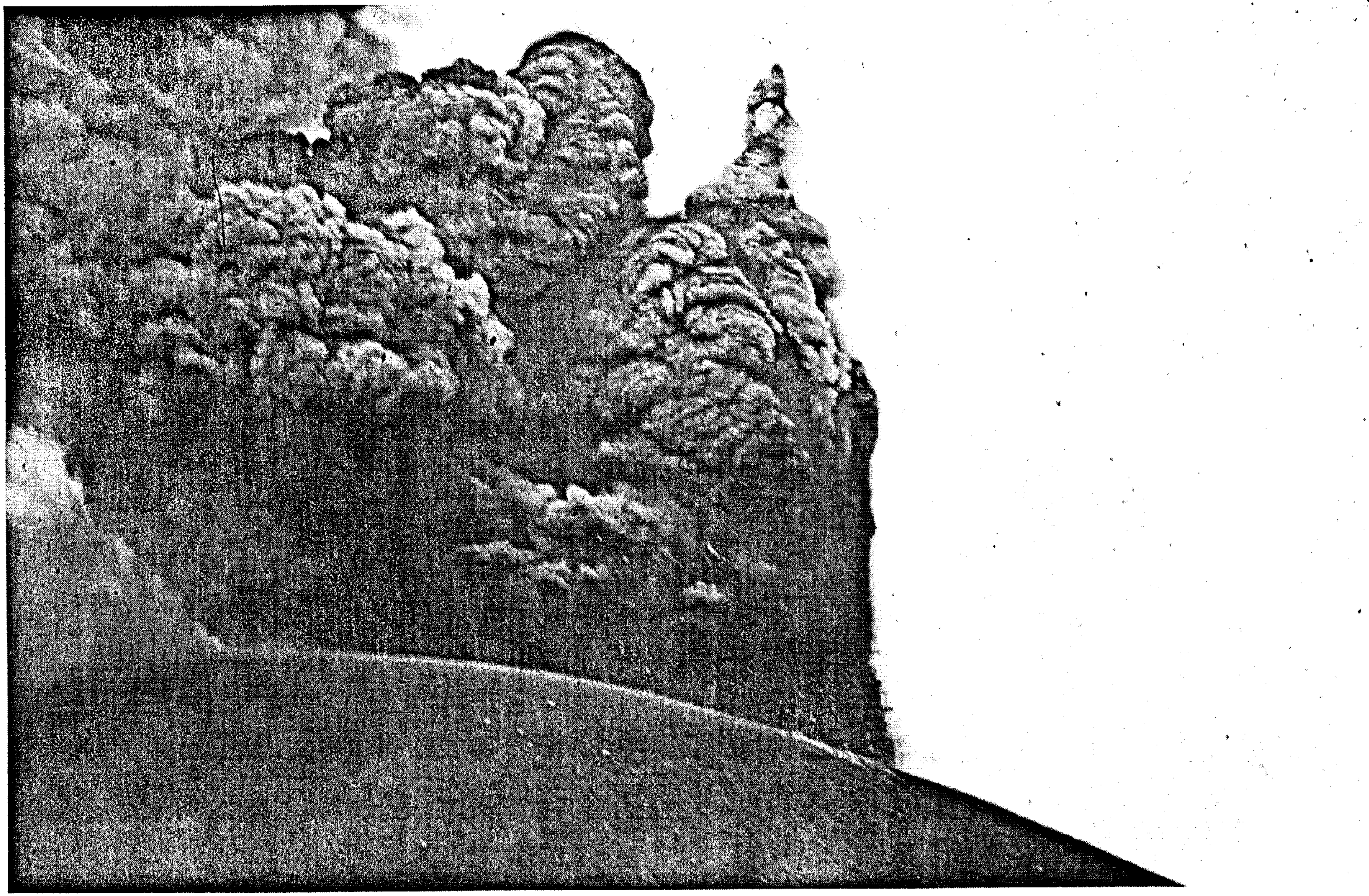
6 KM
$P_v < P_L$
4 KM.
$P_v \simeq P_L$


2 KM
$P_V > P_L$
1 KM

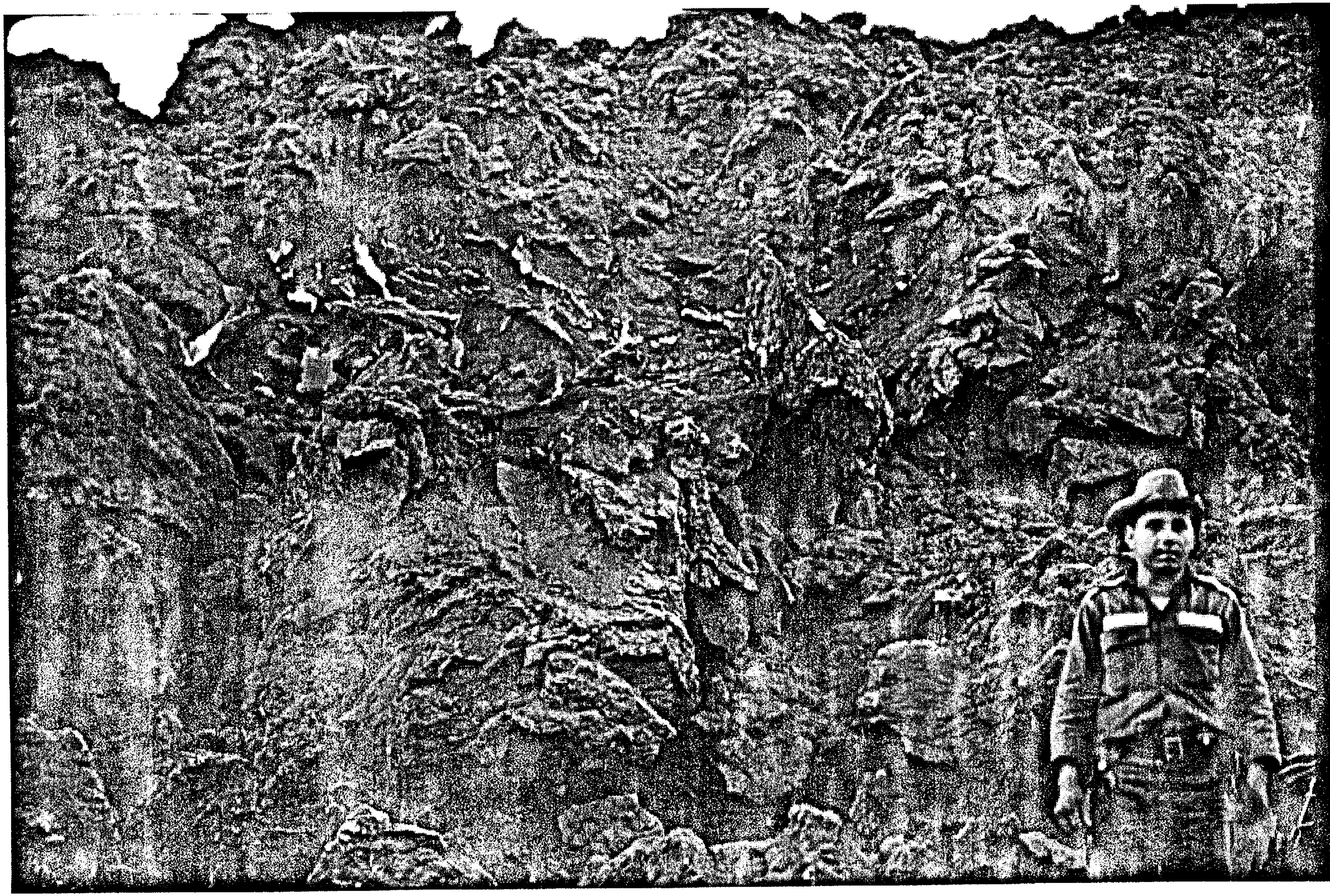

1 KM
$P_V >> P_L$


0 KM

- **Cerro Negro, 1968, Nicaragua, illustrates sequence of increasingly degassesd magmas. Cerro Negro by Conner (CNWRA) cited as similar to some of the cinder cones of Crater Flat.**

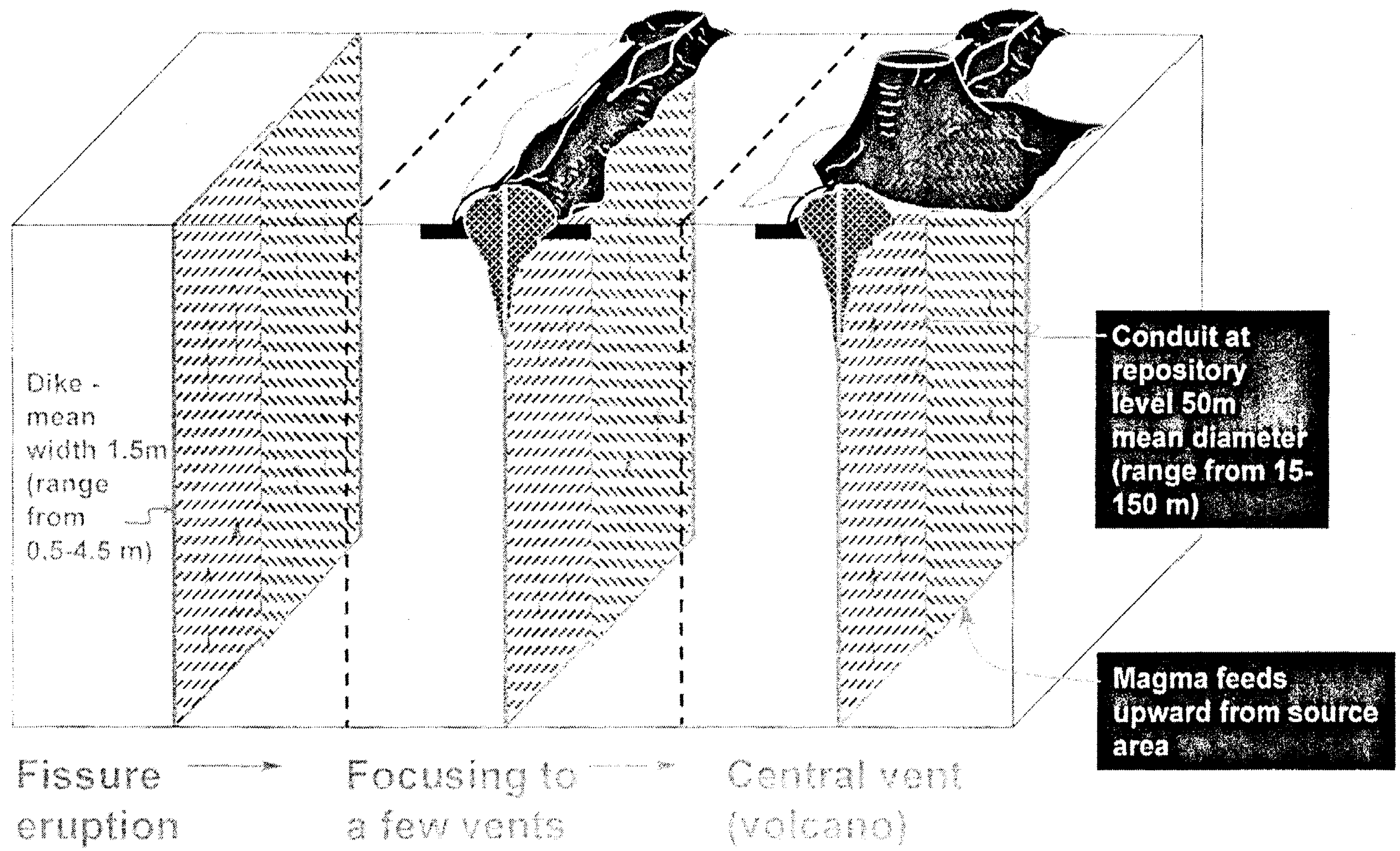


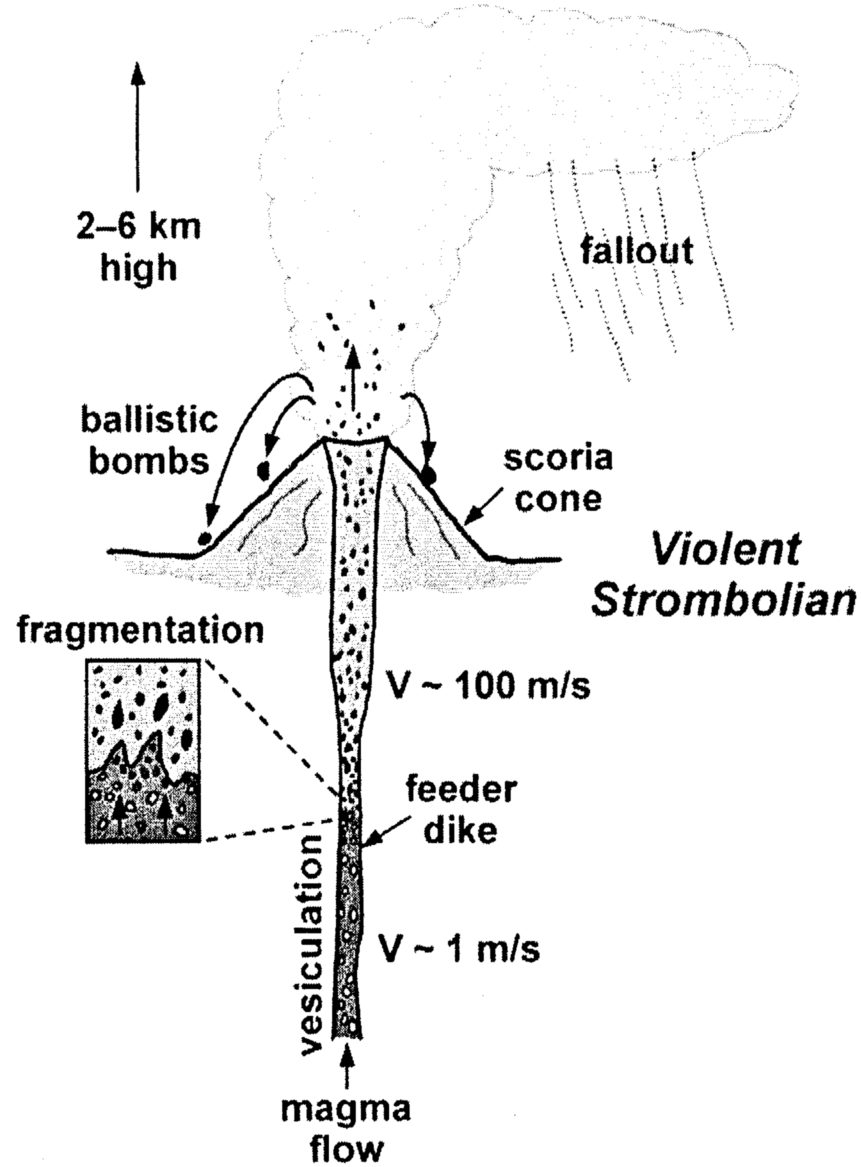
Cerro Negro, 1968



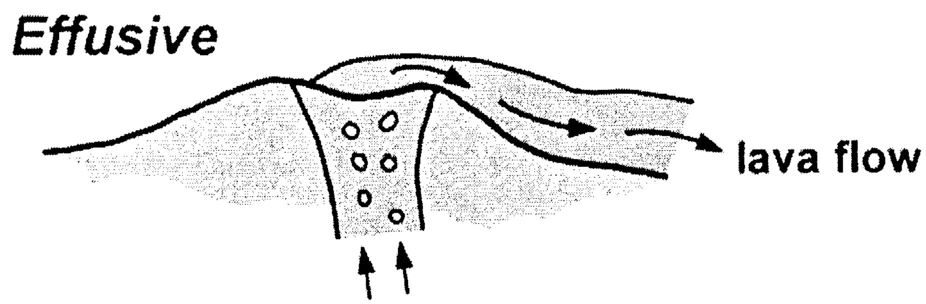
Aa-flow, Cerro Negro, Nicaragua, 1968

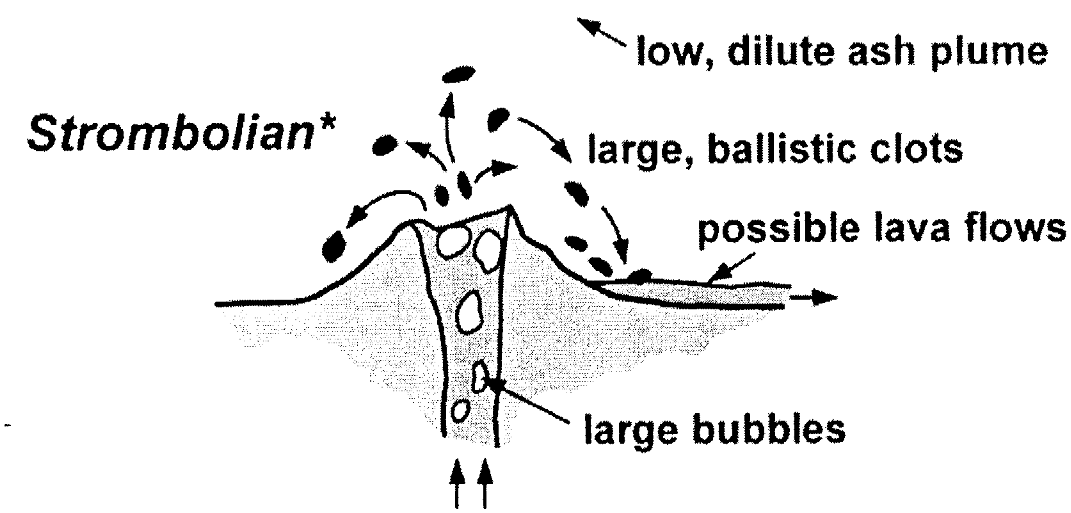
Progression from Intrusion to Surface Cone(s)





Initial Phase may involve intense fountaining and explosions





Longest phase commonly involves lower volume pyroclatic eruptions and lava flows

Work by CNWRA on intrusive consequence has been helpful, including shock wave consequences, and will be commented on by Megan Morrissey and hopefully extended by work of Ed Gaffney of LANL

There are three magmatic parameters that lessen the impact on intersection that have not been adequately taken into account in DOE and CNWRA:

• Cooling and solidification brought on by rapid (explosive) gas expansion (nearly adiabatic expansion)

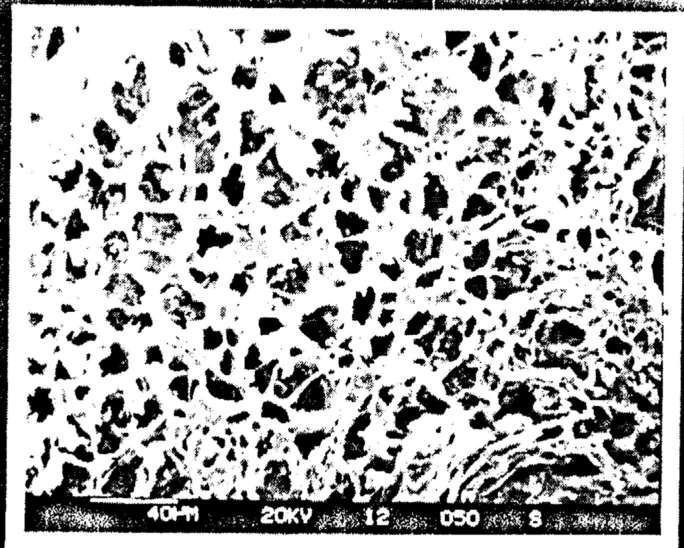
• Lack of excess heat in magmas: they erupt at or below their liquidus. They thus have limited capacity to melt other high-temperature materials without forming a glass or crystallizing. Lava tubes form by magma runoff beneath a solid carapace, not by melting.

•Maximum "momentary overpessures in the Lathrop Wells magma about 2 x 108 Pa (2 kilobars) for maximum water content estimate (4%) and 650 x 107 Pa (650 bars, for 2%) more likely.

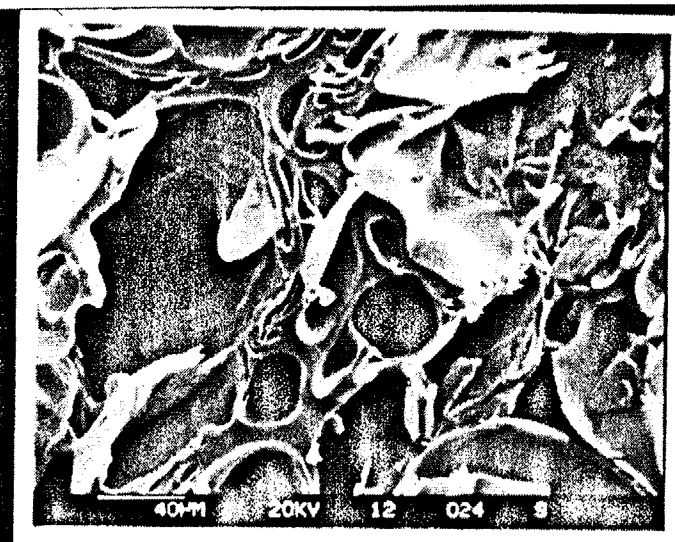
Expected Magma Properties

Valentine, May 21, 2002

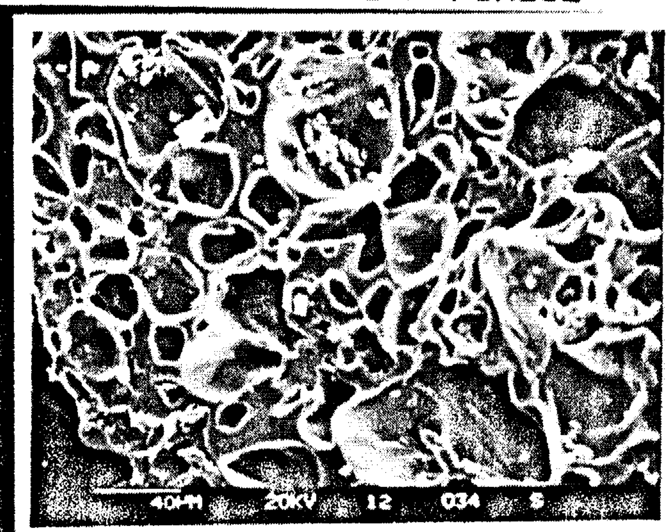
	H_2O Saturation Pressure (Pa)	Liquidus Temperature (C)	Viscosity (log poise)	Density (kg/m^3)
Minimum H_2O content — 0%	1.0×10^5	1169	2.68	2663
Maximum H_2O content — 4%	1.7×10^8	1046	1.96	2474



18MAY80 ST. HELENS PLINIAN PUMICE



13NOV85 RUIZ PLINIAN PUMICE



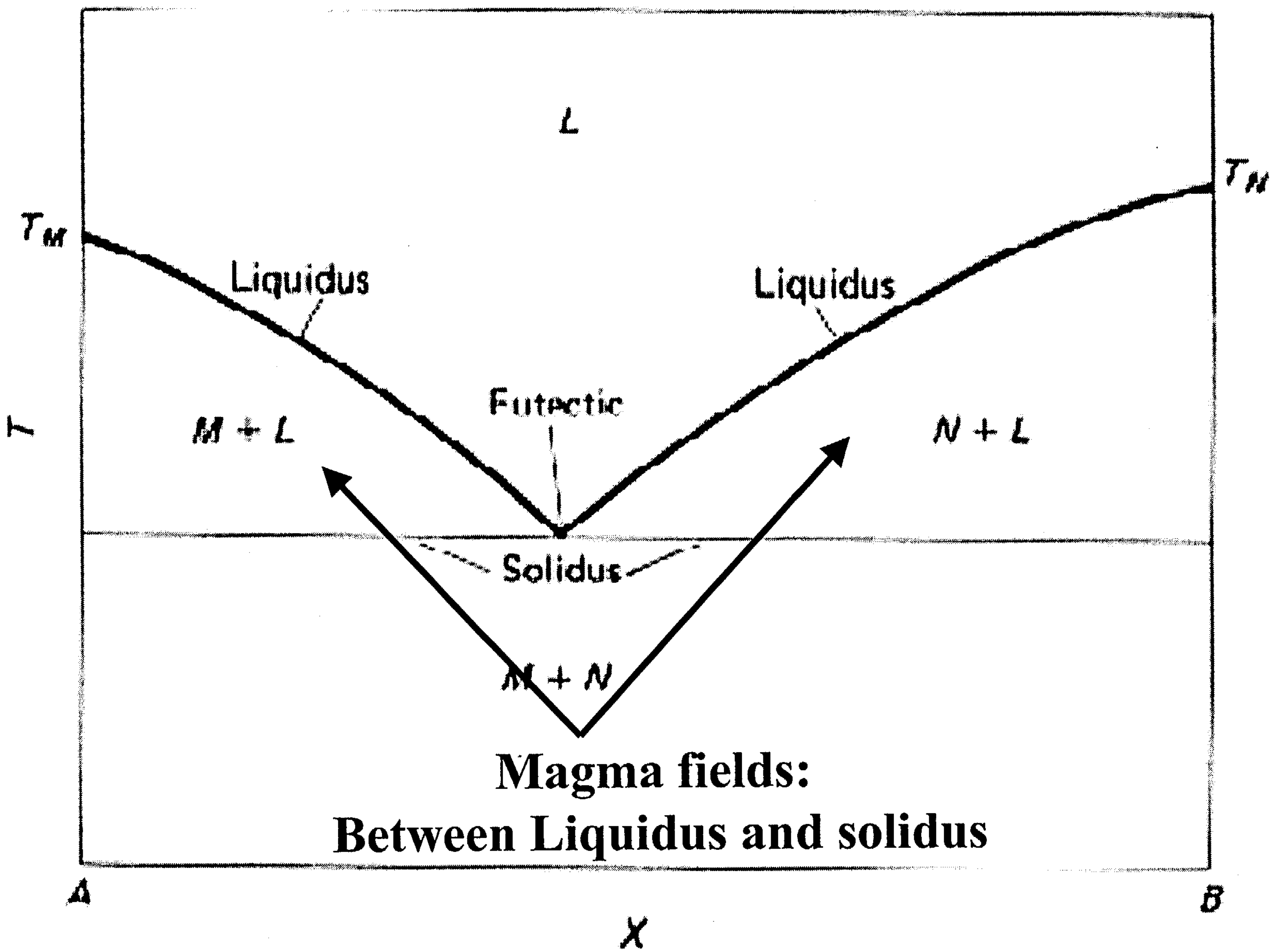
1595 AD RUIZ PLINIAN PUMICE

There are two properties of magmas that lessen their impact on intersection with the repository

- Cooling and solidification brought on by rapid (explosive) gas emission

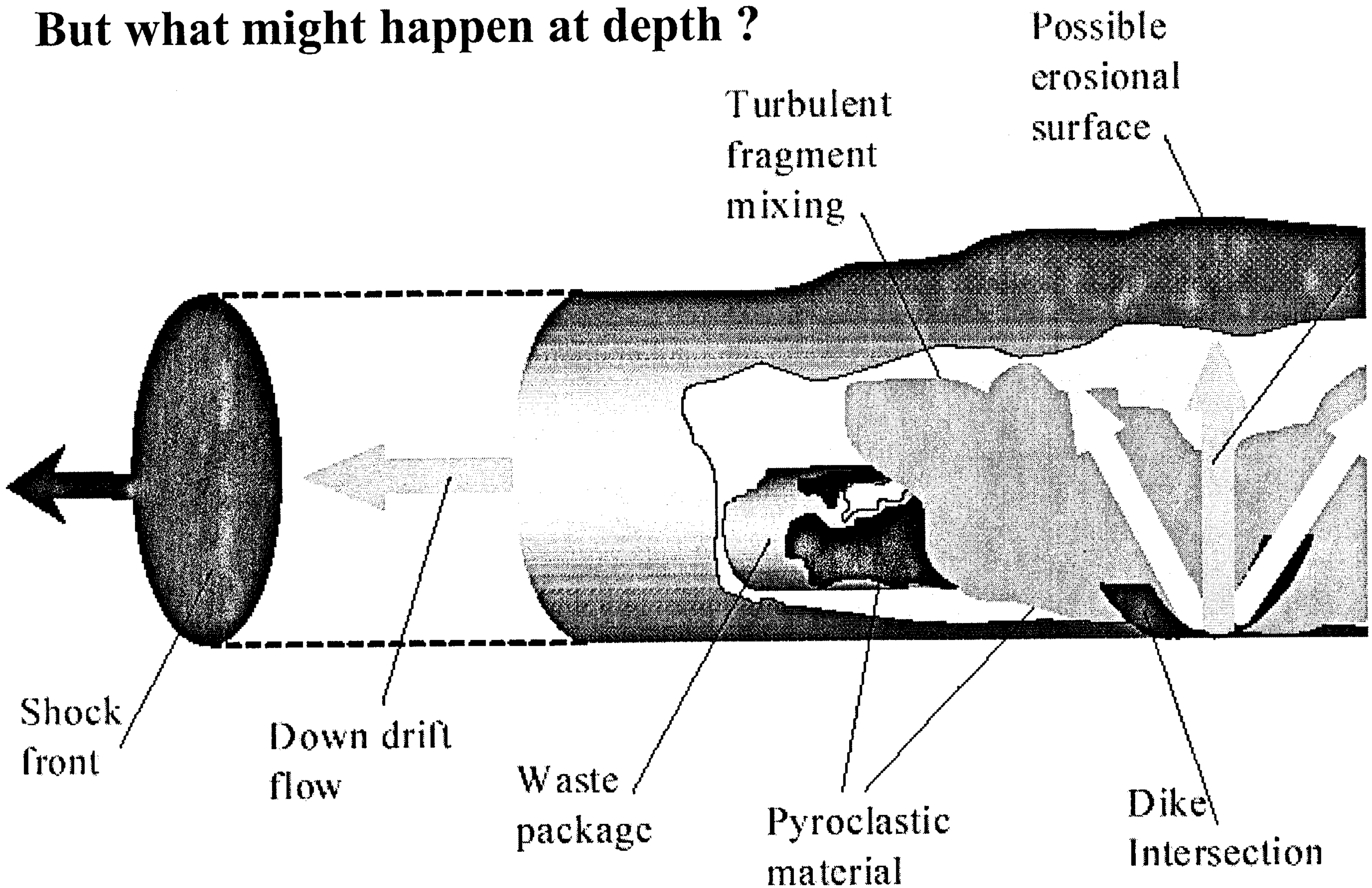
- Lack of excess heat in magmas: they erupt at or below their liquidus. They thus have limited capacity to melt other high-temperature materials without forming a glass or crystallizing. Lava tubes form by magma runoff beneath a solid carapace, not by melting.

- Maximum "momentary" overpessures in the Lathrop Wells magma about 2 x 10^8 Pa (2 kilobars) for maximum water content estimate (4%) and 650 x 10^7 Pa (650 bars, for 2%) more likely.

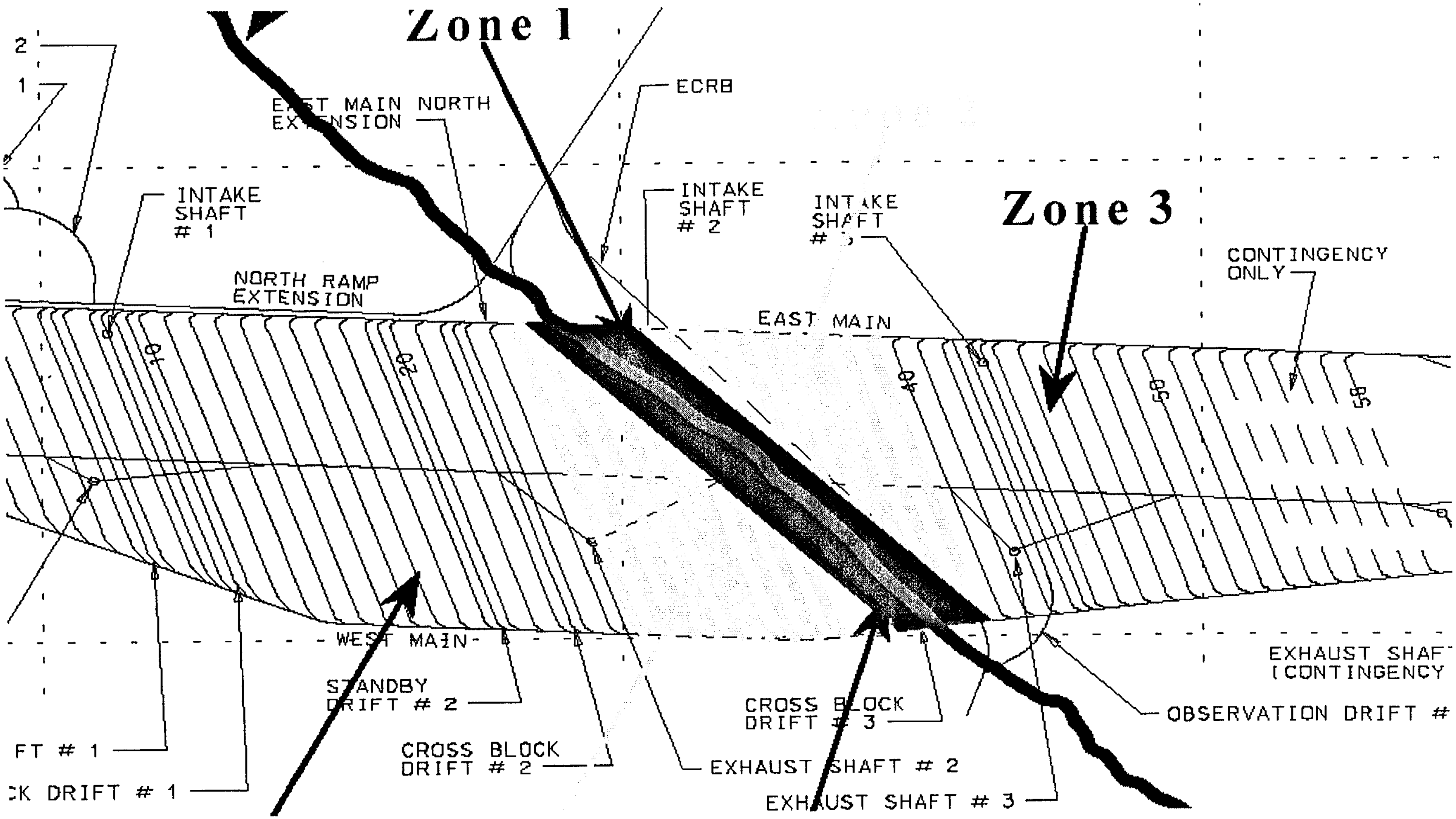


L
T_M
T_N
Liquidus
Liquidus
Eutectic
M + L
N + L
T
Solidus
M + N
A
B
X
Magma fields:
Between Liquidus and solidus

But what might happen at depth ?



From DOE Analysis Model Report (AMR) "Igneous Consequence Modeling for the TSPA-SR", 11/21/00



From DOE Analysis /Model Report (AMR) "Igneous Consequence Modeling for the TSPA-SR", 11/21/00

Summary:

1. Probability estimates will not be greatly changed: Additional magnetic anomaly work will probably not greatly change estimates

2. Main missing analyses concern consequences of intrusion. Past work by DOE and CNWRA helpful in moving process along but must now be extended by broader approach taking into account more parameters using long tested code by Gaffney (LANL) proposed by DOE. Additional studies of Lathrop Cone, analog, and other aspects aimed at consequence analysis by DOE need completion. Code for ASHLUME I believe needs further evaluation and that evaluation is proposed by DOE.

3. DOE peer review will prove critical is assessing DOE work on consequence analysis.

3. DOE and NRC exchanges have identified these and other issues that need resolution and resolution is in process.

My perception is that work on volcanic hazards that needs to be done is either proposed or underway.

Some Rock Mechanics Aspects of Dike-Repository Interaction

Derek Elsworth

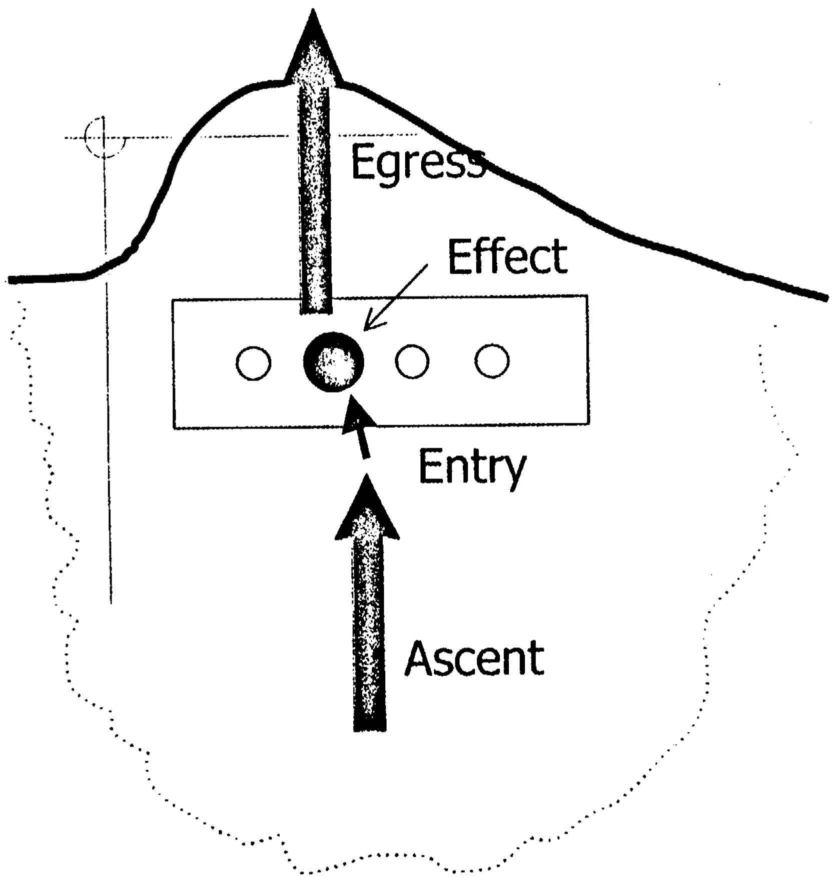
NRC – Advisory Committee on Nuclear Waste
Tuesday, June 18th, 2002
[Modified from NWTRB Meeting of Thursday, November 8th, 2001]

Comments and discussion on reference material – emphasis on magma-rock interactions

- Ascent to repository level
- Entry into drifts
- Effect on drift(s)
- Egress from drift(s)

Comments on proposed DOE and NRC plans for resolving these issues

Overview



Egress from Drift(s)

- Egress locations and form

Effect on Drift(s)

- Ingress location
- Anticipated magma overpressure
- Pressure wave
  - Dynamic effects and failure
  - Relaxation
- Magma ingress
- Effect of in-drift structures
- Maximum sustainable in-drift pressures

Entry into Drift(s)

- Control by local stress state
- Anticipated magma overpressures

Ascent to Repository Horizon

- **Rotation of field stresses**
- **Effect of topography**
- **Role of structure (as stresses rotate)**
- **Anticipated maximum magma overpressures**

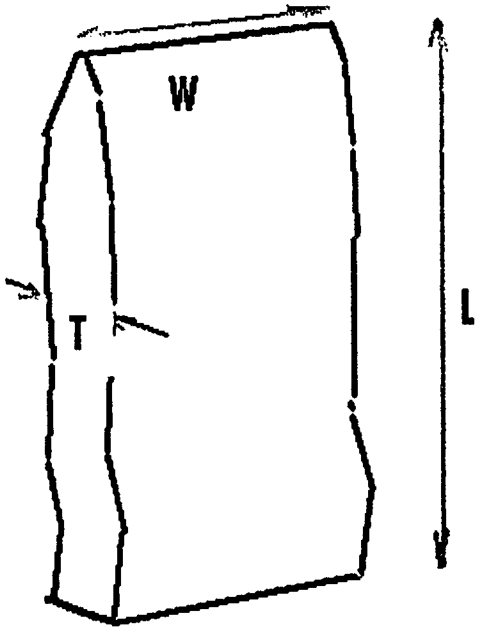
Dike Ascent Mechanisms

Ascent Conditions: $p_m > s_h$

$$T_{\min} = \textit{Thermal Freezing}$$

$$T_{\max} = \frac{(p_m - s_h)}{G/(1-\nu)} W$$

$$K_{Icrit} > K_I = (p_m - s_h)\sqrt{L}$$



1. Driven by buoyancy contrast (Woods et al, 2001)

$$\left.\begin{cases} \rho_{magma} = 2600 kg/m^3 \\ \rho_{crust} = 2400 - 2940 kg/m^3 \end{cases}\right\} \Delta\rho = 70 kg/m^3 \textit{ or } 0.7\ MPa/km$$

builds to 20 MPa over 30 km

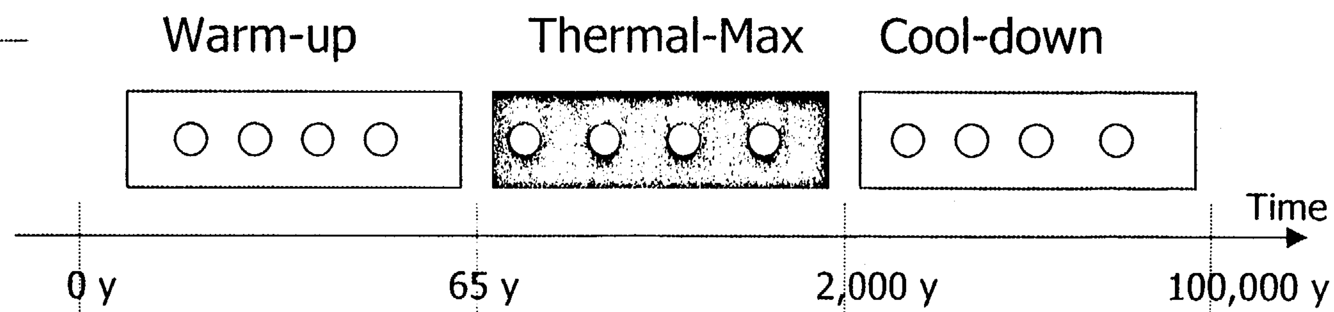
Note ρ_{crust} *of* 2260 – 2940 kg / m³ *gives neutral buoyancy*

2. Will build to maximum magma pressure only as:
   1. Conduit losses diminish (static system)
      [1m dike at 1 m/s loses 0.1 MPa/km]
   2. Tip process-zone allows

For K_{Icrit} =1 MPa m$^{1/2}$ (e.g. Rubin, 1995)

L(km)	(Pm - Sh)(MPa)
30	0.006
5	0.014
1	0.03

Yucca Mountain – Schematic Thermal Rock Mechanics



Drift wall dT	T<80°C	T=150-100°C	T=100-10°C
Average Thermal Zone dT		T=85°-60°C	T=60-10°C
Repository-level Stresses (MPa)	7 3-4	7 11-15	7 3-4

Thermal and Quasi-static Stresses

			Thermal Maximum	Warm-up And Cool-down
Repository Zone Stresses	$\Delta Sh \approx \Delta SH \approx \dfrac{\alpha(ERm)\Delta Tav}{(1-\nu)}$	$\left\{\begin{array}{l} E = 10 - 40\ GPa \\ Rm = 0.15 \\ \nu = 0.25 \\ \alpha = 10^{-5}/{}^{\circ}C \end{array}\right\} \approx$	11 (150°) – 8 MPa (100°)	8 - 1 MPa
Drift-wall Hoop Stresses	$\Delta\sigma_{\theta} \approx \dfrac{\alpha(ER_m)}{1-\nu}(\Delta T_{drift} - \Delta T_{av})$	$\left\{\begin{array}{c} E = 10 - 40\ GPa \\ Rm = 0.15 \\ \upsilon = 0.25 \\ \alpha = 10^{-5}/{}^{\circ}C \end{array}\right\} \approx$	8 (65°) - 5 MPa (40°)	8 – 1 MPa

~0.1 MPa per °C

Quasi-static pressurization

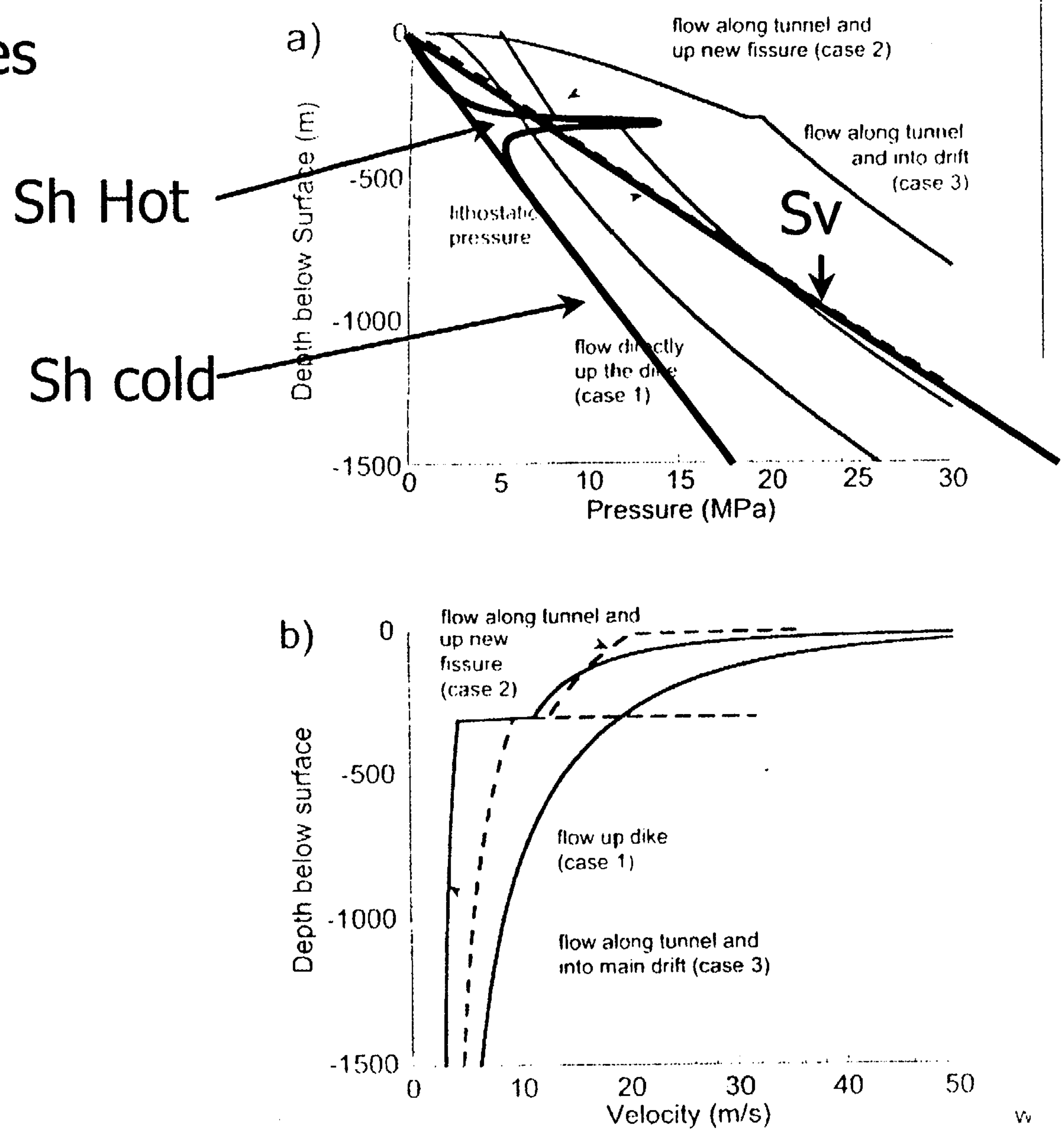
$$\Delta\sigma_{\theta} \approx -\Delta p\frac{a^2}{r^2} \approx -40MPa$$

$$\Delta\sigma_{r} \approx \Delta p\frac{a^2}{r^2} \approx +40MPa$$

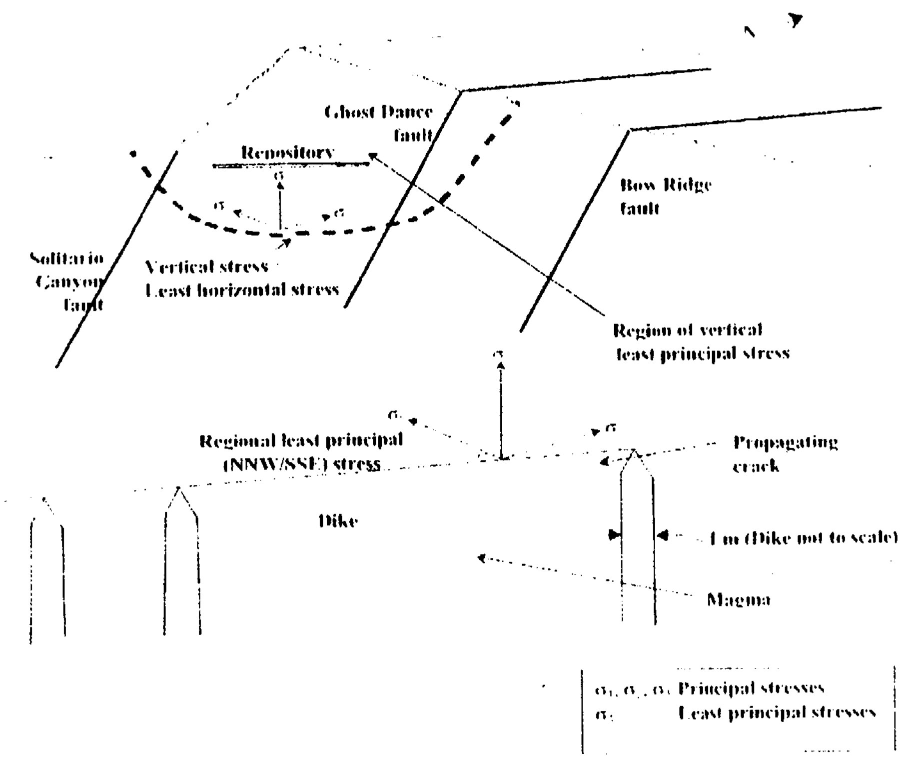
$$\Delta u_{r} \approx \frac{\Delta pa}{2G} \approx 10mm$$

In Situ Stress Profiles

- Mountain-scale vertical stress will change little with heating or cooling of repository
- High horizontal stresses develop at thermal maximum
- Magma pressures and over-pressures limited by rock strength at mountain-scale.



Mountain-Scale Effects

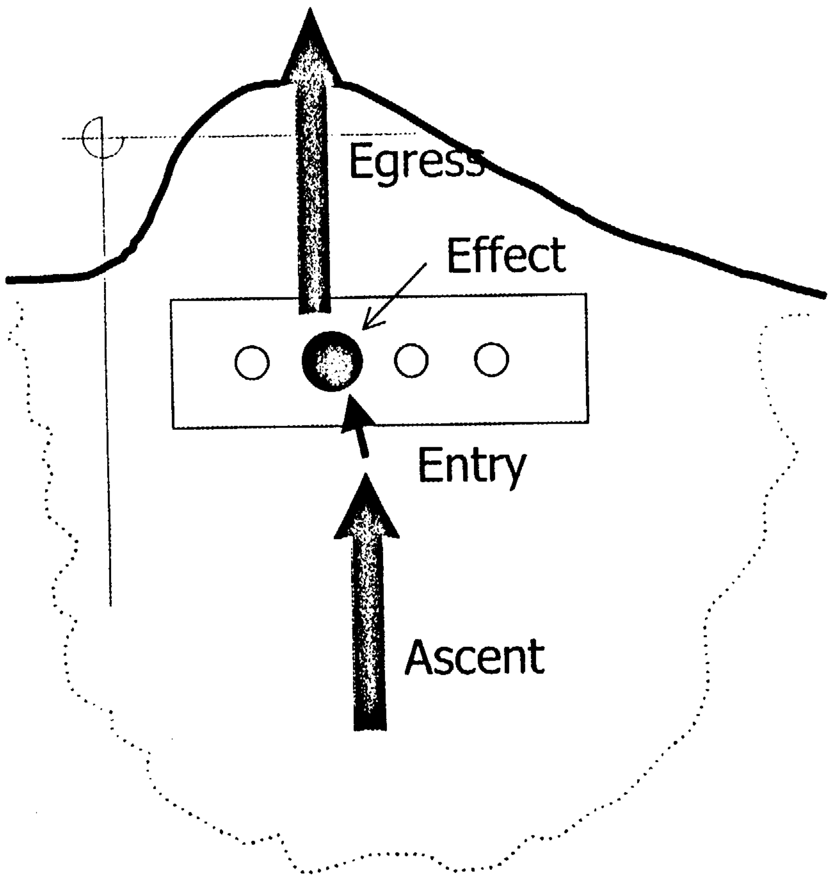


Source: Integrated Site Model-Disruptive Events Report

Issues:

1. Over-pressures limited by failure of the host rock.
2. Thermal stresses in repository horizon will be significant in the maximum thermal period
   - Vertical stress becomes minimum principal stress (65y – 2000y)
   - Barrier zone is thin. Order 40m
   - Weak extensional zone below repository
   - As S_h and S_H become closer structural controls (faults) may assume a larger role on intrusive processes
3. Topographic effects of adjacent Crater-Flats

Overview



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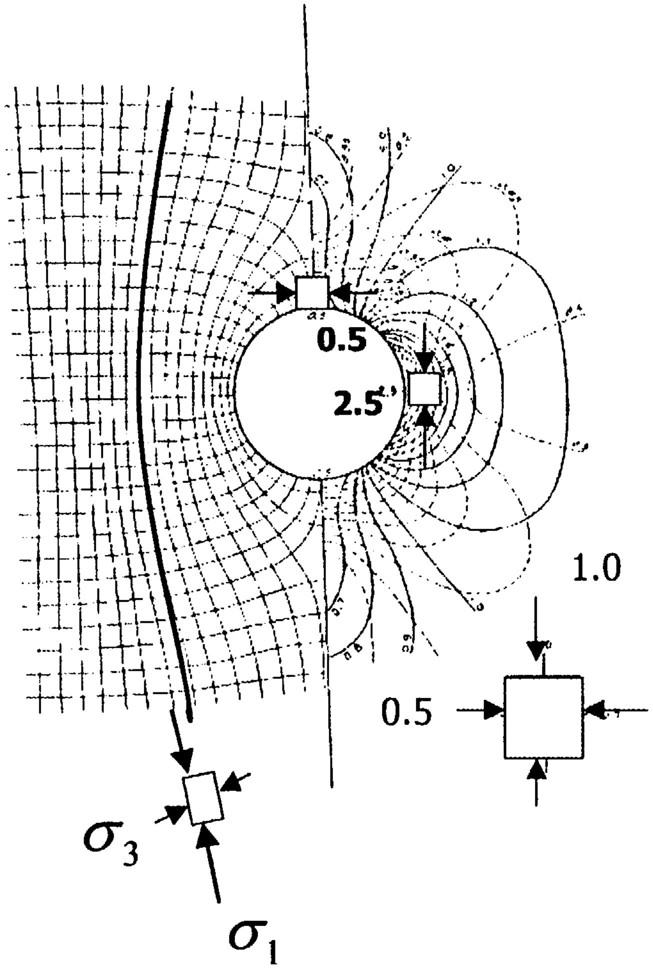
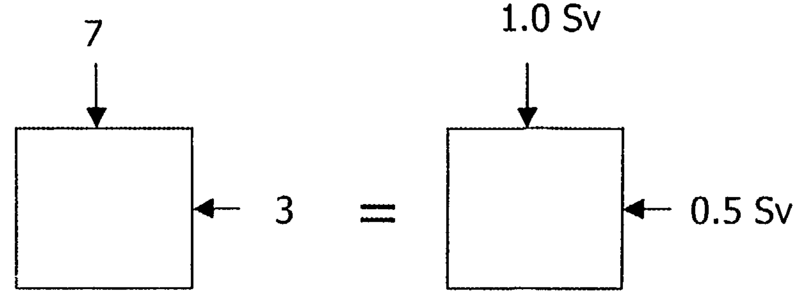
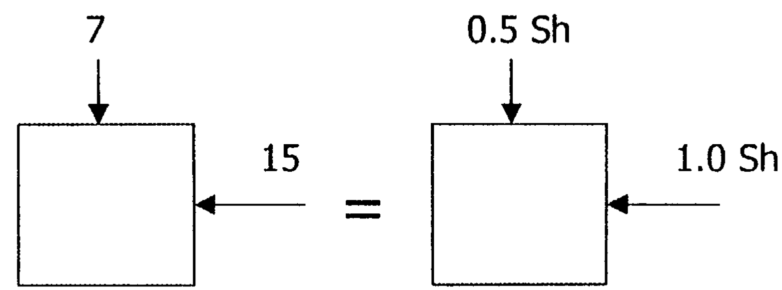
Drift Stresses



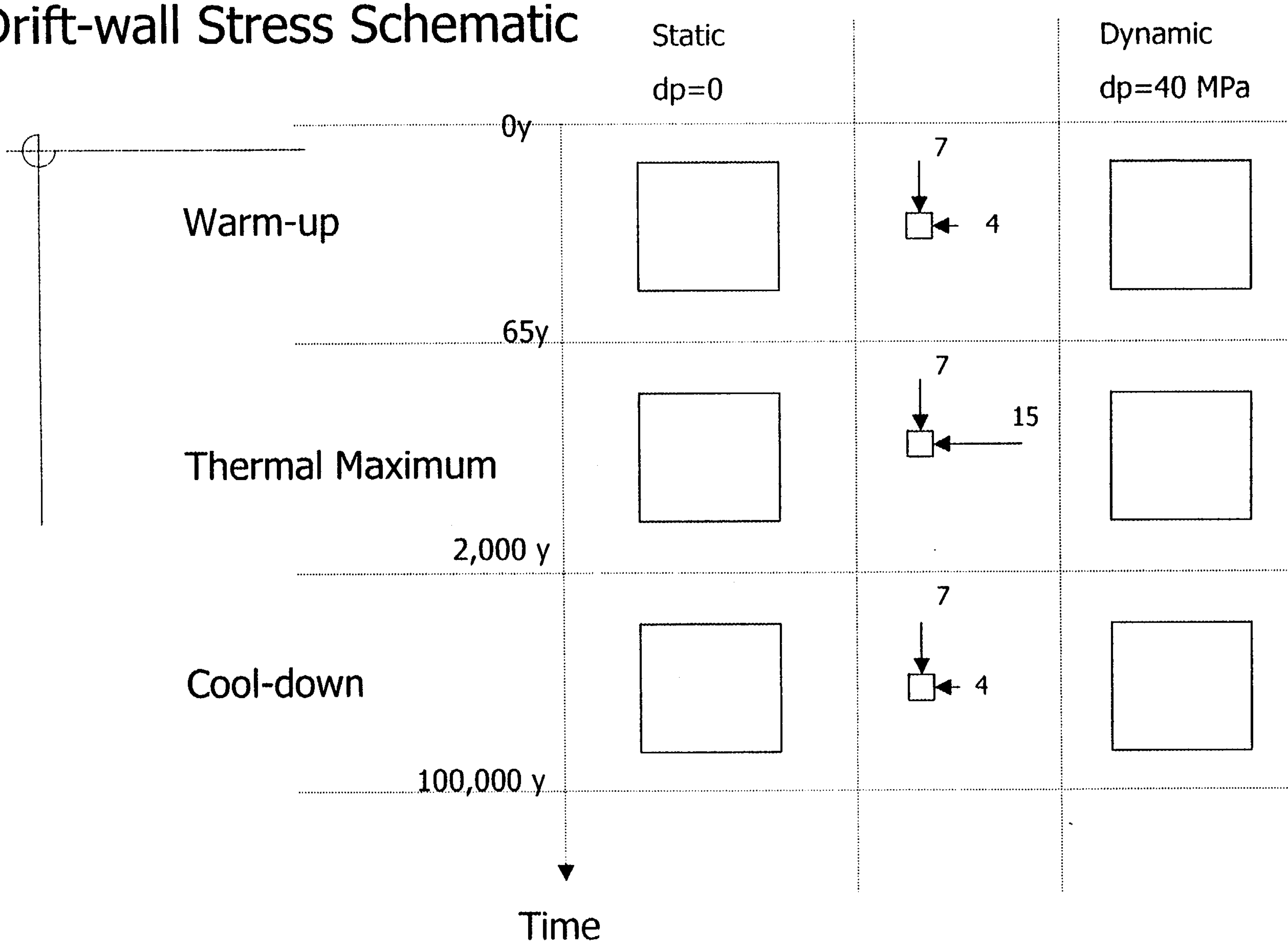
Warm-up and Cool-down



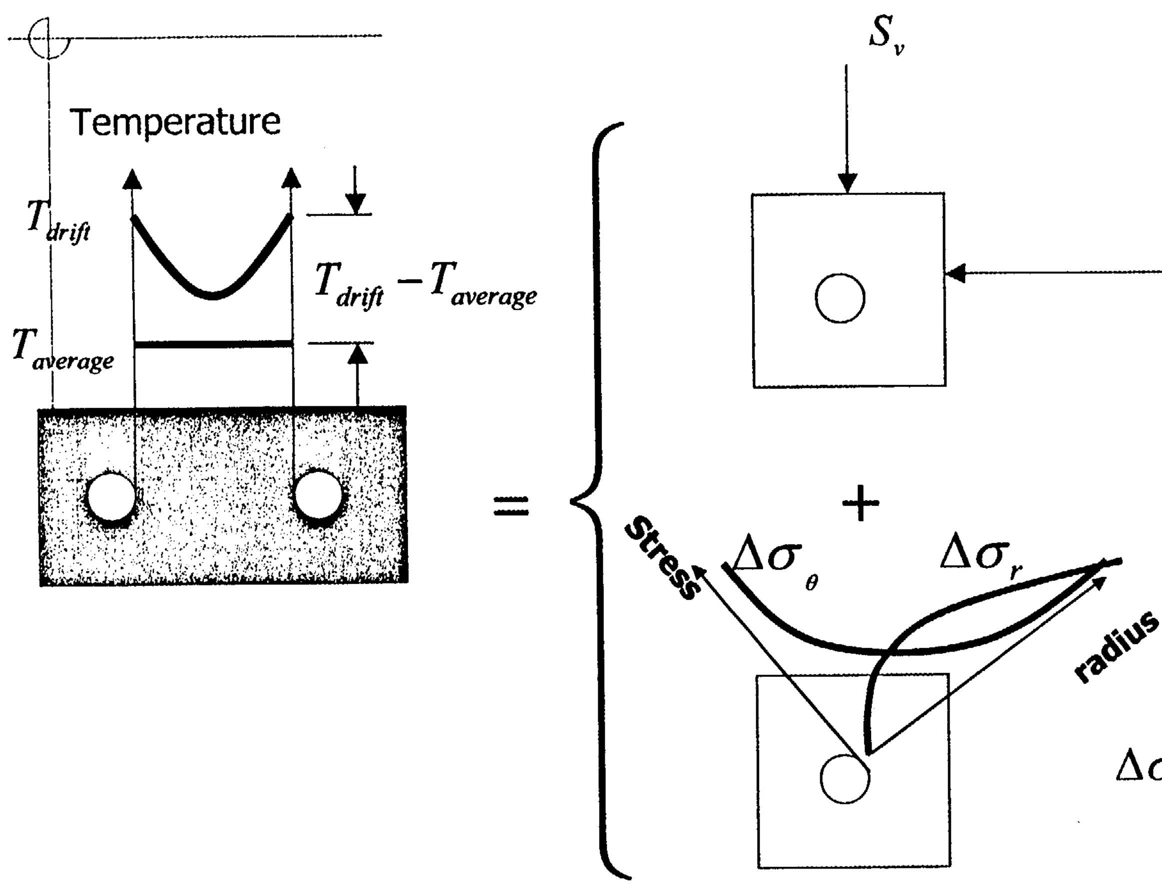
Maximum Thermal



Drift-wall Stress Schematic



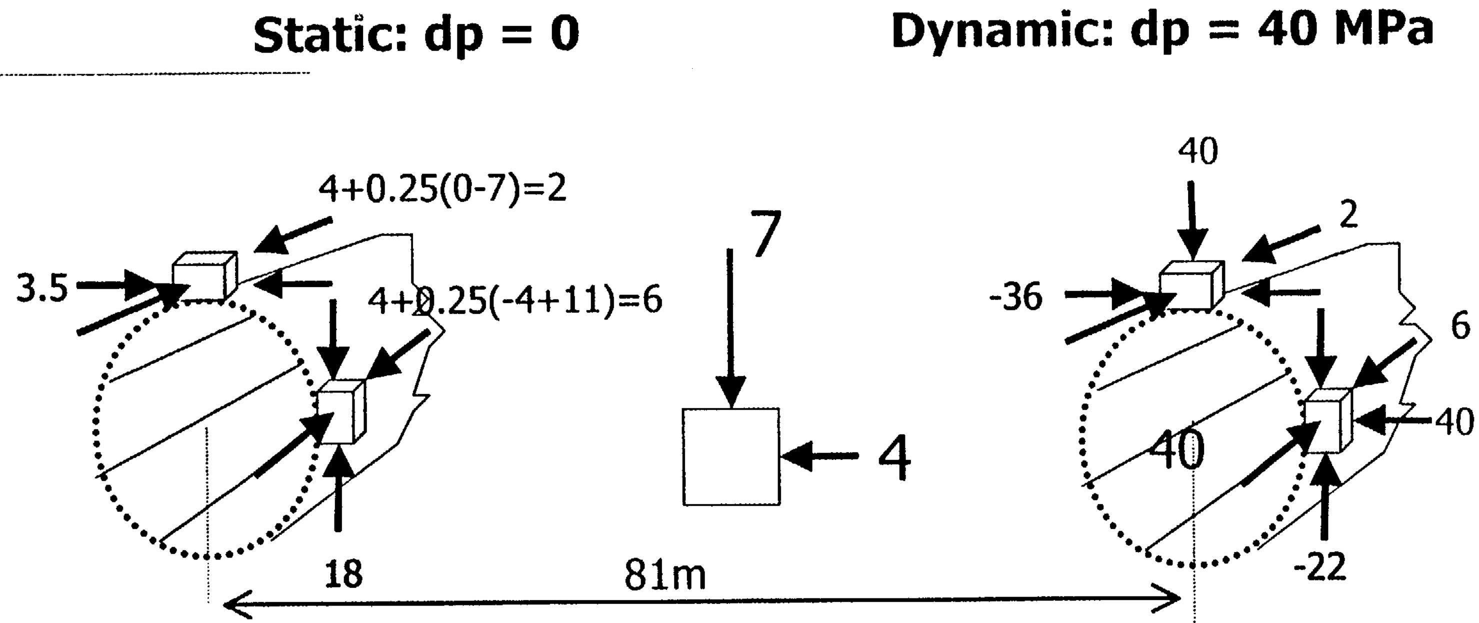
Drift-local Behavior



$$S_{h\,ambient} + \underbrace{\frac{\alpha(ERm)}{(1-\nu)}(T_{av} - T_{ambient})}_{Mountain-scale\ compression}$$

$$\Delta\sigma_{\theta\ \max} \approx \frac{\alpha(ERm)}{(1-\nu)}(T_{drift} - T_{av})$$

Drift Stresses – Warm-up and Cool-down



Implications:

As drift-wall warms – additional compressive hoop stresses build at 0.1 MPa per °C. Acts to deter ingress.

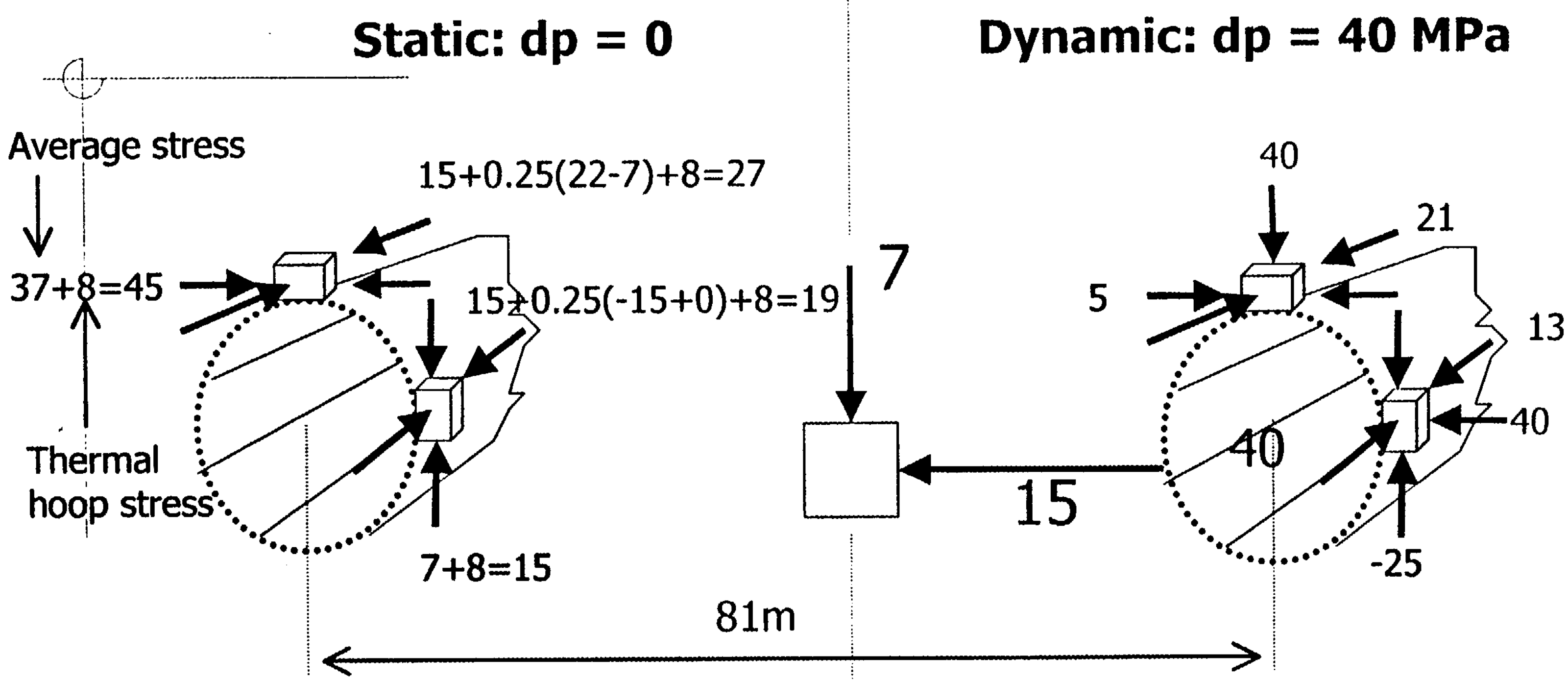
Dike ingress at invert (dp=0). Progressively more difficult as drift warms.

Gas or magma egress along drift crown (dp>0) and twist until normal to S_h

Fracture develops to bleed-off gas pressures

Limiting drift pressure ~ 4 MPa when cold or along favorably aligned pre-existing fractures

Drift Thermal Stresses – Thermal Maximum



Implications:

Ingress?

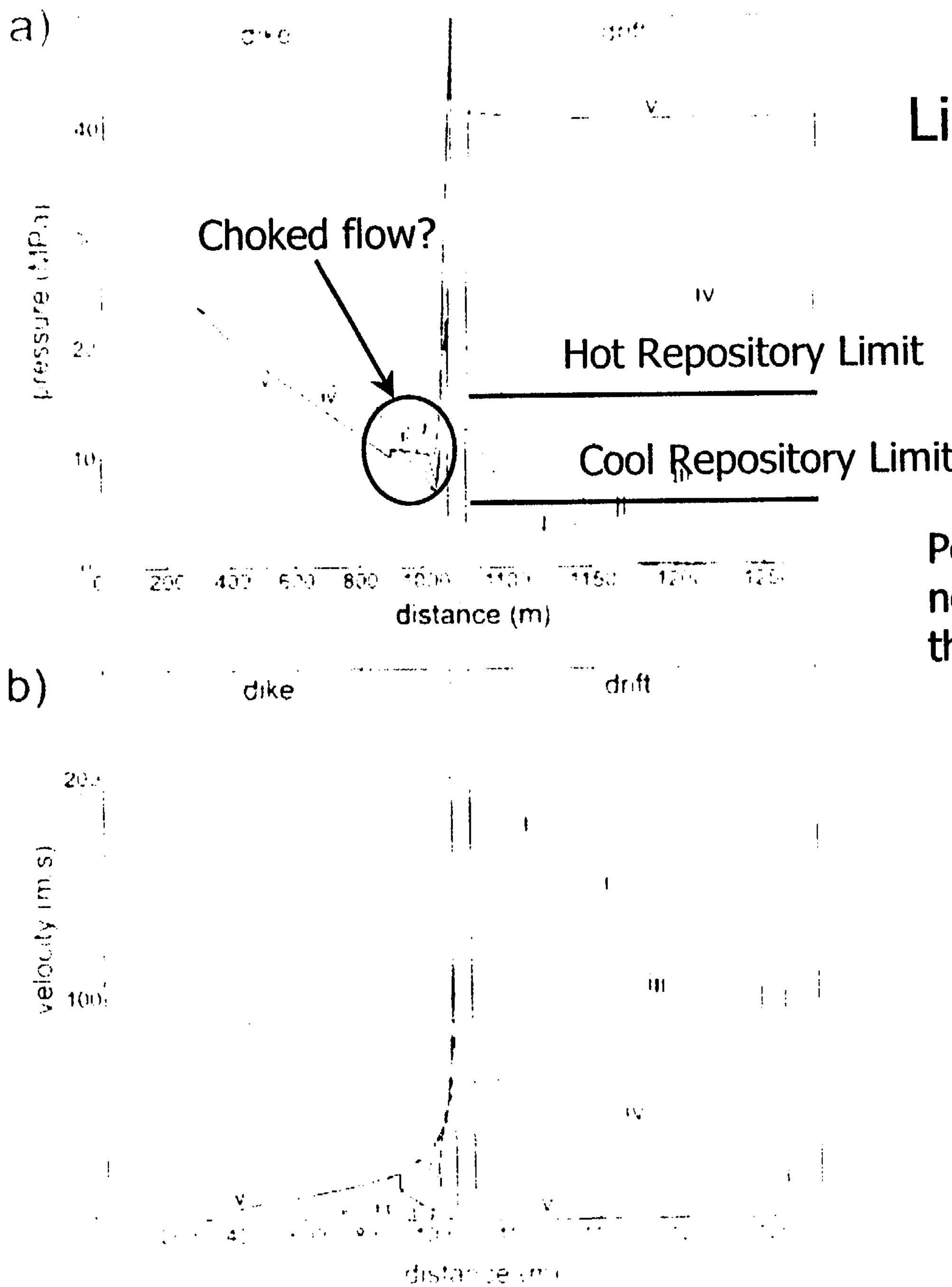
Egress along springline (dp > 0) as horizontal or vertical dike

Fractures develop to bleed off gas pressures

Limiting drift pressure ~ 15 MPa. Lower breakout pressures at cooler (and shallower?) edges of repository.

Analogs on NTS for dynamic wave?

Limiting drift pressures

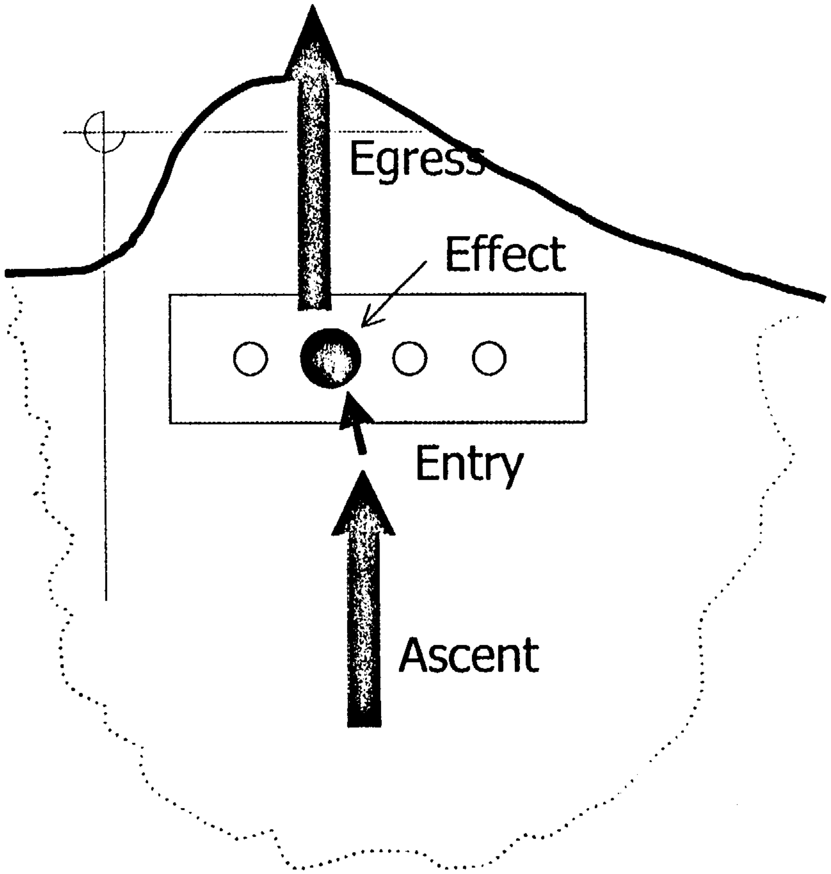


Cold: ~2-4 MPa

Hot: 15 MPa?

Peak drift pressures controlled by near-drift stress regime and failure of the drift.

Overview



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Effect on Drift(s)

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- **Pressure wave**
  - **Dynamic effects and failure**
  - **Relaxation**
- **Magma ingress**
- **Effect of in-drift structures**
- **Maximum sustainable in-drift pressures**

Entry into Drift(s)

- Control by local stress state
- Anticipated magma overpressures

Ascent to Repository Horizon

- Rotation of field stresses
- Effect of topography
- Role of structure (as stresses rotate)
- Anticipated maximum magma overpressures

In-Drift Obstructions

Waste Packages and Drip Shields

- Roof-falls following initial pressure pulse and after pressure release
- Large enough to rupture drip shields?
- Full length of drift affected?
- Some dynamic effects on adjacent drifts?

Cross-section Partially Backfilled

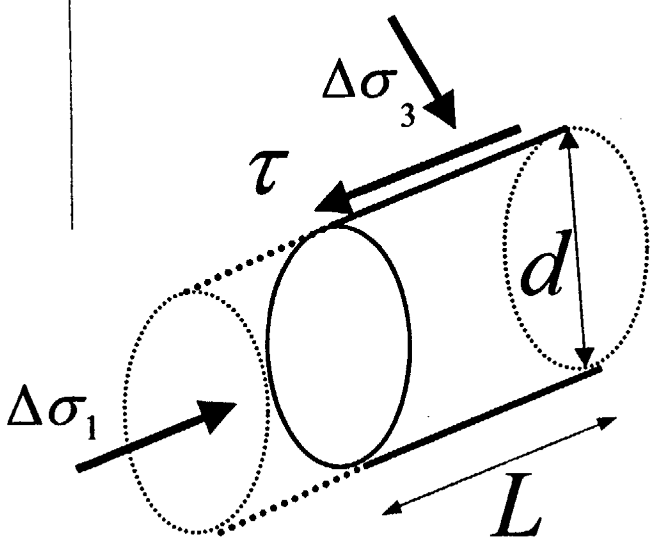
- Expansion volume reduced
    - Erosion of surface
    - Bulldozing extent of pulse
- Protection from roof-fall

Cross-section Fully Backfilled – or bulkheads

- Bulkheads separating packages (TSw2?)
- Stem dynamic expansion and force dike to continue
- Requirements
    - Low enough gas permeability to stem expansion
    - High enough strength to prevent displacement

Bulkhead "Strength" Constraints

- Radial displacements small. Order of 10mm for 40 MPa overpressure. Therefore rigid plug also feasible.
- Plug sizing



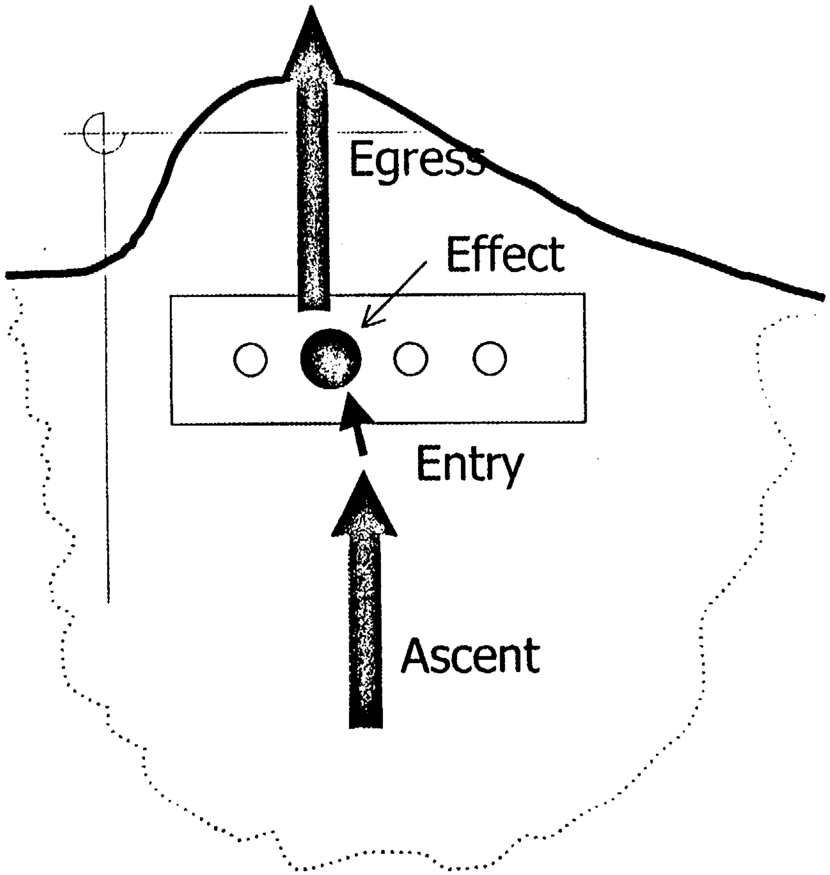
$$Elastic: \quad \sigma_3 \approx \frac{\nu}{1-\nu}\sigma_1 \approx \frac{1}{3}\sigma_1$$

$$Plastic: \quad \sigma_3 \approx \frac{1-\sin\phi}{1+\sin\phi}\sigma_1 \approx 0.3\,\sigma_1$$

$$\sigma_1 \frac{\pi}{4} d^2 = \pi\, d\, L\, \sigma_3 \tan\phi$$

$$\frac{L}{d} \approx \frac{3}{4}\frac{1}{\tan\phi} \approx 1$$

Overview



Egress from Drift(s)

- Egress locations and form

Effect on Drift(s)

- Ingress location
- Anticipated magma overpressure
- Pressure wave
  - Dynamic effects and failure
  - Relaxation
- Magma ingress
- Effect of in-drift structures
- Maximum sustainable in-drift pressures

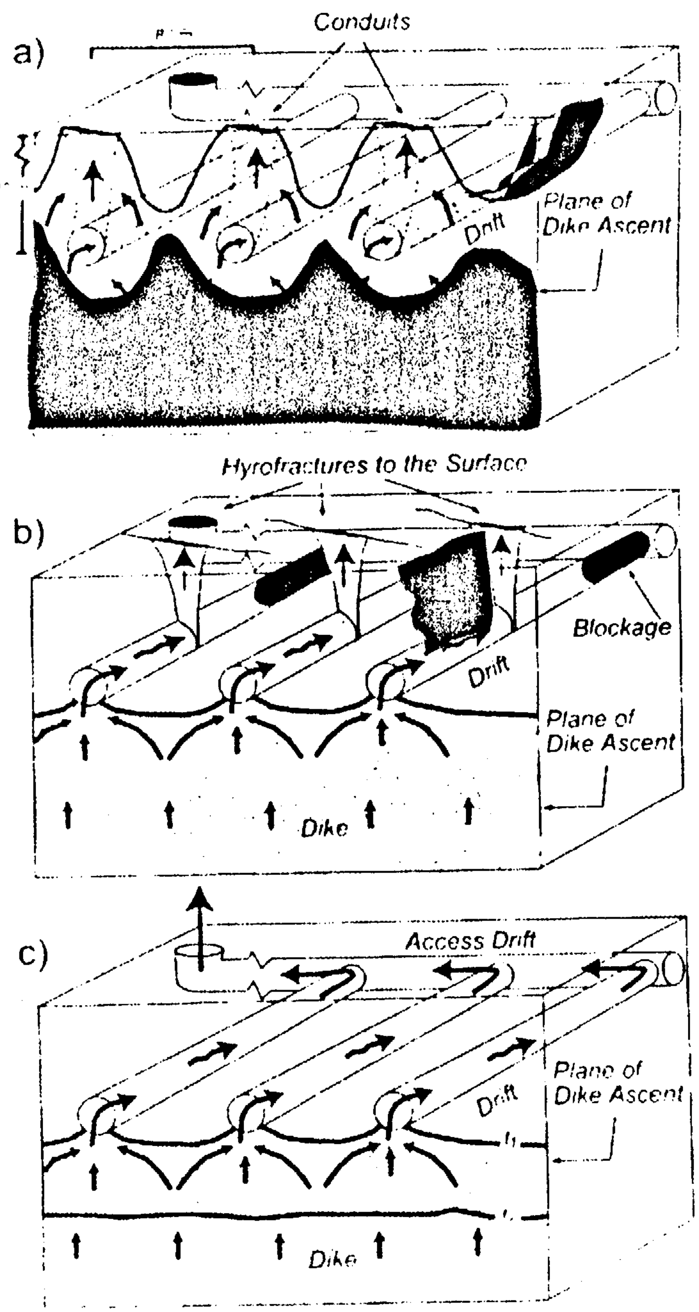
Entry into Drift(s)

- Control by local stress state
- Anticipated magma overpressures

Ascent to Repository Horizon

- Rotation of field stresses
- Effect of topography
- Role of structure (as stresses rotate)
- Anticipated maximum magma overpressures

Egress from Drift



Hot Repository

Ingress easiest at repository periphery

Stress regime around drifts deters ingress

Egress easiest along original dike intersection

Cold Repository

Dike develops most readily perpendicular to minimum field stress

Pressurized drift fails first at crown and escape feature rotates until perpendicular to field stress.

Summarized Observations

- Maximum dike overpressures above S_{min} expected to be moderated by rock strength. Likely of the order of less than ~1 MPa
- Cold repository (80% of 10,000 y)
  - Entry at total magma pressure of 2-5 MPa
  - Drifts fail at pressure of the order of ~4 MPa
- Hot repository (20% of 10,000 y)
  - Significantly higher entry pressures and exit pressures than for cold drifts
  - Can ingress occur?
- Backfill or backfill bulkheads could reduce the effects of in-drift decompression and magma ingress.

Additional Perspectives Following the May 21-22, 2002 Peer Review Meeting

- Current Understanding of Processes
  - Broad and not tightly constrained
  - Large spatial-/temporal-scale tests impossible
- Proposed Studies
  - Field/Geologic Provenance Studies
  - Magma/Gas-Drift Interaction Studies
  - Rock Mechanics Studies

} Process understanding in the absence of large tests

Geologic Constrain Studies

- Focus on local 200ka volcanic activity as key to the future 10ky
- Process-based studies
  - Cones present in flats –vs- piercing ridges
  - Effect of fault bounding
  - Predominant orientations of dikes
  - Confirm eruption sequencing – dike to conduit
  - Determine potential role of stress-field(s)

Proposed Magma/Gas-Drift Interaction Studies

- Code currently developed
  - Care in applying representative initial and boundary conditions
- Define likelihood of drift acting as shock-tube
  - Correlation with detonation tests
- Define modes of magma ingress
- Define modes of gas/magma breakout
- Could include an analysis of mitigative measures

Magma-Drift Mechanics Interaction Studies

- Particularly complex problem
  - Complex interaction of fluid and solid mechancis
  - Heterogeneous stress and parameter fields
- No currently-operational code available
- State-of-the-art understanding of interacting processes is poor
  - Comprehensive codes not available
  - Understanding of broad process-interactions is poor
  - Must understand process in broad form and their impacts on the repository → rational design modifications

U.S. Nuclear Regulatory Commission
and
Sandia National Laboratories:

Overview of the Package Performance Study

Presentation to:

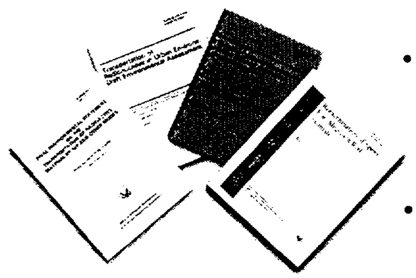
The Advisory Committee on Nuclear Waste

Ken B. Sorenson
Jeremy Sprung
Sandia National Laboratories
April 10, 2002
Albuquerque, New Mexico

Contents

- History of Major NRC Transportation Studies
- NUREG/CR-6672
- Package Performance Study
  - Issues Report
  - Test Protocols

History of Major NRC Transportation Studies



- NUREG-0170, 1977
  - Final Environmental Statement of the Transportation of Radioactive Materials by Air and Other Modes
- NUREG/CR-0743, 1980
  - Transportation of Radionuclides in Urban Environs: Draft Environmental Assessment - The Urban Study
- NUREG/CR-4829, 1987
  - Shipping Container Response to Severe Highway and Railway Accident Conditions - The Modal Study
- NUREG/CR-6672, 2000
  - Reexamination of Spent Fuel Shipment Risk Assessments

Slide # 3

NUREG/CR-6672

Slide # 4

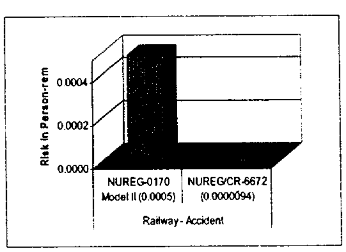
Conclusions From NUREG/CR-6672

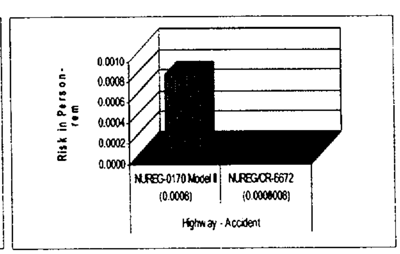
- **Transport risks to the public are better estimates than those computed in NUREG-0170 due to:**
  - More advanced analysis techniques
  - More detailed evaluation of transport routes
  - Newer/better data
- **Non-accident and accident transport risks estimated in NUREG/CR-6672 are lower than those from NUREG-0170 and thus continue to support the appropriateness of the existing regulations**

Slide # 5

Accident Risk Results

- **Dose risks from impact and thermal accident conditions are orders of magnitude smaller than those computer in NUREG/0170**





Slide # 6

Elements that Add Conservatism

- Impact analyses
  - All end and corner impacts are on closure
  - All impact energy goes into cask deformation
  - Canister neglected - not analyzed
- Thermal analyses
  - All fires are optically dense and completely surround the cask for the entire duration of the fire
  - Fire temperature is 1000°C
- Source terms
  - 3-year cooled high-burnup fuel

Slide # 7

Package Performance Study

Slide # 8

Background

- The Package Performance Study (PPS) will identify and implement near-term R&D transportation work for the NRC.
  - The goal of the PPS is to validate the assumptions and methodologies used to assess the appropriateness of the NRC regulations, demonstrate the safety of RAM transport, and advance the knowledge base of cask and spent fuel behavior in transport accident environments.
  - The PPS uses the results of NUREG/CR-6672 and the Issues Report to help define needed R&D work.
  - As the work scope becomes better defined, public input will be solicited in order to obtain feedback for the PPS.

Issues Report

- Purpose of Package Performance Study is to support the evaluation of the safety of spent fuel transportation
- The PPS began in 1999 with a scoping phase, the results of which were published in the Issues Report (June 2000).
- The Issues Report translates stakeholder input from previous meetings into proposals for the Package Performance Study R&D

Issues Report

- **Stakeholder input obtained via:**
  - Four public meetings held in 1999.
  - Distribution of the Issues Report for comment
  - Interactive website:
    ttd.sandia.gov/nrc/modal.htm
  - Four additional public meetings were held in 2000.
- **Stakeholders include:**
  - Nuclear industry groups
  - Transportation industry groups
  - DOE, DOT
  - State, Local, and Tribal governments
  - Public interest groups
  - Members of the public

PPS Work Scope

- **The PPS Work Scope follows the five recommendations listed in the Issues Report:**
  - Perform 3-D finite element analyses to capture cask and fuel behavior in severe mechanical loading environments
  - Perform 3-D finite element analysis to capture cask and fuel behavior in severe thermal environments
  - Conduct impact tests on fuel elements to characterize rod and fuel behavior in dynamic loading environments
  - Conduct high speed rail impact test and thermal test
  - Reconstruct the accident event trees and accident speed and fire duration distributions

PPS Test Protocols

<u>The PPS Test Protocols:</u>

- **Define conceptual levels of impact, fire, and fuel tests,**
- **Will be published for comment in the summer of 2002, and**
- **Will be used as a basis for developing detailed test plans after review and comment period.**

- **Non-test issues in the PPS that are handled separately and are not included in these test protocols include the reconstruction of the accident event trees and accident speed and fire duration distributions.**

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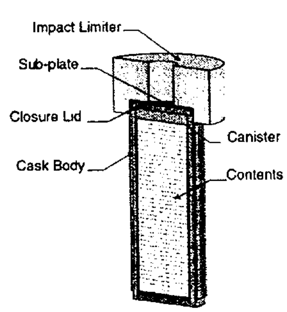
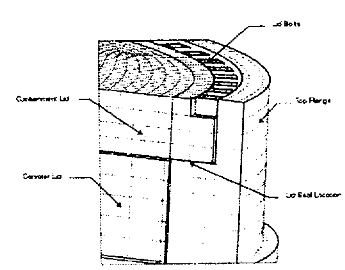
Test Protocols
Structural Analyses

Preliminary Structural Analyses have been performed on the HOLTEC Hi-Star Transportation Cask





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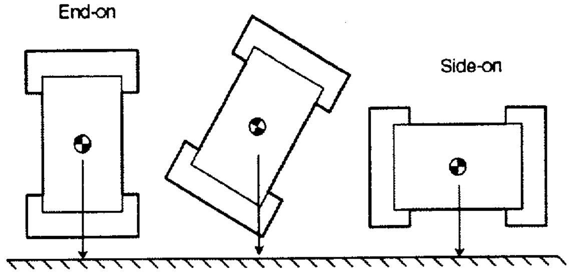
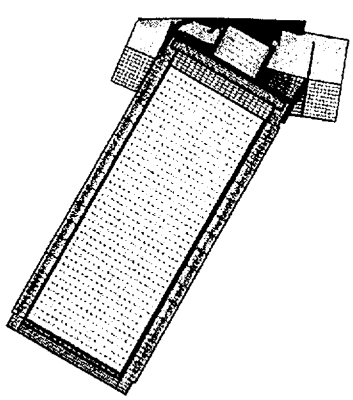
Test Protocols
Structural Analyses

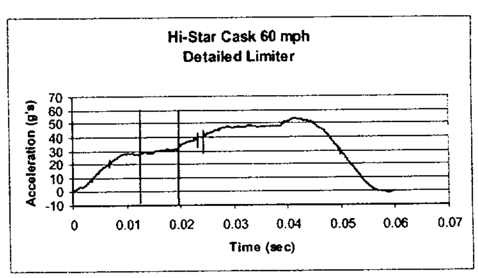
Three Impact Orientations were analyzed at 60 and 90mph



Test Protocols
Structural Analyses

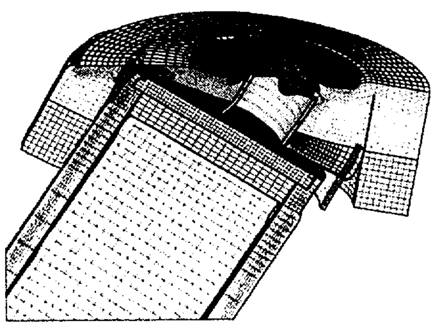
C.G.-Over-Corner impact at 60 mph

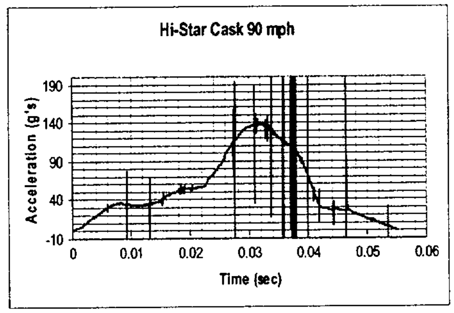




Test Protocols
Structural Analyses

C.G.-Over-Corner impact at 90 mph





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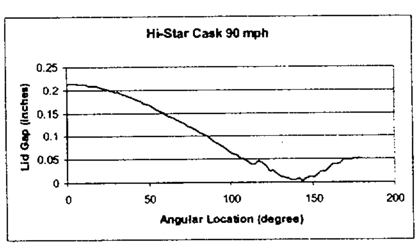
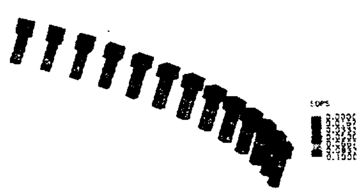
Test Protocols
Structural Analyses

Closure and bolt performance at 90 mph impact, c.g. over corner





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Test Protocols
Structural Analyses

Recommendations:

- **Conduct detailed finite element analyses of the HOLTEC Hi-Star cask with impact limiters for the final Test Procedures**
    - **Based on the preliminary analyses, the detailed analyses will only address a center-of-gravity over corner high speed impact.**
    - **The impact speed will be in the range of 60-90 mph**
    - **Increased attention will be addressed in modeling the closure lid, the bolts, and the impact limiter**

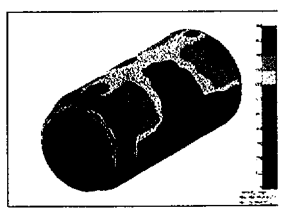
Test Protocols
Thermal Analyses

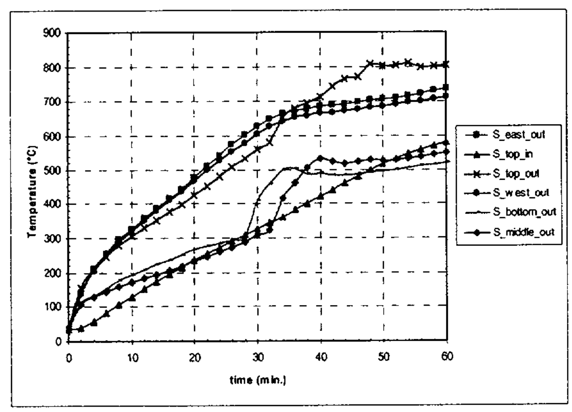
Preliminary analyses investigated thermal response to three locations in the pool fire:

- **Case 1: 1.3 meters above the pool, no wind**
    - **standard regulatory conditions**
- **Case 2: 0.3 meters above the pool, no wind**
    - **increases thermal gradients, and thus thermal stresses at the surface of the cask**
- **Case 3: 3.3 meters above the pool, no wind**
    - **entire cask is above the vapor dome so that the entire surface of the cask is exposed to combustion**

Test Protocols
Thermal Analyses

Case 1: 1.3 m above the pool fire, no wind - Regulatory conditions





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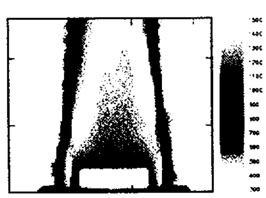
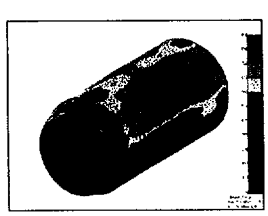
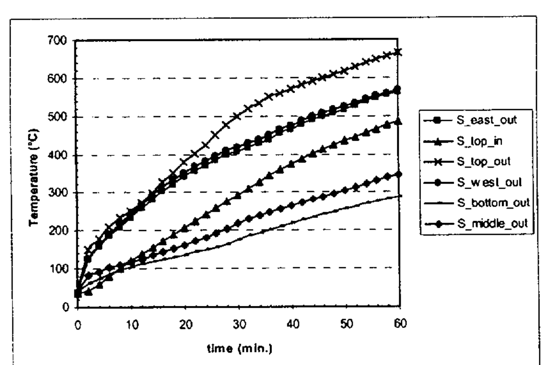
Test Protocols
Thermal Analyses

Case 2: 0.3 m above the pool, no wind







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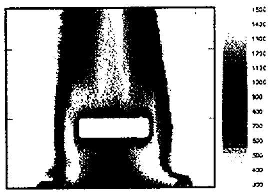
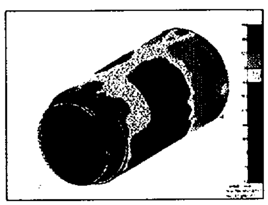
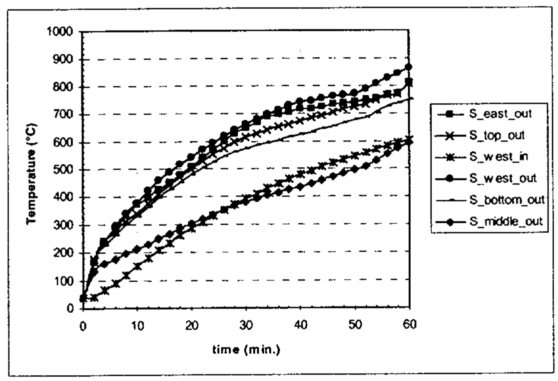
Test Protocols
Thermal Analyses

Case 3: 3.3 m above the pool, no wind







Test Protocols
Thermal Analyses

Recommendations:

- Conduct more detailed modeling and analyses for calorimeter tests
- Perform two full-scale calorimeter tests
  - one test above the vapor dome
  - one test on or near the ground
- Conduct detailed modeling and analyses for full-scale cask based on calorimeter tests
- Conduct two full-scale fire tests based on the calorimeter tests

Test Protocols
Draft Fuel Experimental Plan

Objectives

Given particle release from a failed spent fuel rod, the goal of the rod, pellet, and CRUD impact tests is to develop data that can show:

(1) whether fuel fines form particle beds inside of spent fuel rods,
(2) if particle beds form, whether they efficiently filter the particles that pass through them,
(3) whether CRUD particles will spall off of spent fuel rod surfaces, if the rods are subjected to mechanical impacts or thermal stresses, and
(4) what is the size distribution of the released particles.

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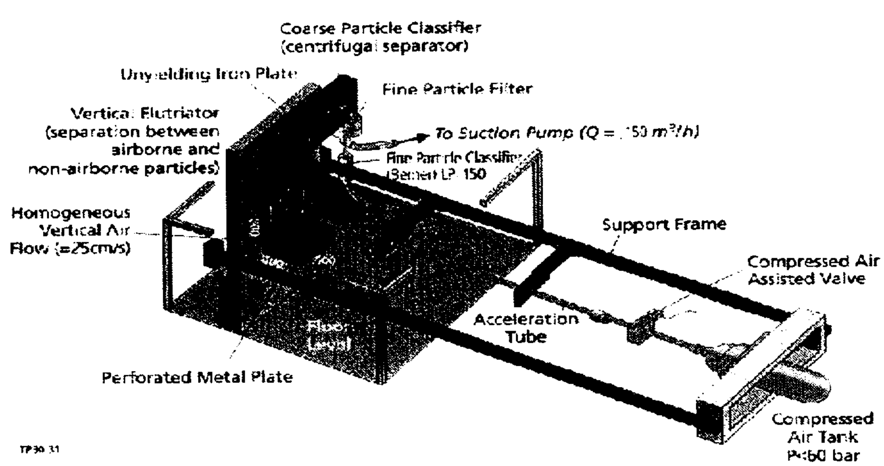
Test Protocols
Draft Fuel Experimental Plan

Test Apparatus



TP30 31

Expert Panel Review
Conducted April 10-11, 2002
Albuquerque, New Mexico

Purpose: Structural and thermal expert panels have been formed by Sandia to provide independent technical review of the draft Test Protocols before the Protocols are distributed for public review.

Panel Compositions
- Five members for each panel
- Members from academia, national laboratories, and industry
- NRC approved the selection of members
- Convene in March/April timeframe

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Expert Panel Review
Conducted April 10-11, 2002
Albuquerque, New Mexico

Principal Results of Structural Review Panel:
- Agreed with the basic approach as developed in the protocols
- Conduct one regulatory and one extra-regulatory test
- Extra-regulatory test should focus on closure damage with drop height sufficient to bottom-out the impact limiter and achieve closure deformation
- Emphasize, as a measure of success, deformation with less emphasis on decelerations/strains

Principal Results of Thermal Review Panel:
- Agreed with the basic approach as developed in the protocols
- Conduct 3 additional calorimeter tests to evaluation low, medium, and high wind conditions

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Test Procedures

The detailed Test Procedures are currently planned for completion in the 4th Quarter of calendar year 2002. Outstanding issues include;

- **Final configuration of calorimeter and cask thermal tests**
- **Selection of actual test article for impact test**
- **Full-scale vs. scale model test article**
- **Pre-test prediction made with a commercially available code**
- **Round-robin analyses**

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Field Tests

Planned Testing Dates

Fuel	
• Surrogate pellet impact tests	Fall '02
• Surrogate CRUD tests	Fall '02
• Rod section impact tests	Fall '02
Thermal	
• First calorimeter tests	
• full-scale rail calorimeter:	TBD
• Cask fire tests	
• cask thermal tests:	Fall 2004
Impact	
• Impact test:	Summer 2004

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