# Diet Coke and Mentos: What is really behind this physical reaction?

Tonya Coffey

*Published in the American Journal of Physics, June 2008

# In case you hadn't heard… Diet Coke and Mentos is a major fad!

1st shown on the Letterman show in 1999 by chemistry teacher Lee Marek

YouTube
Broadcast Yourself™

Subject of countless YouTube videos

Subject of a 2006 episode of Mythbusters

EepyBird.com
Entertainment for the Curious Mind

# Why on earth do I care so much about Mentos?


Originally to give my PHY2210 students the experience of participating in a real research project, not a canned lab.


But I admit the project exploded beyond my original vision…

# Bubble Theory: Why do sodas fizz when you open them?


We like our drinks nice and fizzy.

Thanks, Henry's Law!

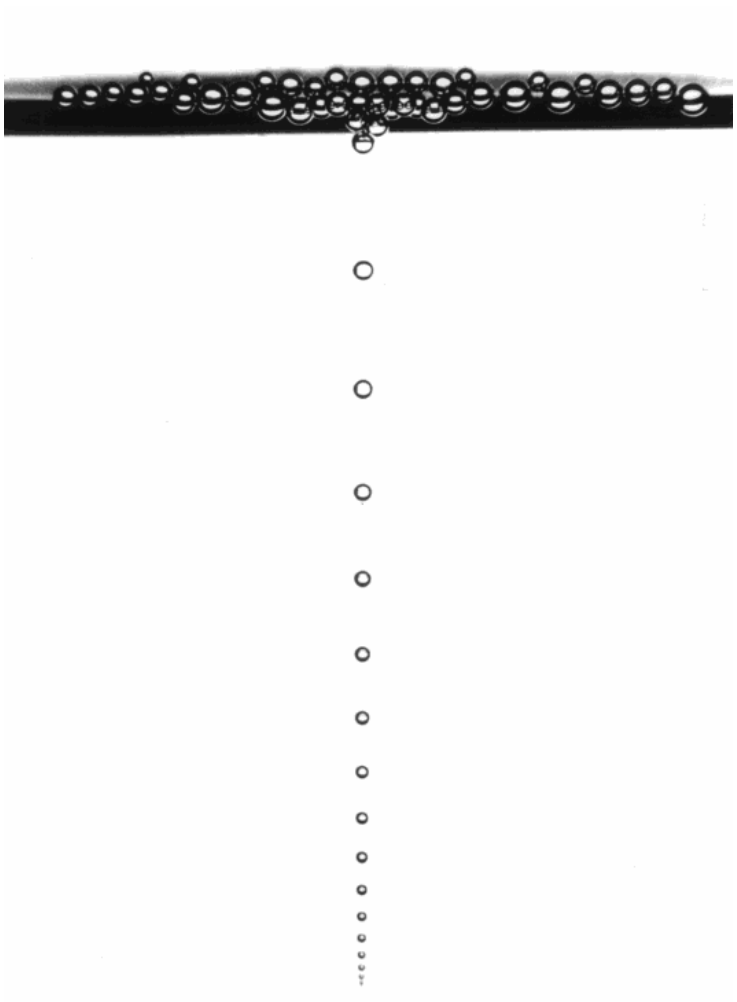
**P=Kc**

Here P is partial pressure of gas above liquid,
K is a constant, and c is the molar concentration of solute.

The partial pressure of the gas above the solution is directly proportional to the concentration of solute gas in the solution.

So when you pop the top, the equilibrium within the bottle or can is broken, and the concentrated carbon dioxide gas leaves the container. The partial pressure of carbon dioxide in the surrounding gas then drops, forcing the concentration of the solute gas to drop, so it bubbles out.

# Bubble theory: How bubbles form in liquids



*Liger-Belair and Jeandet, Europhysics News

In most liquids, there is some dissolved gas. In high surface tension liquids, like water, it is tough for bubbles to form, because water molecules like to be next to other water molecules (capillary forces).

To overcome this, a nucleation site is generally needed. Gas molecules congregate next to nucleation sites, which break up the network of water molecules. When enough are gathered, they form a bubble.

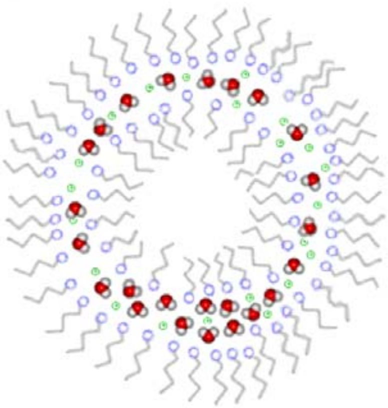
Due to capillary forces, the bubble will initially stay at its nucleation site. But usually, the buoyancy of the bubble will eventually cause it to rise, as more and more gas molecules collect in the bubble.

# More fun bubble facts…

When a soda is bottled, it is bottled under a relatively high pressure of $CO_2$ that exceeds the solubility of $CO_2$ in the rest of the formula (mostly water). When the can is opened without shaking high pressure $CO_2$ above the liquid escapes, making the familiar hiss.  The $CO_2$ in the liquid slowly escapes until equilibrium is achieved. When the unopened can is shaken, some of the gaseous $CO_2$ gets mixed into the liquid, forming a supersaturated solution.  The mixed in gas also provide growth sites for the dissolved $CO_2$. The growth sites allow the $CO_2$ to escape much more rapidly-- hence the "explosive" evolution of $CO_2$ gas.

# Bubble Theory: The importance of surfactants

- Adding surfactants to water reduce the work required to form a bubble, making bubbles easier to form and longer lasting
- Surfactants are long chained molecules (like soap) that have a water loving and water fearing end



# What burning questions did the Mythbusters leave for me?

- Main Mentos contributors to the reaction: *gum arabic and gelatin*
- Main Diet Coke contributors to the reaction: *caffeine, apsartame, potassium benzoate*
- *Rough surface of Mentos provides growth sites for the carbon dioxide dissolved in Diet Coke*
- How rough is Mentos compared to other samples and how much does roughness matter compared to presence of surfactants in soda or candy?
- What is relative contribution of ingredients to reaction, and why do they work? Surfactants?
- Are there any other factors in play?

# It’s not an acid/base reaction!


The classic baking soda and vinegar acid-base reaction produces unstable carbonic acid that rapidly decomposes into water and carbon dioxide, which escapes as a gas. For the Mentos–Diet Coke reaction, the carbonic acid and carbon dioxide are not products of a chemical reaction but are already present in the Diet Coke, whose equilibrium is disturbed by the addition of the Mentos.

- Lots of speculation on the web.
- We measured pH of soda before and after Diet Coke/Mentos reaction using a pH meter with a 2 point calibration. It was the same, 3.0.
- Also, none of the ingredients in Mentos are basic: sugar, glucose syrup, hydrogenated coconut oil, gelatin, dextrin, natural flavor, corn starch, gum arabic.
- But you can make a fun acid/base reaction, by adding baking soda to Diet Coke. pH before: 3.0 pH after: 6.1

# Procedure

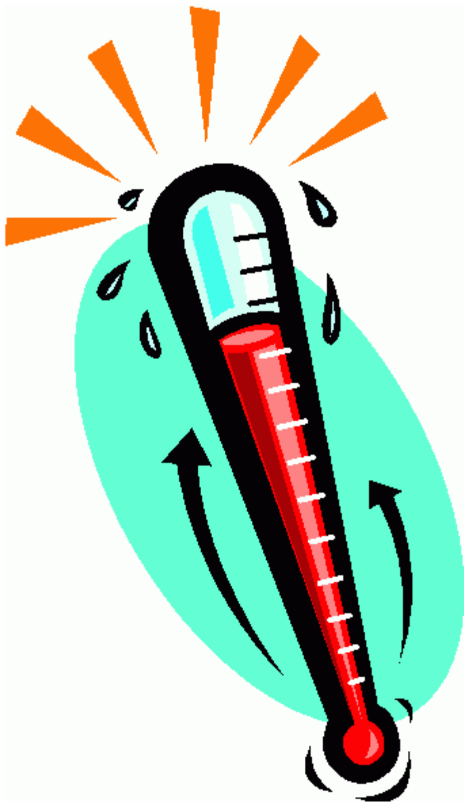
- Sodas tested: Diet Coke, Caffeine Free Diet Coke, Coca-Cola Classic, Caffeine Free Coca-Cola Classic, seltzer water, seltzer water with potassium benzoate added, seltzer water with aspartame added, tonic water, and diet tonic water.
- Samples tested: Mint Mentos, Fruit Mentos, a mixture of Dawn Dishwashing detergent and water, playground sand, table salt, rock salt, Wint-o-green Lifesavers, a mixture of baking soda and water, liquid gum arabic, and molecular sieve beads.

# Procedure

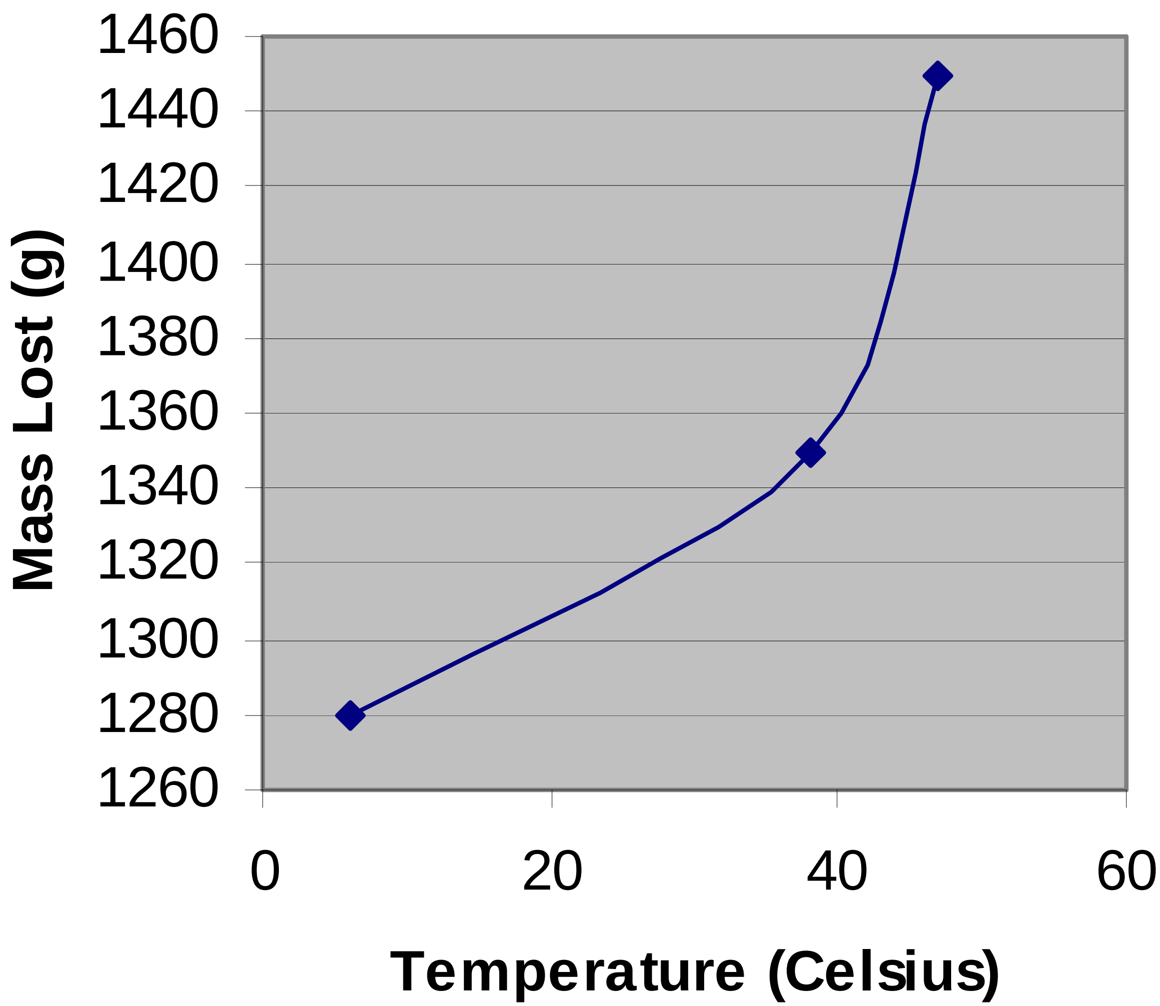
- We constructed a bottle stand to prevent the bottles from tipping over and to prevent the liquid from falling back into the bottle. We also constructed a tube to fit over the mouth of the bottle and a delivery mechanism for the solid materials to maintain consistency in our results.
- We measured the mass of the bottle using a double pan balance before and after the reaction to determine the mass lost in the reaction. We measured the horizontal distance traveled by the soda's spray using marker flags and video. Also using video, we acquired time duration of reaction.

# One of those other factors: Temperature!

- For temperature dependent trials we refrigerated a Diet Coke bottle for several hour prior to the experiment.
- Other bottles were heated in a water bath on a hot plate for approximately 10-20 minutes. To prevent explosion of the bottles during heating, the heated bottles were opened to release some of the internal pressure, then closed again.
- This may have caused some systematic error as compared to the room temperature trials.
- Soda temperature was measured with mercury thermometer immediately prior to reaction.

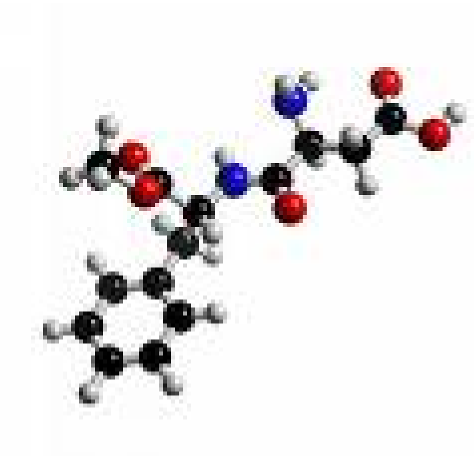


# Temperature Matters!

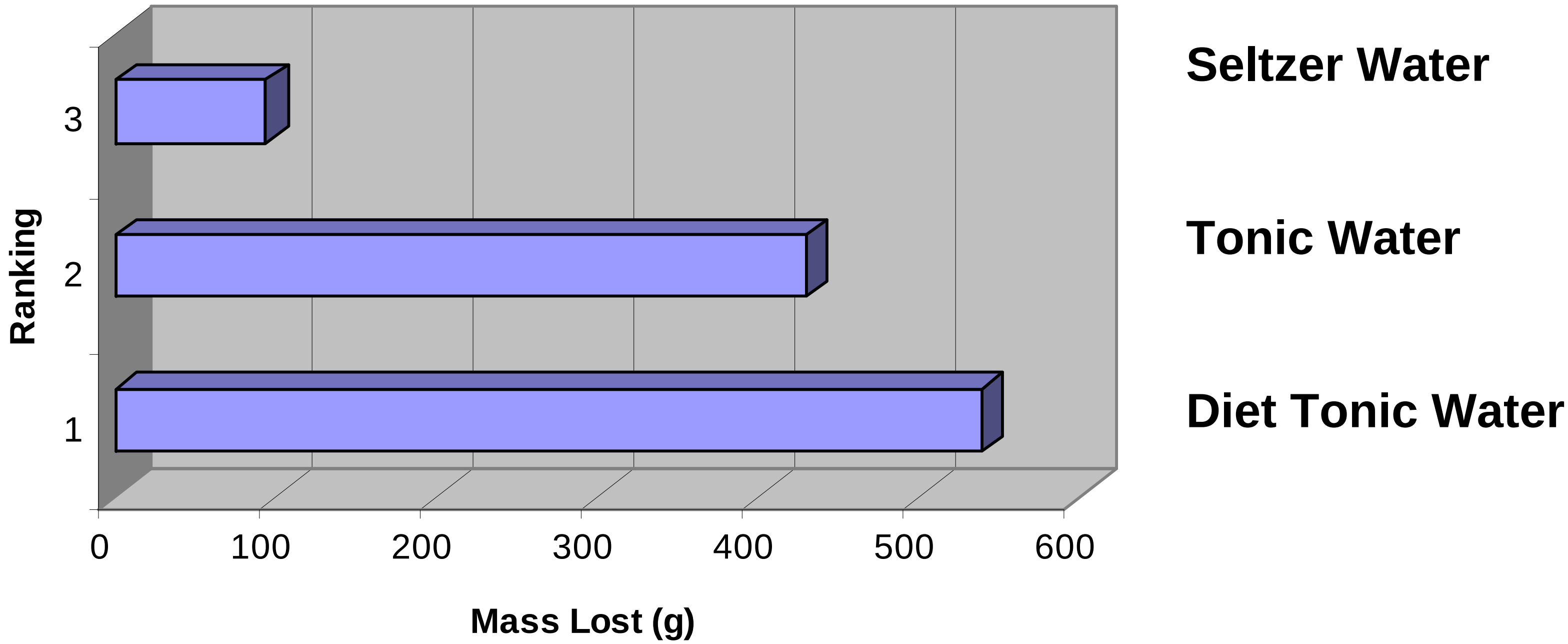



Remember Henry's Law?
**P=Kc**
The Henry's Law constant **K** changes with temperature, generally increasing as the temperature increases. This means that the molar concentration of the gas in the solution must drop for the same value of the partial pressure, which means that gases are less soluble in liquids as the temperature increases.

# Which soda ingredients cause the biggest reaction?



# Results—Mass lost during reaction of Mentos in Seltzer, Tonic Water, Diet Tonic Water (Uncertainty roughly 10%)



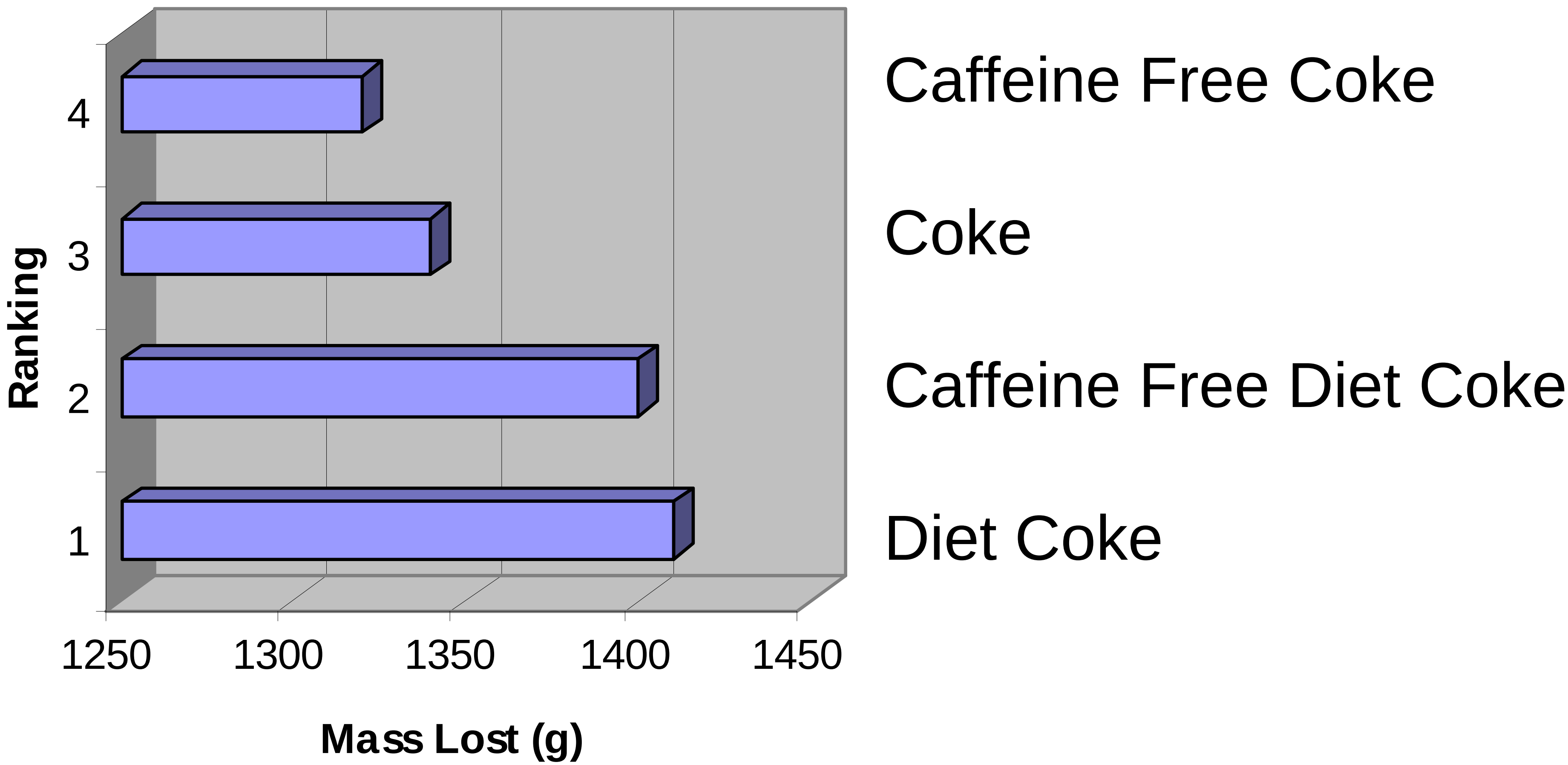

**Artificial Sweeteners cause bigger explosions than sugar. None of these drinks contain caffeine.**

Seltzer ingredients: Carbonated water

Tonic Water Ingredients: Carbonated water, corn syrup, citric acid, natural and artificial flavors, quinine

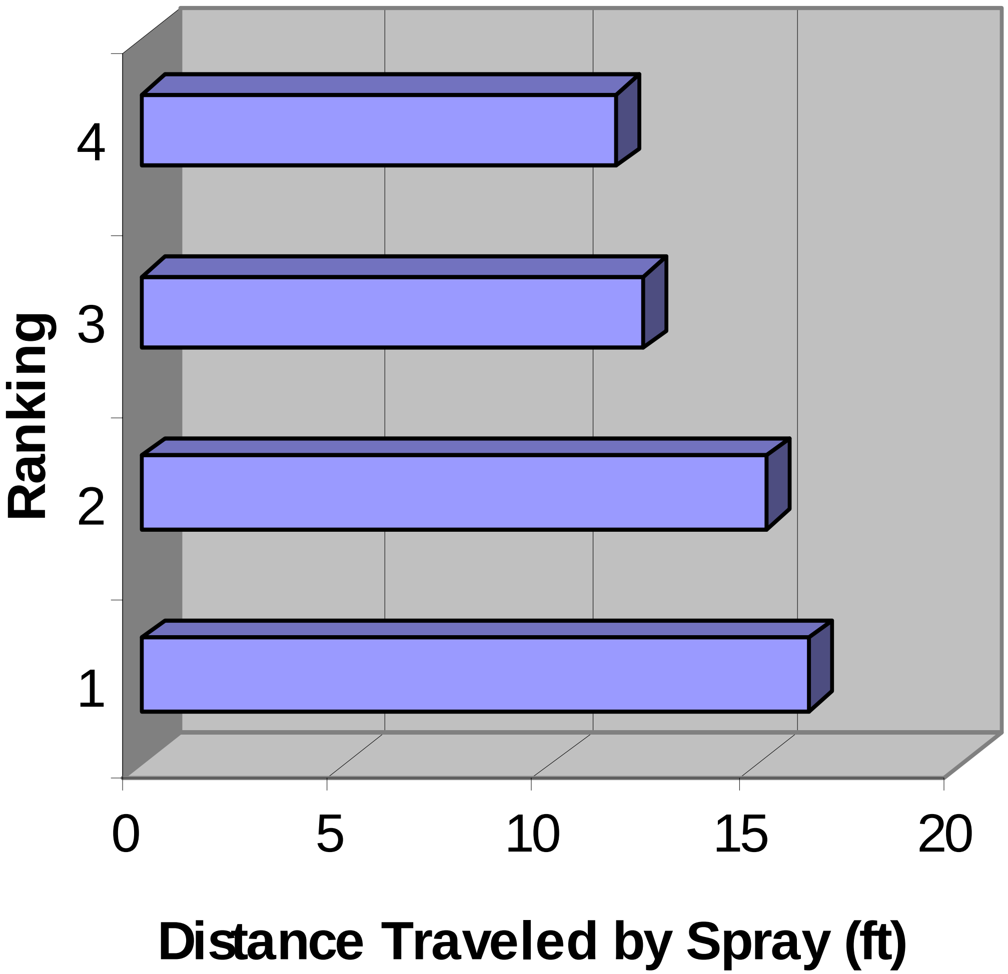
Diet Tonic Water Ingredients: Carbonated water, citric acid, natural and artificial flavors, aspartame, potassium benzoate, quinine

# Results—Mass lost during reaction of Mentos in Various Coke Products (Uncertainty roughly 10%)




Presence/absence of aspartame matters more than presence/absence of caffeine.

# Results—Horizontal distance traveled by spray during reaction of Mentos in Various Coke Products (Uncertainty roughly 10%)



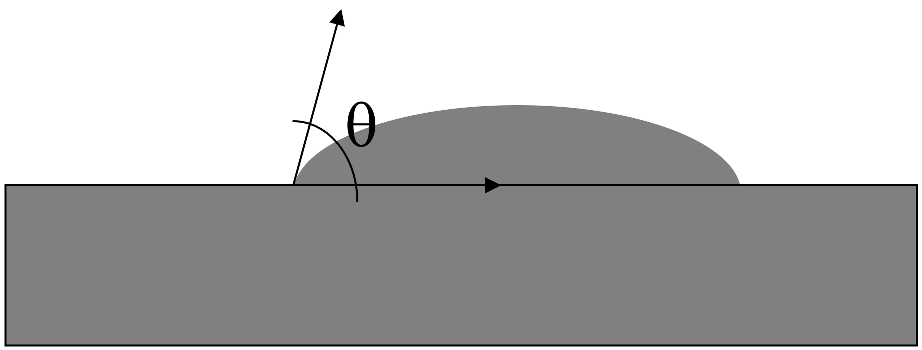

Presence/absence of aspartame matters more than presence/absence of caffeine.

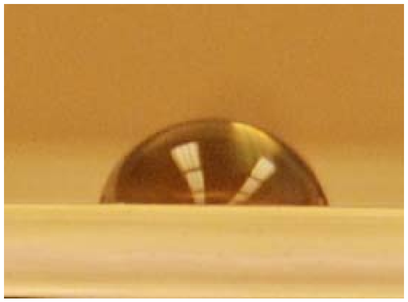
# What about caffeine?

- Matters a little, but the differences are within the experimental error, so….
- The Mythbusters added “enough caffeine to kill you” and saw a reaction. Hopefully the Coca-cola company doesn’t add that much!

# Why does aspartame/sugar matter more than caffeine/caffeine free?

- To answer this question, we took contact angle measurements. What is contact angle? What does it tell us?



$$W = \frac{16\pi\gamma_{LV}^{3}}{\left(P' - P\right)} f\left(\theta\right)$$

$$f\left(\theta\right) = \frac{\left(1 - \cos\theta\right)^{2}\left(2 + \cos\theta\right)}{4}$$

The work required to form a bubble in a liquid. Here, $\gamma_{LV}$ is the liquid-vapor surface tension, P'-P is the pressure difference across the interface, is the contact angle, and *f* is a function of contact angle.

# Contact Angle Results

| Sample | Contact angle in degrees (uncertainty of +/- 3 degrees) | $\frac{W_{soln}}{W_{H20}} = \left(\frac{\gamma_{LV,2}}{\gamma_{LV,1}}\right)^3 \frac{f(\theta_2)}{f(\theta_1)}$ |
|---|---|---|
| DI $H_20$ | 85 | 1 |
| DI $H_20$-sugar solution | 80 | 0.74 |
| DI $H_20$-aspartame solution | 77 | 0.67 |
| DI $H_20$-potassium benzoate solution | 75 | 0.60 |
| Diet Coke | 75 | 0.62 |
| Caffeine Free Diet Coke | 78 | 0.69 |

The smaller the ratio, the less work is required to form a bubble.

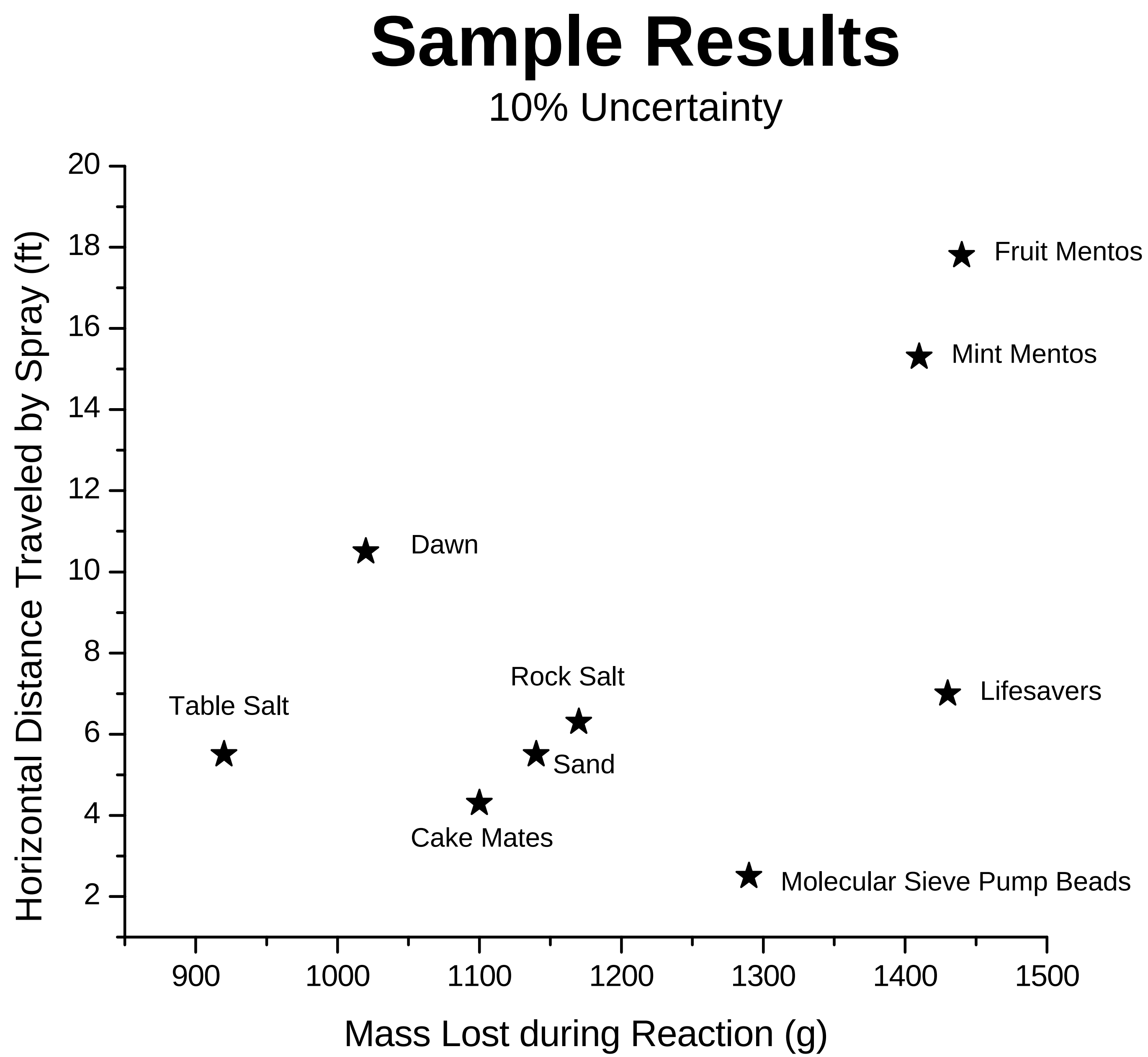
Aspartame reduces the work more than sugar.

Potassium benzoate, the preservative they add to beverages containing aspartame (like Diet Coke) is even better.

Above, we assumed that the liquid-vapor surface tension was reduced by 5% for the second system as compared to the de-ionized water (system 1).

# So…

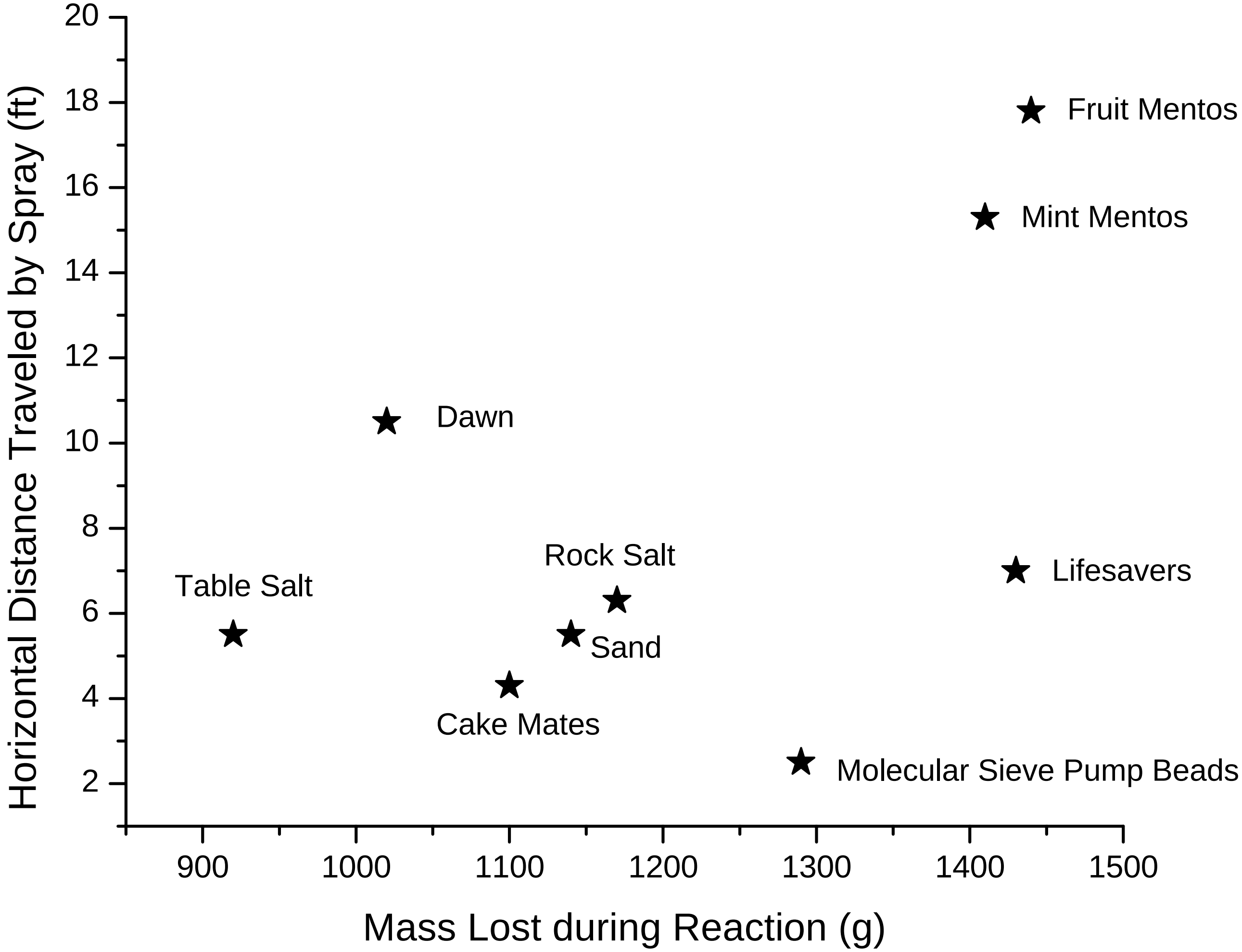
- Caffeine, sugar, aspartame, and potassium benzoate all reduce the work required to form a bubble
- However, the amount of caffeine in Diet Coke isn’t large enough to significantly affect the explosion
- Sugar doesn’t do as good of a job as aspartame and potassium benzoate
- They always add a preservative to drinks containing aspartame, so it makes an effective 1-2 combo!


Sample Results
10% Uncertainty
Horizontal Distance Traveled by Spray (ft)
Mass Lost during Reaction (g)
20
18
16
14
12
10
8
6
4
2
900
1000
1100
1200
1300
1400
1500
Fruit Mentos
Mint Mentos
Dawn
Rock Salt
Table Salt
Lifesavers
Sand
Cake Mates
Molecular Sieve Pump Beads

# Just about anything will make the fizz!

- Dropping any solid into soda will provide nucleation sites for the bubbles.
- We injected some liquids that are known surfactants (Dawn/water mixture, liquid gum arabic) into the bottom of the soda pop bottles. That works too!
- So 2 important factors: nucleation sites and surfactants which reduce work required to form a bubble.
- Any other factors?  And why do Mentos work better than anything else?

# Rate of Reaction Matters!




Discrepancies exist between the amount of mass lost and distance traveled. Notable samples: Lifesavers, Molecular Sieve Pump Beads, Dawn. These can be explained by the rate of reaction. Reactions that take longer to occur lose lots of mass but the spray doesn't travel very far. Think Mt. St. Helens vs. Kilauea.

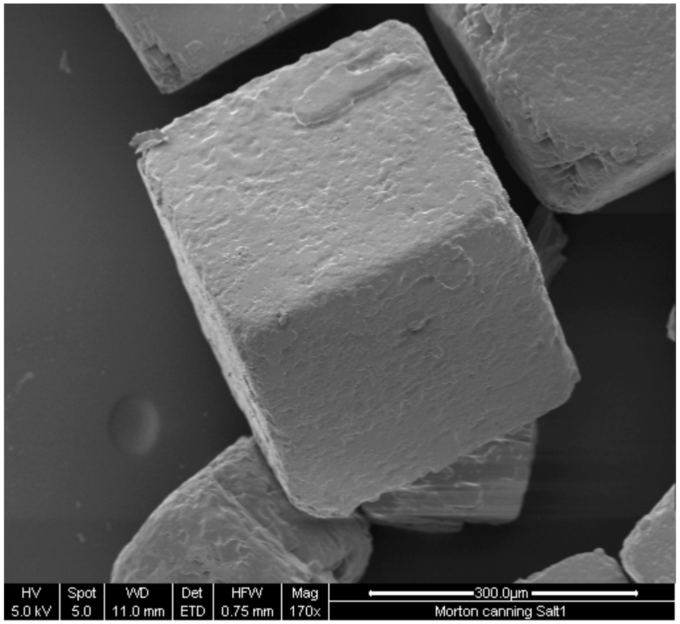
# Why are rates of reaction different?

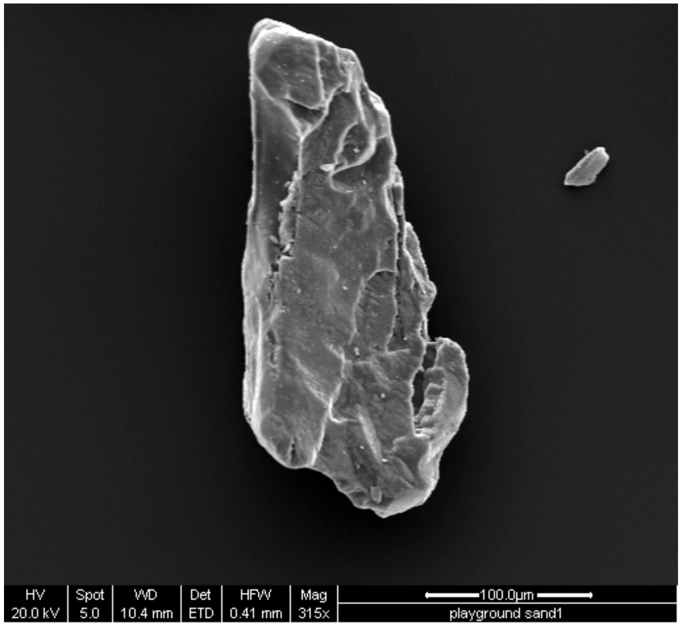
| Sample | Fall Time |
|---|---|
| Mentos | 0.7 s |
| Rock Salt and Lifesavers | 1.0 s |
| Table Salt and Sand | 1.5 s |

| Sample | Reaction Duration |
|---|---|
| Fruit Mentos | 3.4 s |
| Mint Mentos | 3.8 s |
| Lifesavers | 4.9 s |
| Molecular Sieve Beads | >12 s |

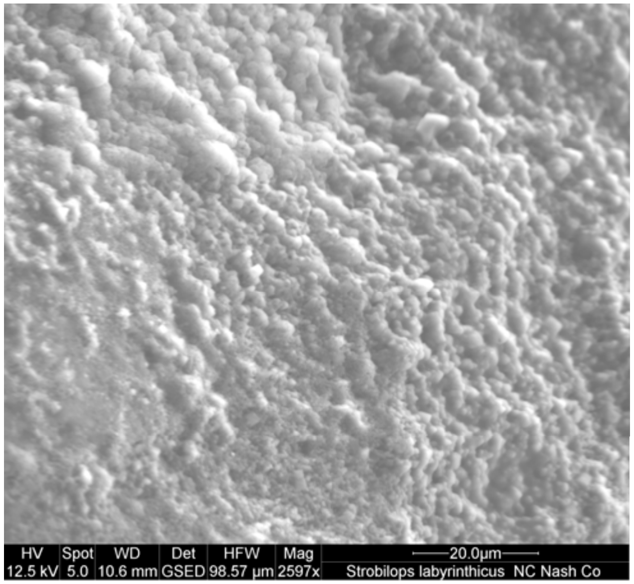
The porosity of the sample and the time to fall to the bottom of the bottle both contribute to the duration of the reaction. So for spray that goes a long way, you want a sample that plummets to the bottom of the bottle, not one that drifts slowly down.

# Roughness: SEM images of Samples



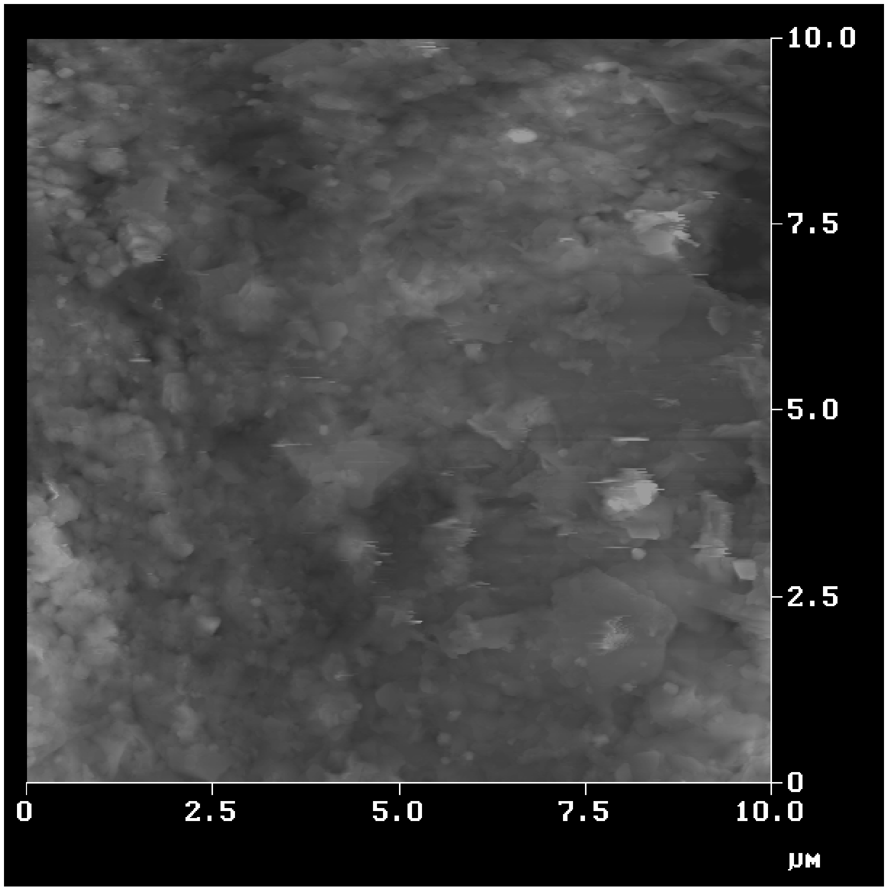

We can get a qualitative feel for the roughness of samples with SEM, but not get quantitative. Unfortunately, we couldn't image all of our samples in AFM due to sample height variation restrictions.

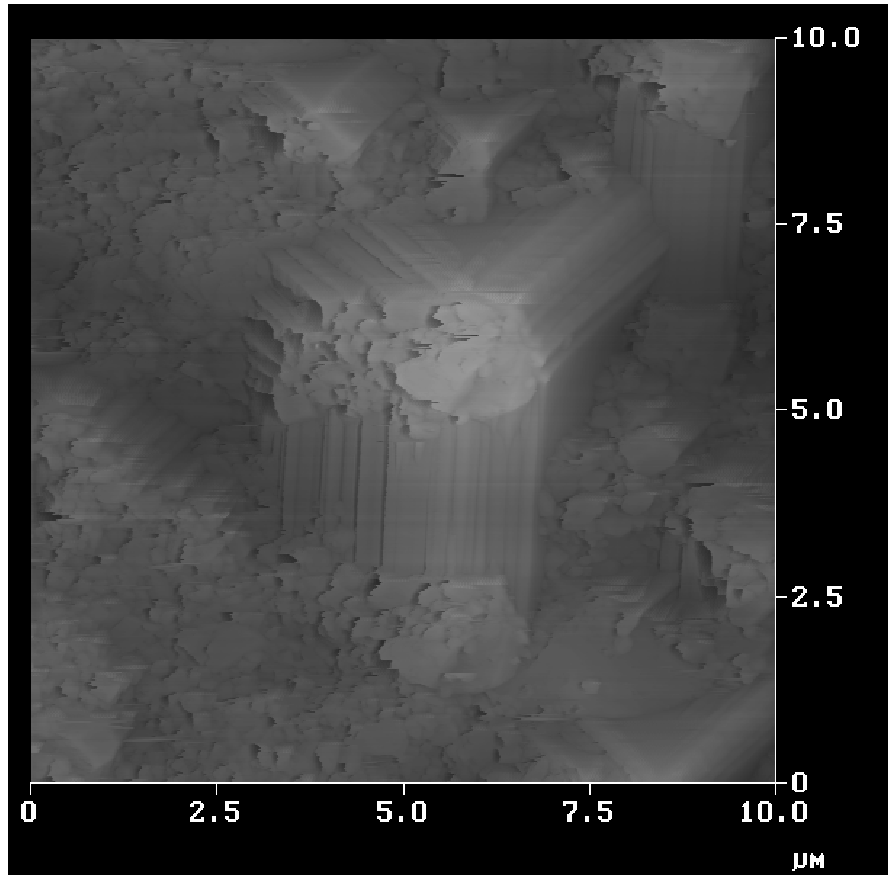



Mint Mentos

Large surface area to volume ratio means more growth sites!

# AFM Roughness Measurements




Left: Mint Mentos.  Z range: 3 microns.  Right: Wintogreen Lifesavers.  Z range: 18 microns

# AFM rms roughness measurements

| Sample | Root mean square roughness (nm) |
|---|---|
| Wint-o-green Lifesavers | 2630 |
| Fruit Mentos | 443 |
| Mint Mentos | 442 |
| Rock salt | 174 |

These measurements are all from a 10 micron x 10 micron image of the sample. Roughness does matter, but it isn't everything! The presence of surfactants in the candy, like gum arabic in the Mentos outer coating, also makes the reaction more explosive. You also have to factor in reaction duration, etc. This is a complex system!!

# What makes Diet Coke and Mentos so explosive?

- It’s not an acid/base reaction.
- Higher temperatures mean bigger explosions.
- The aspartame and potassium benzoate in the Diet Coke do a better job than sugar.
- There’s not enough caffeine to matter much.

- A faster explosion is more impressive than a slower one.
- The quick reaction time, and rough surface combined with the surfactants in the candy coating on the Mentos make it the most explosive.  Fruit Mentos have a thicker candy coating but same roughness, so they’re better for bigger explosions than Mint Mentos.

# Thanks!!

- This work was supported in part by the Petroleum Research Fund, grant number PRF# 44936-GB5, an NC Space Grant, New Investigations award, and the ASU College of Arts and Sciences. We would like to thank the Dewel Microscopy Facility for their donation of the time on the SEM.
- Guichuan Hou, Phil Russell, and Donovan Leonard
- PHY2210 students: Will Beuttell, Jason Burch, Blake Clark, Robert Duke, Jama Greene, AJ Hall, Jonathan Hearing, Leander Hutton, Kelly Izlar, Cully Little, James Lugenbell, Michael Mace, Bonnie Myers, Carla Penders, Zach Russell, Shane Shields, Adrian Steffen, Tony Sturtzel, and Zach Yokley
- Summer Research Assistants: AJ Hall, Magdalena Jaramillo, Cully Little, and Zach Russell, and Jon Jones
- Thanks for asking me to speak today.