SAND2007-4759C

Probing Deviations from Traditional Colloid Filtration Theory by Atomic Force Microscopy

AGU Fall Meeting Presentation
December 15, 2006

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OUTLINE

- What are colloids and why do we care about them?
- How do we describe colloid behavior?
  - Colloid Filtration Theory (CFT)
  - Derjaguin-Landau-Verwey-Overbeek (DLVO) Theory
- Deviations From Traditional Theory
- Research Objectives
- Probing Deviations
  - Atomic Force Microscopy and the Colloid Probe Technique
  - Measuring the secondary energy minimum
- Preliminary Results
- Future Work

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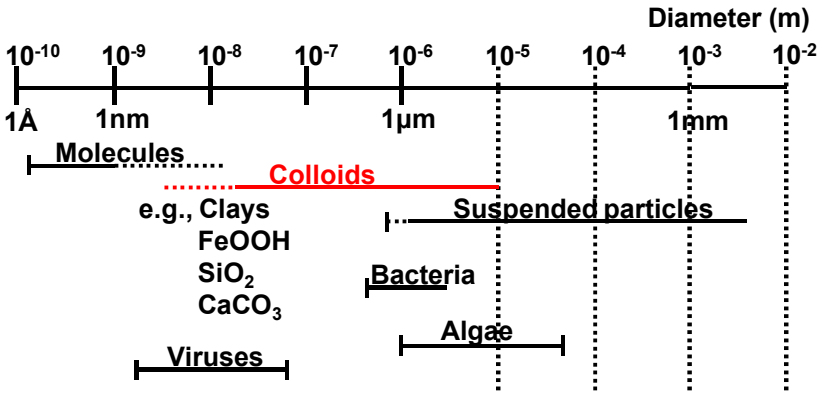
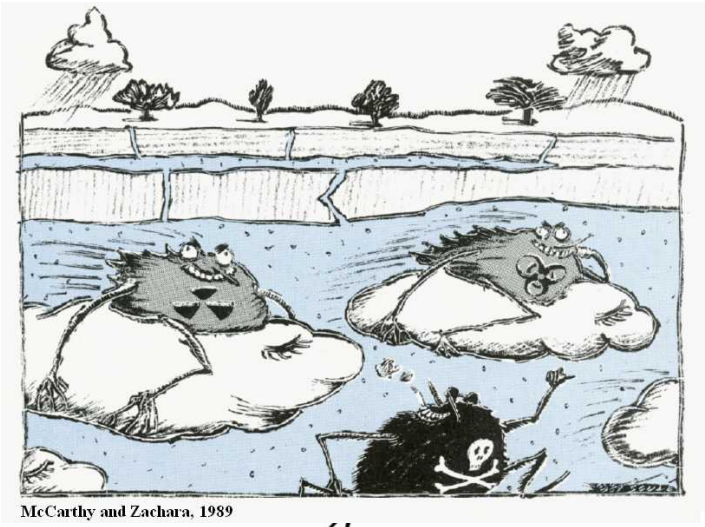
Colloids: What and Why

- What?
  - Particle with diameter of 0.001 to 10 μm
  - Particle with a high specific surface area per unit mass
  - Particle that occurs in groundwater (e.g., mineral fragments, bacteria)



Source: McCarthy, J.F.; Zachara, J.M. "Subsurface Transport of Contaminants." *ES&T*, 23(5), 496-502.



McCarthy and Zachara, 1989

- Why?
  - Contaminant transport in groundwater
  - Radionuclide transport at the NTS and LANL
  - Fouling of RO membranes
  - Precipitate during treatment of produced water

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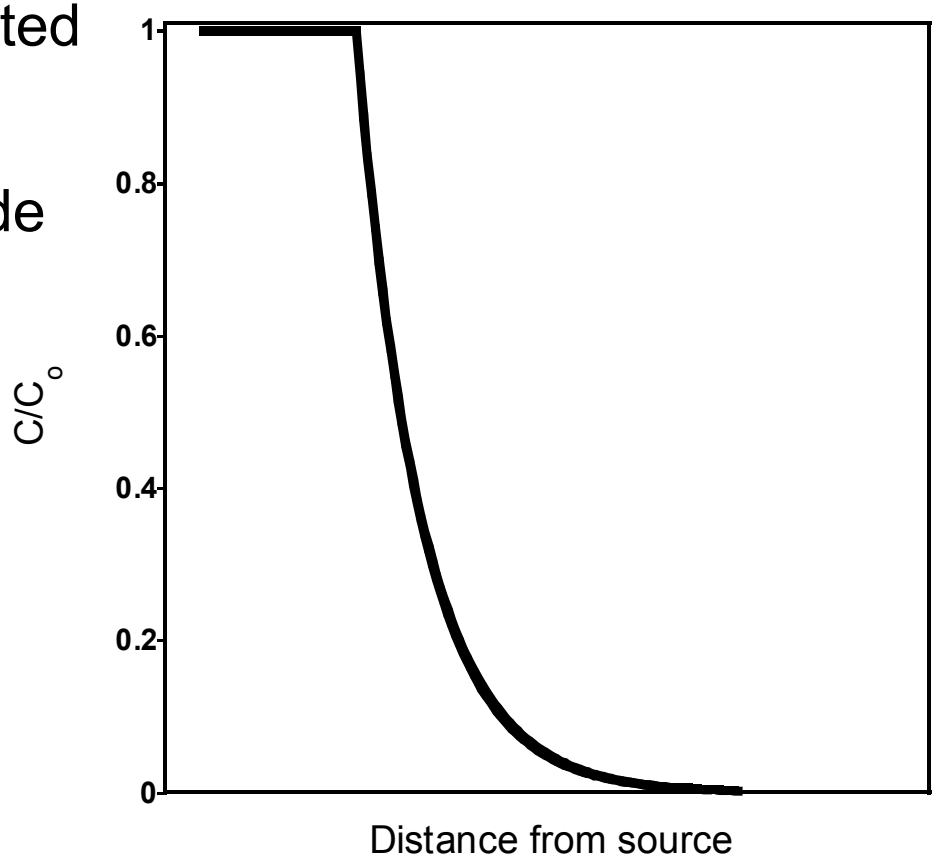
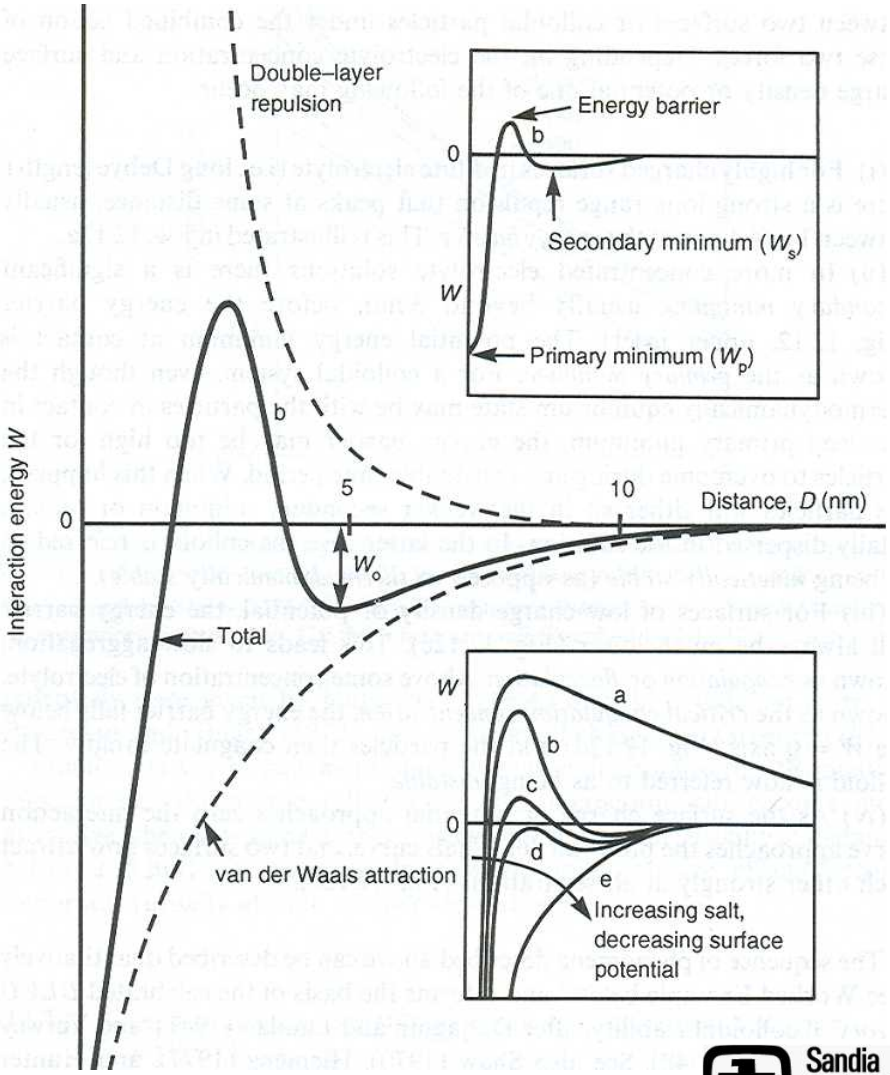
CFT Theory

- Widely used to predict particle deposition behavior in saturated porous media
- Transport mechanisms include advection, dispersion, and deposition
- Predicts
  - Exponential decrease in concentration with travel distance
  - 1:1 relationship between attachment efficiencies from breakthrough curves and from retained particle profiles



DLVO Theory

- Predicts the total interaction energy (W) between two charged surfaces (i.e., attachment or repulsion) interacting across an electrolyte solution
- W is a function of
  - Particle geometry and surface properties
  - Properties of medium separating surfaces
- $W = W_{vdwSP} + W_{RSP} + W_{BSP}$
- Irreversible attachment



Israelachvili, J., *Intermolecular and Surface Forces*, Elsevier, London, 1992, Figure 12.12.

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Deviations From Traditional Theory

- How does colloid behavior deviate from predictions of traditional theory?
  - CFT: Non-exponential decrease in concentration with travel distance
  - CFT: Non-linear relationship between attachment efficiencies determined from breakthrough curves and from retained particle profiles
  - DLVO: Reversible attachment
- What mechanisms have been proposed to account for these deviations?
  - Colloidal particle surface charge heterogeneities
  - Porous media surface charge heterogeneities
  - Deposition in the secondary energy minimum
  - Straining and exclusion

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Research Objectives

- Directly observe nanoscale forces between colloids and geologic surfaces using Atomic Force Microscopy, in an effort to further elucidate deviation mechanism(s)

- Measure the theoretically predicted secondary energy minimum with the Atomic Force Microscope (AFM)

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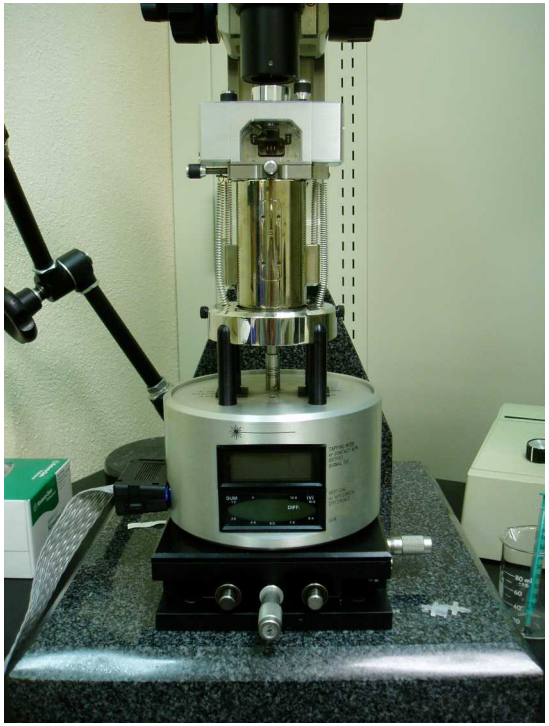
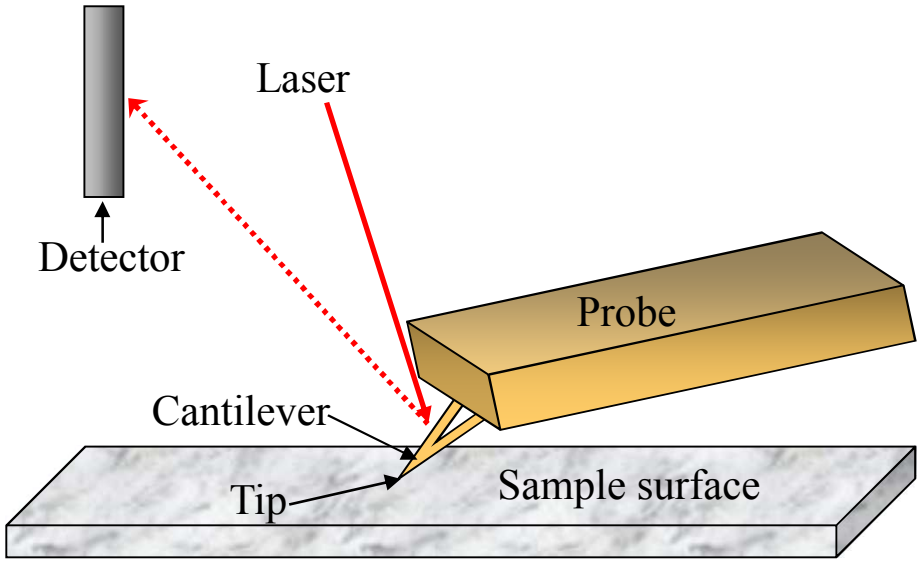
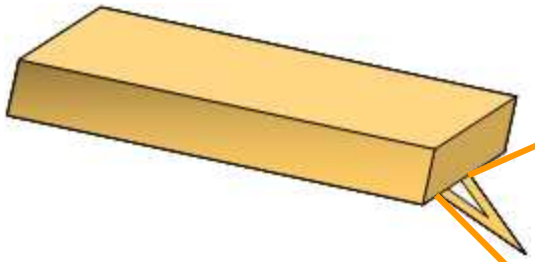
Atomic Force Microscope (AFM) Observations

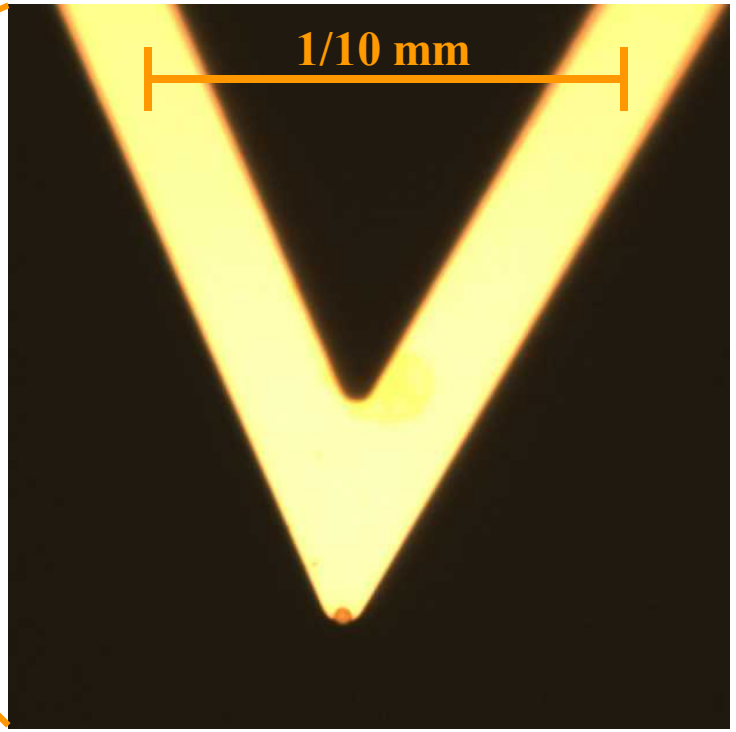




- Sample surface (+/- charge)
- Tip (+/- charge)
- Cantilever responding to interaction
- Response is captured by laser reflection into detector

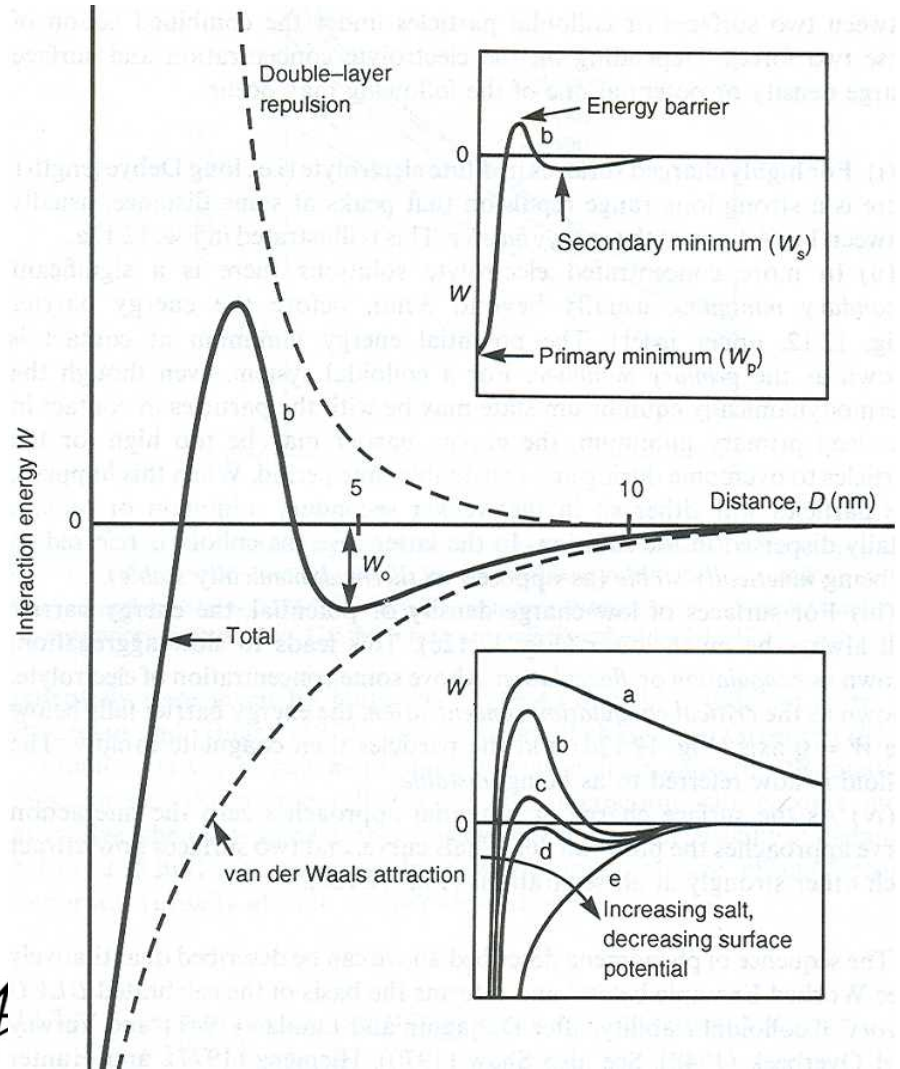
Colloid Probe Technique





- Existing AFM studies
  - Sharpened silicon nitride
  - Silica microspheres
  - Colloidal montmorillonite, kaolinte
  - Bacteria
- This research
  - Carboxylate-modified polystyrene microspheres

Secondary Energy Minimum: General DLVO Theoretical Predictions



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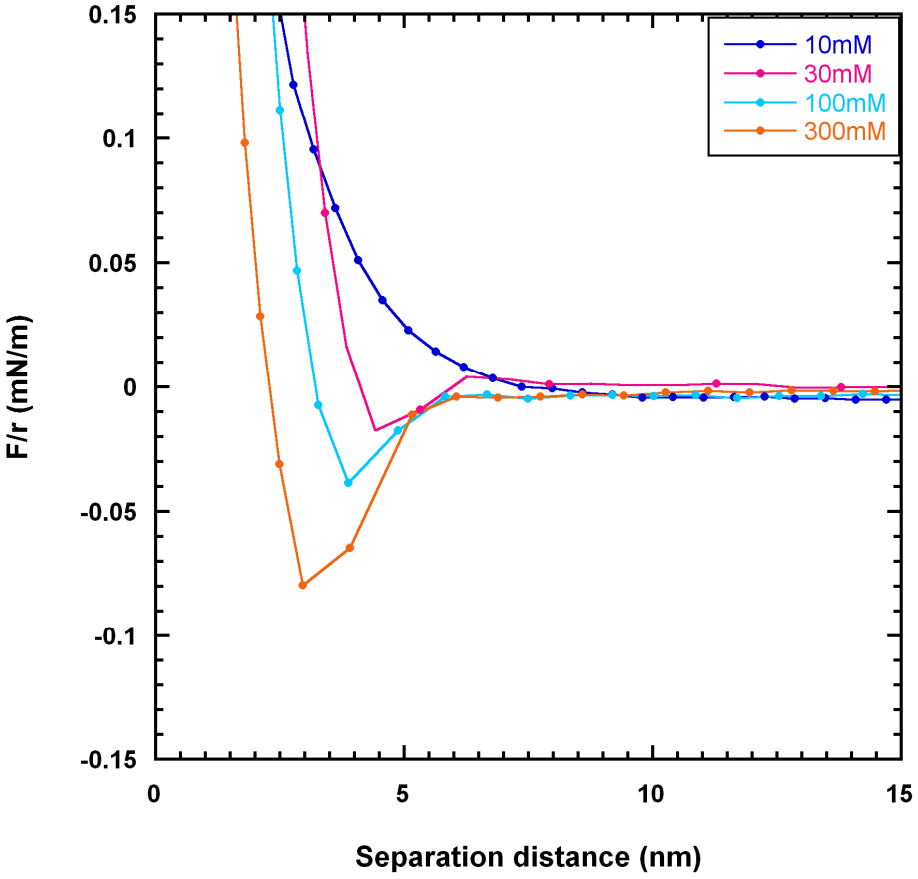
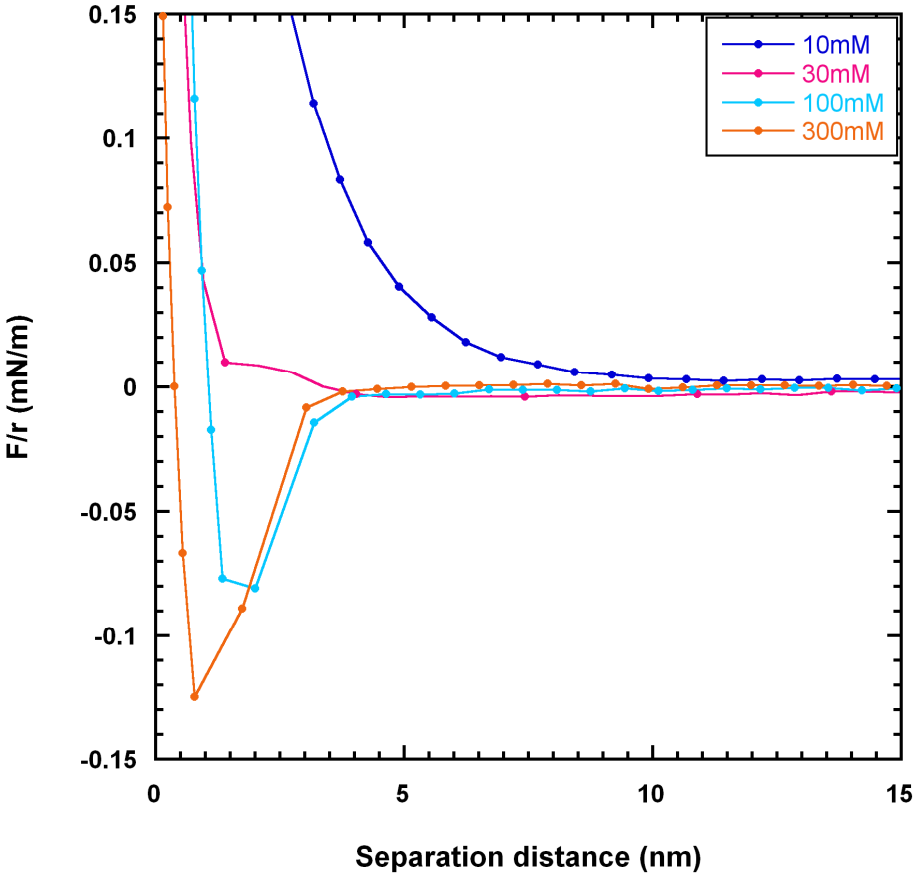
Preliminary Results

Mica surface
2 μm carboxylate-modified sphere
Data collected 10-02-2006



Mica surface
2 μm carboxylate-modified sphere
Data collected 10-04-2006



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Future Work

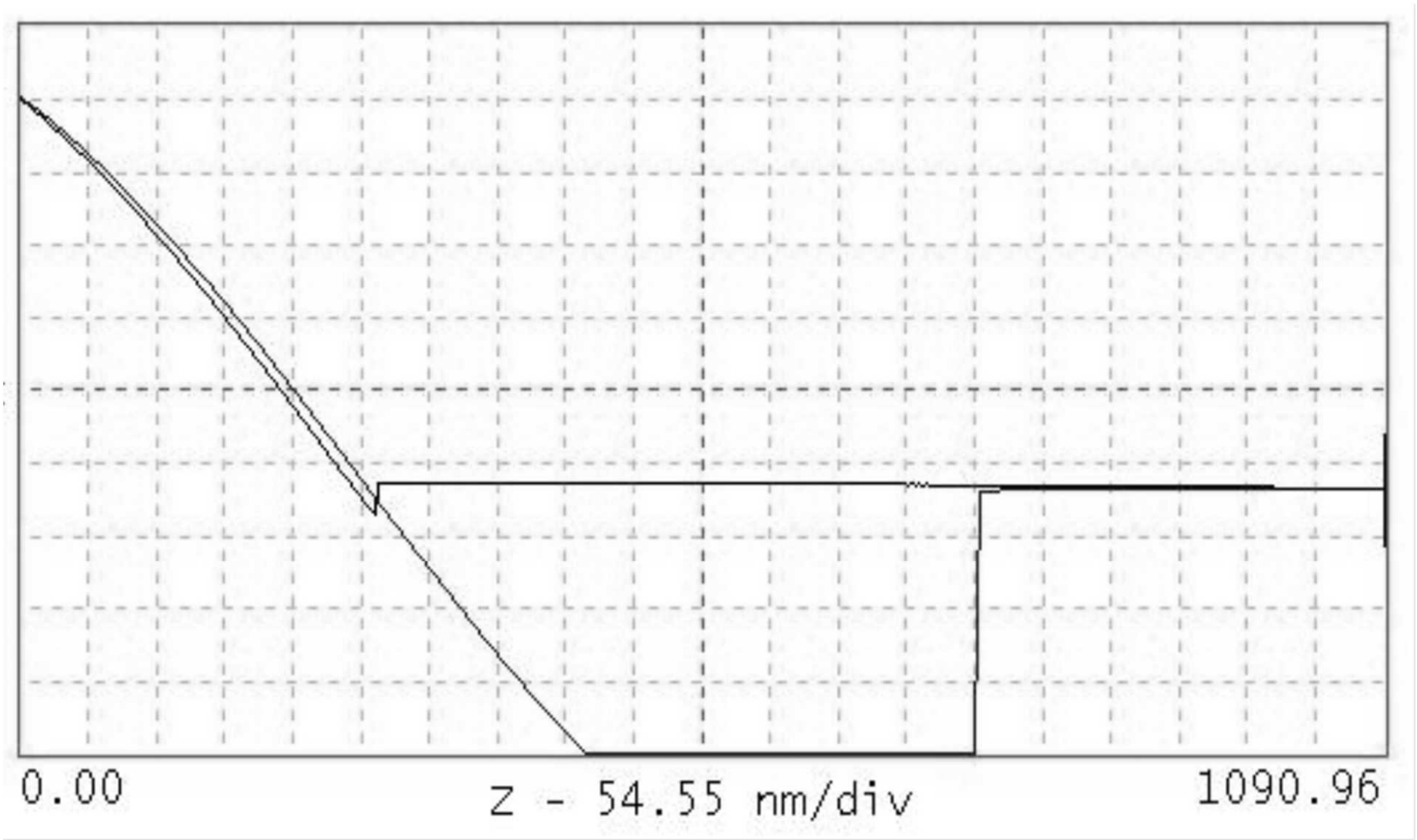
- Calculate theoretical DLVO curves for mica—carboxylate-modified polystyrene—KCl system
  - What are the theoretcially-predicted depths of the secondary energy minimums?
  - Can we reasonably expect to measure these with the AFM?
- Perform additional AFM experiments to test the effects of surface charge heterogeneities on observed force curves
- Perform additional AFM experiments using cantilever of lowest spring constant k possible

Questions

McCarthy and Zachara, 1989

Extra Slides

AFM Example Output



Proposed Deviation Mechanisms

- Experimental work by Tufenkji and Elimelech (2005) suggests that deviations from CFT arise due to the combined effects of surface charge heterogeneities (of both porous media and colloid population) and secondary energy minimum deposition
- Johnson and Li (2005) maintain that the deviations observed by Tufenjki and Elimelech (2005) arise because of surface charge heterogeneities within the colloid population only
- Deviations attributable to physical factors (i.e., straining and exclusion) argued by Scott Bradford and others