Shrinkage in Frozen Desserts:

Past, Present, and Future

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Food Science
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F D C
Frozen Dessert Center

Shrinkage

- Frozen dessert no longer fills the volume of the container
- Textural defect in the air phase: collapse of the frozen foam
- Studied extensively from 1940-1955


HALO
320

TOP

HALO

© pictureexclusive.com

Breyers
340
MINT
Chip
© pictureexclusive.com


vitamin
zero

What we know about shrinkage

- Ingredients
  - Fat, serum ingredients
- Processing factors
  - Freezing, hardening
- Post-production factors
  - Packaging, transportation, storage
- Measurement of shrinkage

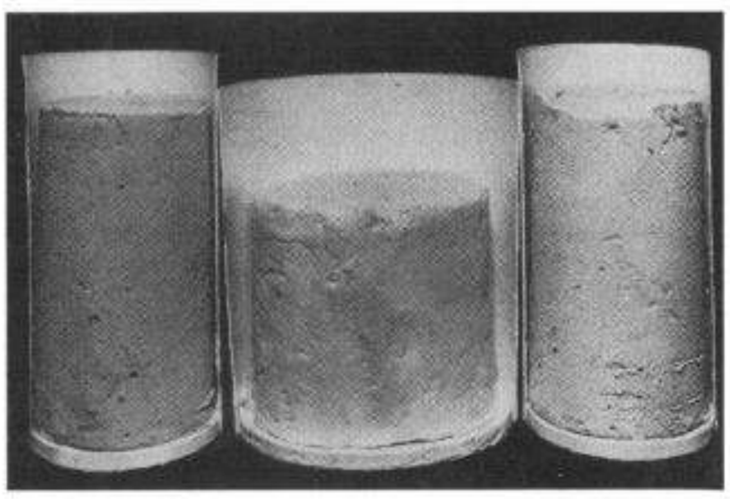


Fig. 1. Shrinkage in packaged ice cream.

Nickerson and Tarassuk (1955)

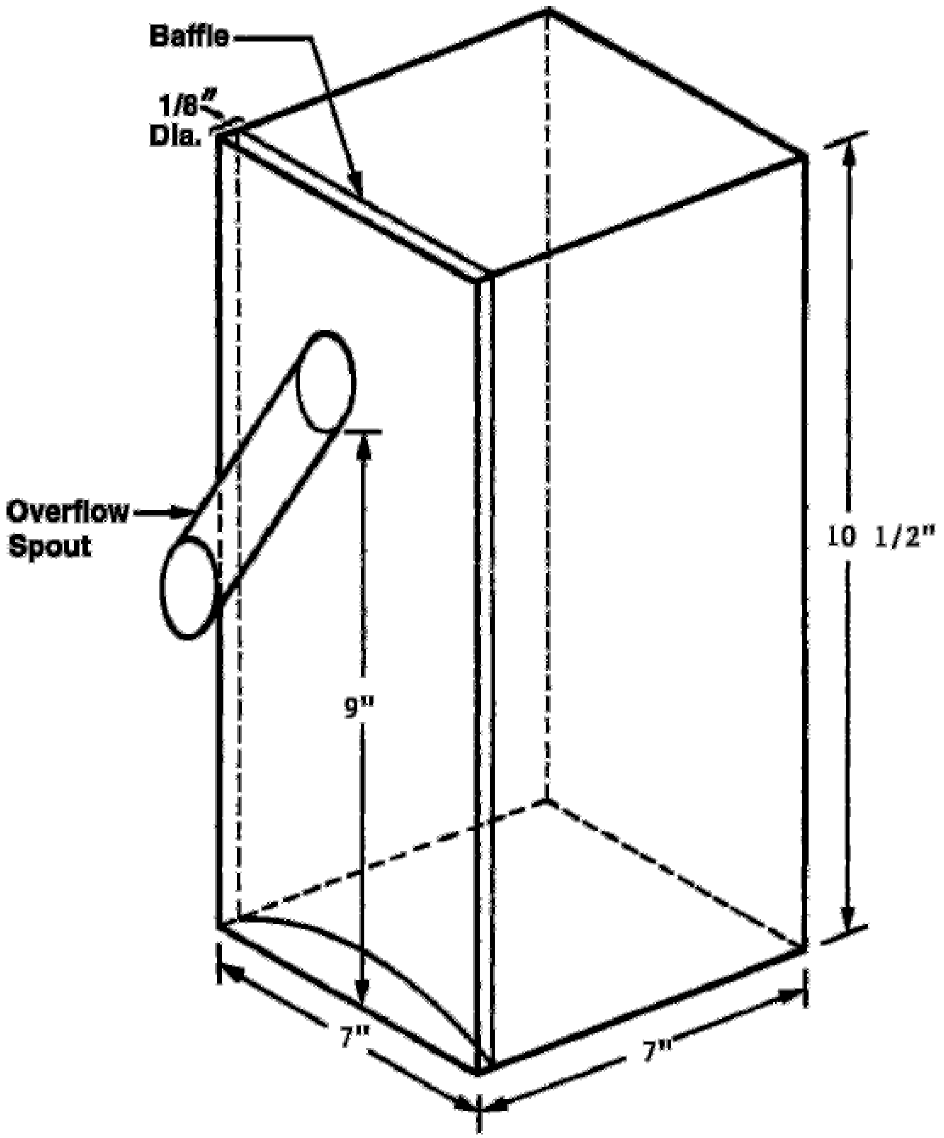
Measurement

Measurement

- Volume displacement
  - Low temperature to prevent melting
  - Solvent (kerosene, antifreeze, water)

- Distance measurement (as change in height)

- Volume calculation
  - L × W × H



Dubey and White (1996, 1997)

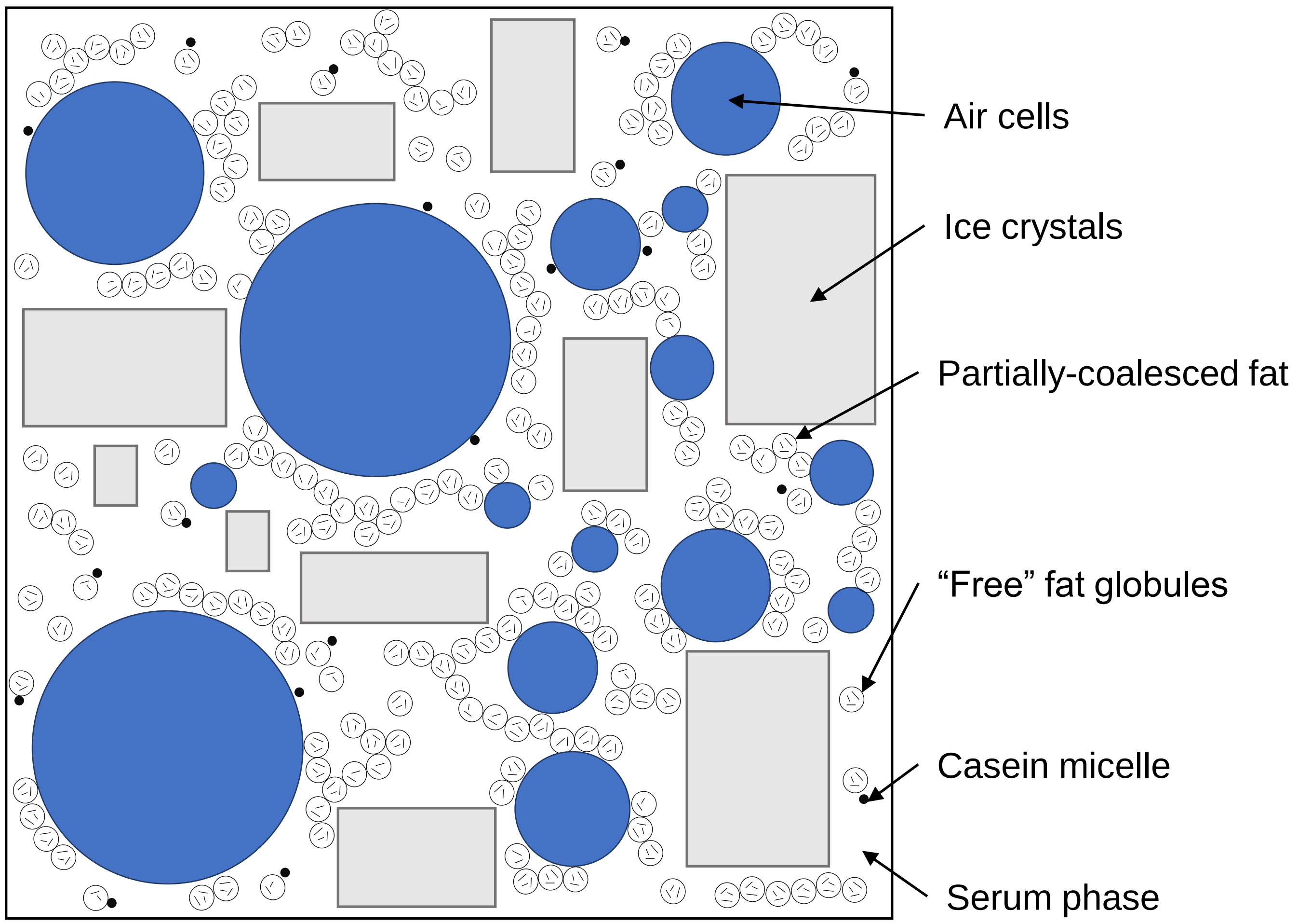
Effects of Ingredients

Effects of ingredients

- Fat

- Sweeteners
- Stabilizers
- Protein
- Emulsifiers

- Water

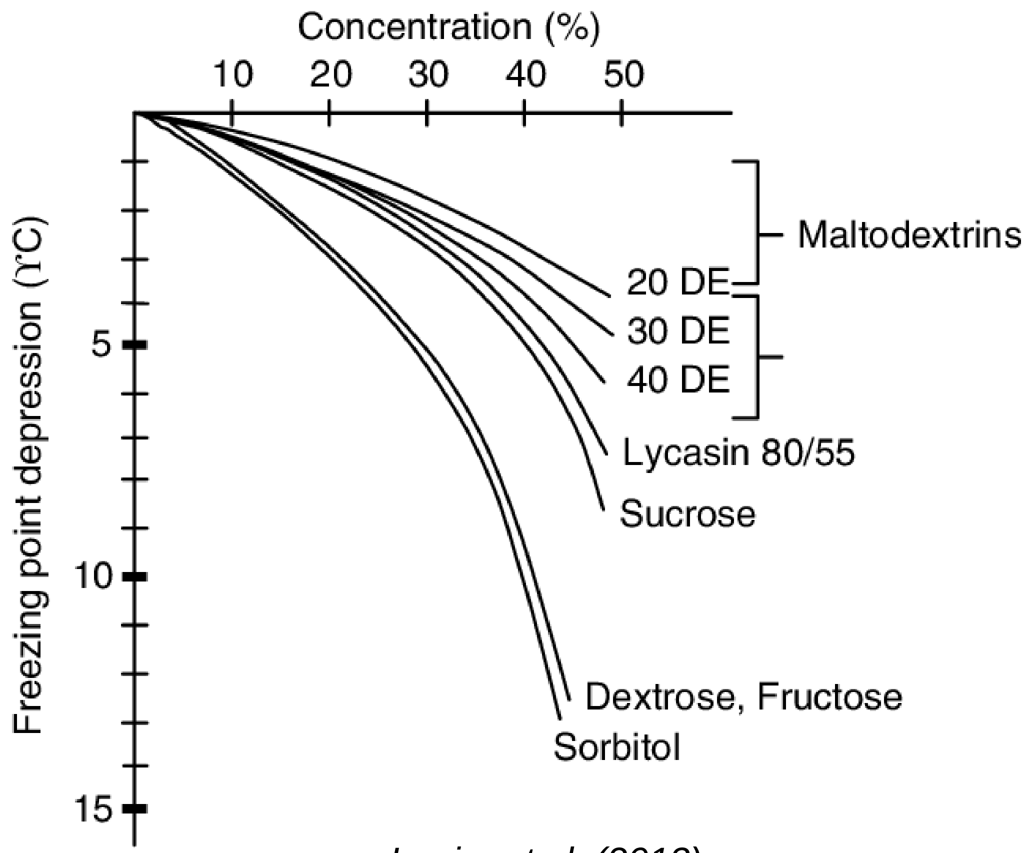


Sweeteners

- Higher sugar content is more likely to cause shrinkage
- Dextrose, corn syrup, honey, wheat syrups all increased shrinkage

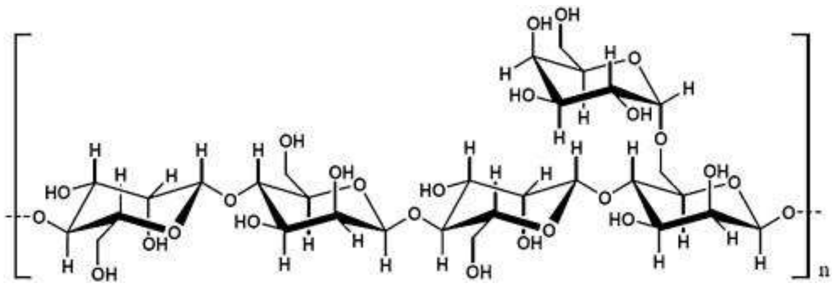
- Lower freezing point decreases serum phase viscosity and promotes air cell destabilization

- Few historical studies on non-nutritive sweeteners or sugar alcohols



Lanier et al. (2013)

Stabilizers



Locust bean gum

- Early research is conflicting
  - Some say it has no effect, and some say it increases shrinkage
- Dubey and White (1996): study of 5 common stabilizers
  - CMC had most, LBG (w/ CMC, carrageenan, or alone) had least
- Stabilizers promote stable foams
  - Increase serum viscosity, some are surface active
  - Preventing ice recrystallization may promote foam stability
- Be wary of protein/hydrocolloid phase incompatibility

Low molecular weight surfactants

- Conflicting results in early studies
- Egg yolk increased shrinkage

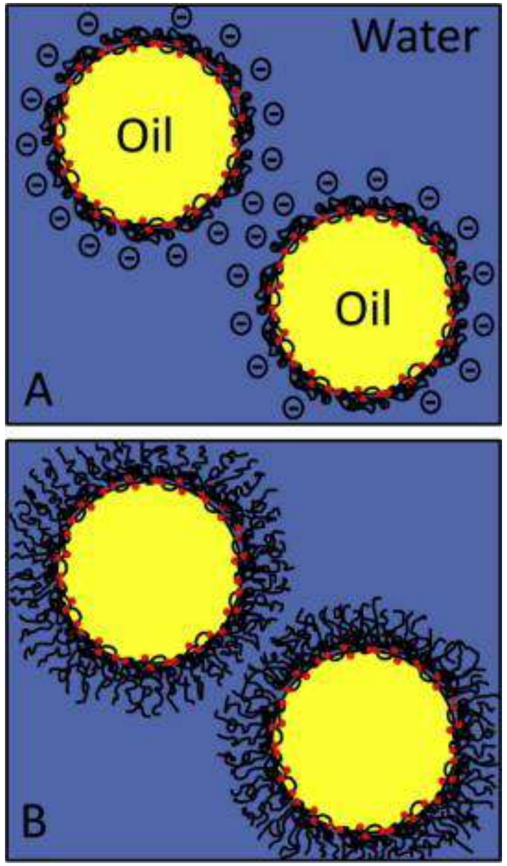
- Effects on fat phase
  - Prevent shrinkage because they promote a strong fat network
    - Partially-coalesced fat may adsorb to the air interface and provide physical barrier to air migration or channeling
  - LMWS also shown to prevent shrinkage in low-fat products (Dubey and White 1996)

- Surface activity important for foam stability

Protein

- Whey protein in bulk and at interface influences shrinkage
- Whey ingredients may reduce shrinkage, but not always
  - Undenatured whey proteins reduced shrinkage
  - Thermal or chemical denaturation of whey proteins increased shrinkage

- Caseinates decreased shrinkage
- Hydrolyzed casein increased shrinkage
- Calcium may enhance shrinkage because it destabilizes casein



Lam and Nickerson (2013)

Protein

- Protein-polysaccharide thermodynamic incompatibility
- Low temperature instability
  - Coagulation or cryogelation
- Peptides may stabilize foams and prevent shrinkage
- High protein content is linked to shrinkage

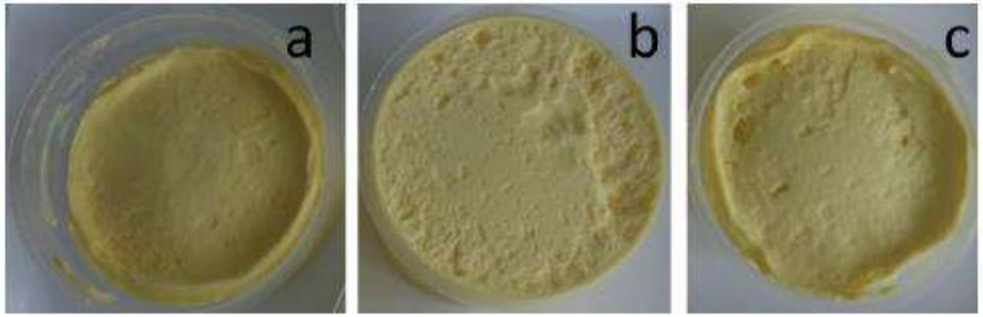


Fig. 1. Pictures of a: thawed reference mousse after 12 months frozen storage; b: thawed mousse with gelatin peptides after 12 months frozen storage; c: thawed mousse with milk powder after 12 months frozen storage.

Duquenne et al. (2016)

Effects of Processing

Mix processing

- High pasteurization T showed mixed results
- High homogenization P increases shrinkage
  - Effects on fat and protein structures
- Aging
  - Change in composition of fat globule membrane
  - Hydration of proteins

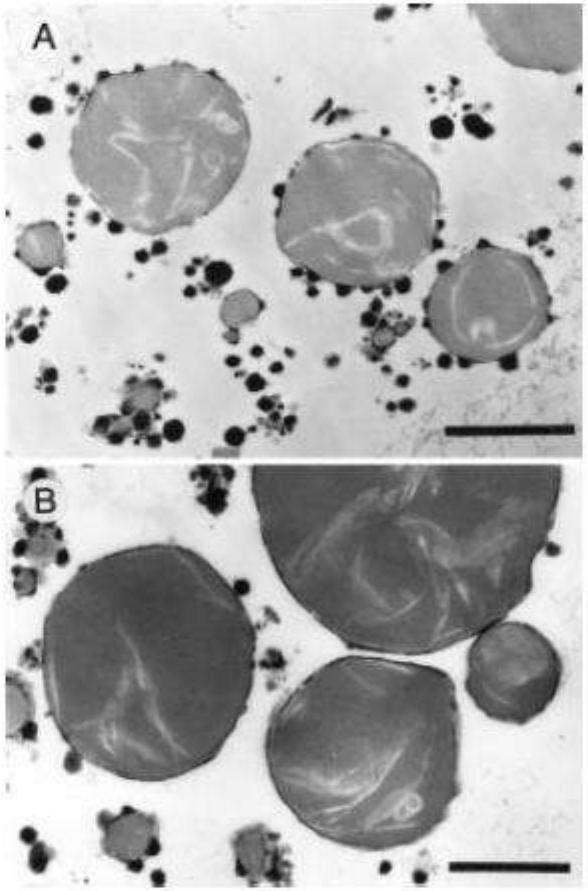


Figure 3. Transmission electron micrograph of an ice cream mix emulsion in the absence (A) and presence (B) of 0.08% polysorbate 80. Bar = 1 μm (37).

Goff (1997)

Freezing

- Fine microstructure increased likelihood of shrinkage
  - More interfaces = more thermodynamic instability

- Lucky timing: mass production
  - Continuous freezing
  - Novel packaging
  - Transportation and production
  - Storage at home

Freezing

- Continuous freezing promoted shrinkage
  - Fine microstructure
  - Pressure drop
- Higher overrun promotes shrinkage
  - Thinner air cell lamellae
  - More instability of discrete cells
  - Despite other microstructural elements, more prone to foam collapse
- Faster hardening decreases channeling
- Soft-serve, gelato, other unhardened: rarely shrink because product melts quickly and is consumed immediately

Breyers Ice Cream (1948)

Post-production effects

Packaging

- Appearance of shrinkage defect correlates with introduction of wide use of paper containers
- Gas diffusion: Unlined paper containers had most shrinkage. Treatment with paraffin, aluminum foil, other gas barriers reduced shrinkage.
- Adhesive force between product and container: paraffin coating on interior prevented shrinkage, but exterior had no affect
- Study of ice cream removed from container (Hankinson and Dahle, 1944): no volume lost, but samples collapsed under their own weight
- Best prevention practices: limit gas diffusion (to environment)

Temperature fluctuations

- The single largest cause of all textural defects, including shrinkage
  - Ice recrystallization
  - Air cells grow, experience disproportionation and coalescence during storage (Chang and Hartel, 2002)

- Melt/refreeze recrystallization
  - Affects chemistry of serum phase, and can destabilize air
  - Melting: drainage of watery lamellae between air cells, accelerated gas diffusion, hydration of proteins
  - Refreeze: Ice crystal growth could puncture air cells, protein hydration

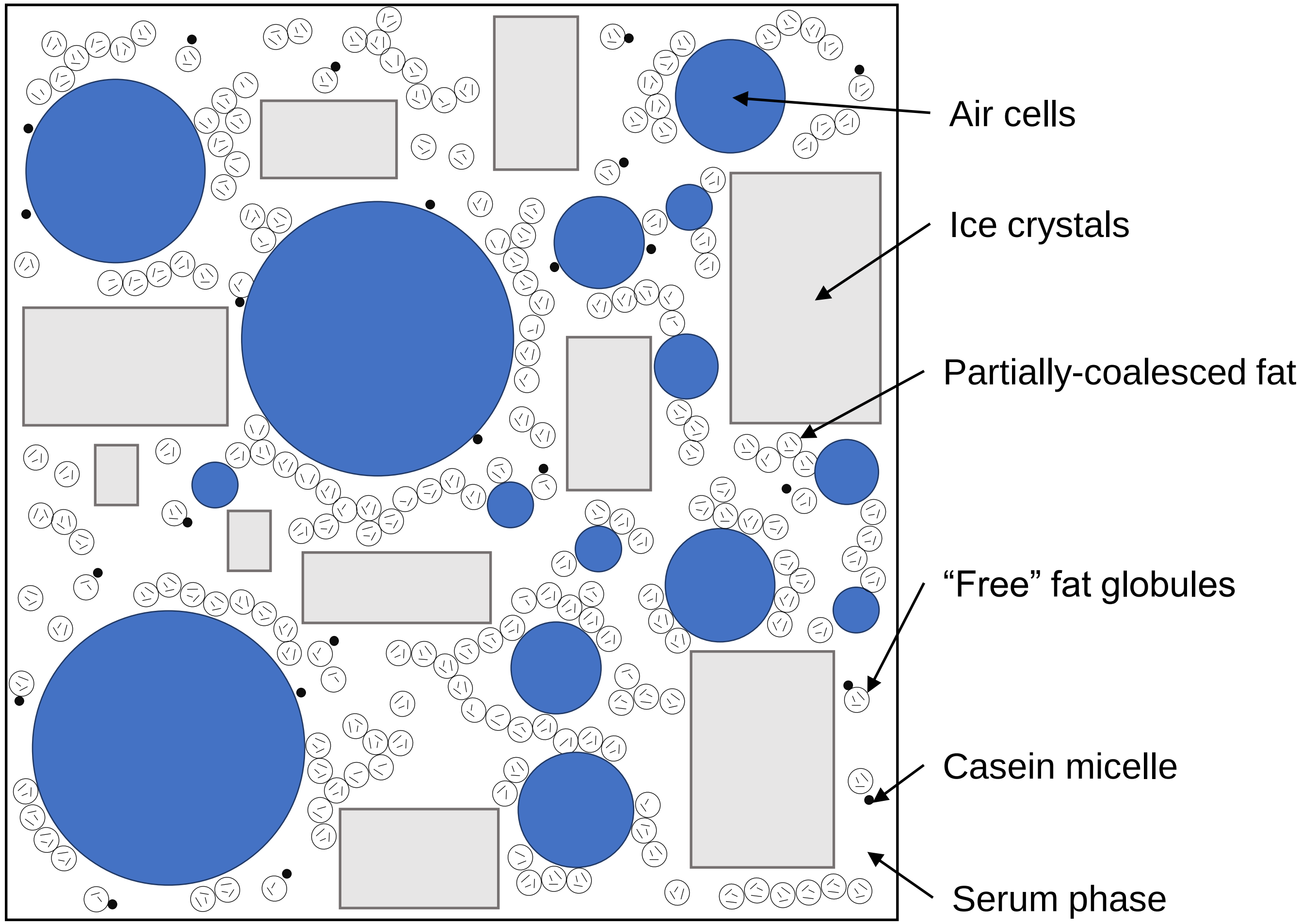
Pressure changes

- Originally thought to be one of the drivers of modern shrinkage: transportation over mountains
- Still likely to be a culprit especially once it reaches consumers
- Ideal gas law: $PV=nRT$
- Subjecting frozen desserts to vacuum causes shrinkage

Frozen desserts as a frozen foam

A multiphase system of interfaces

- Thermodynamically unstable, but kinetically stable at low T
- Liquid/liquid interfaces: Oil/water, oil/air
- Solid/liquid interfaces: water/ice, fat/oil
- Liquid/gas interfaces: oil/air, water/air

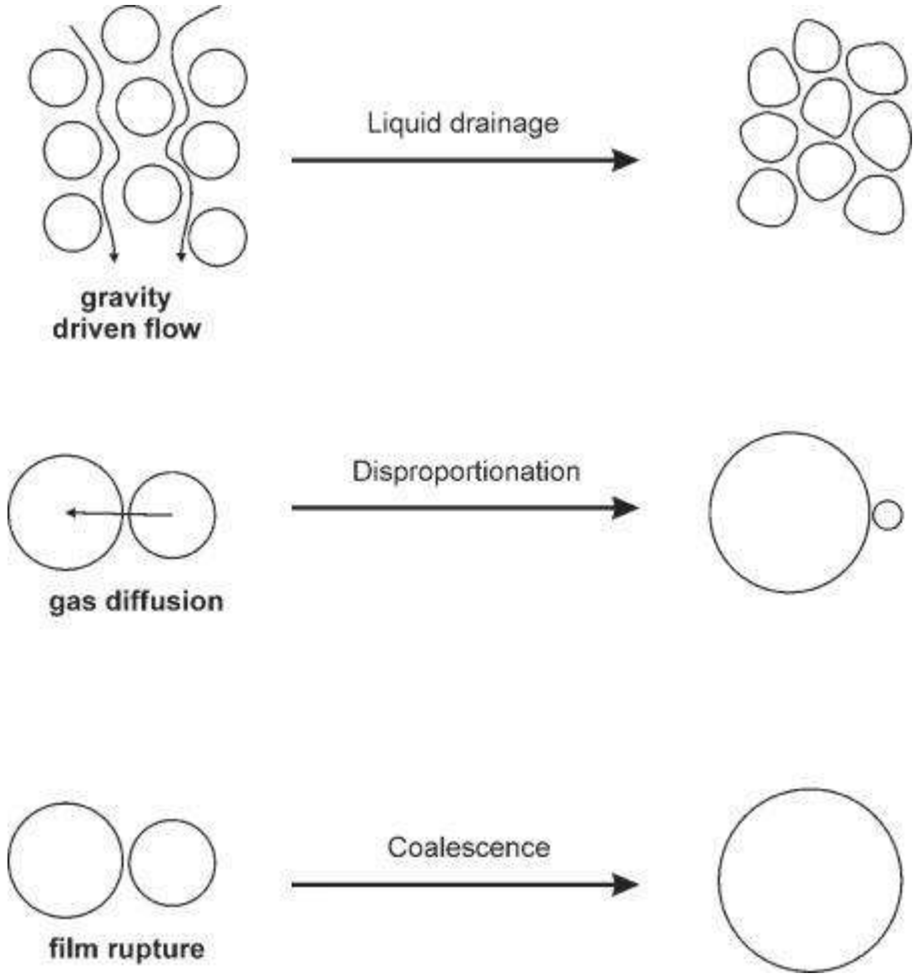


Frozen desserts as a frozen foam

- Air phase dispersed in a continuous, semi-frozen aqueous serum

- Foam destabilization
  - Drainage
  - Disproportionation (Ostwald ripening)
  - Coalescence

- Destabilization of foam → collapse



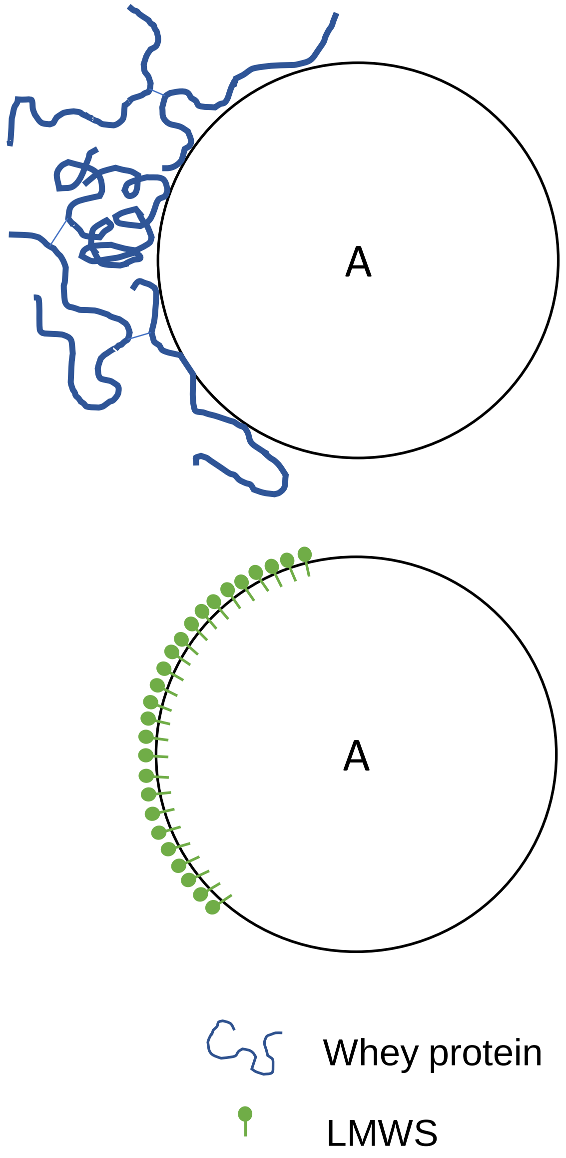
Germain and Aguilera (1999)

Foam stabilization

- Proteins: viscoelastic film
  - Steric, electrostatic, mechanical stabilization
  - Thick coating

- LMWS: Gibbs-Marangoni mechanism
  - Thin coating
  - Fluid interface
  - Low interfacial tension

- Competitive displacement



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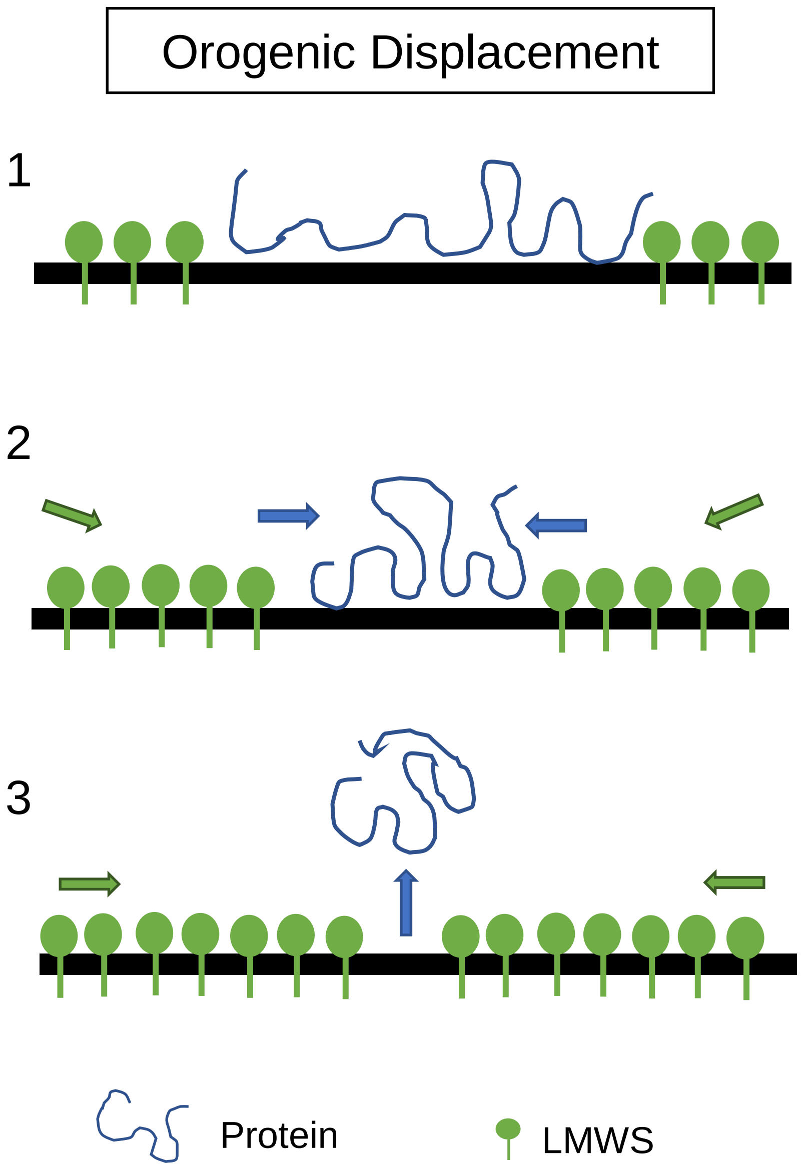
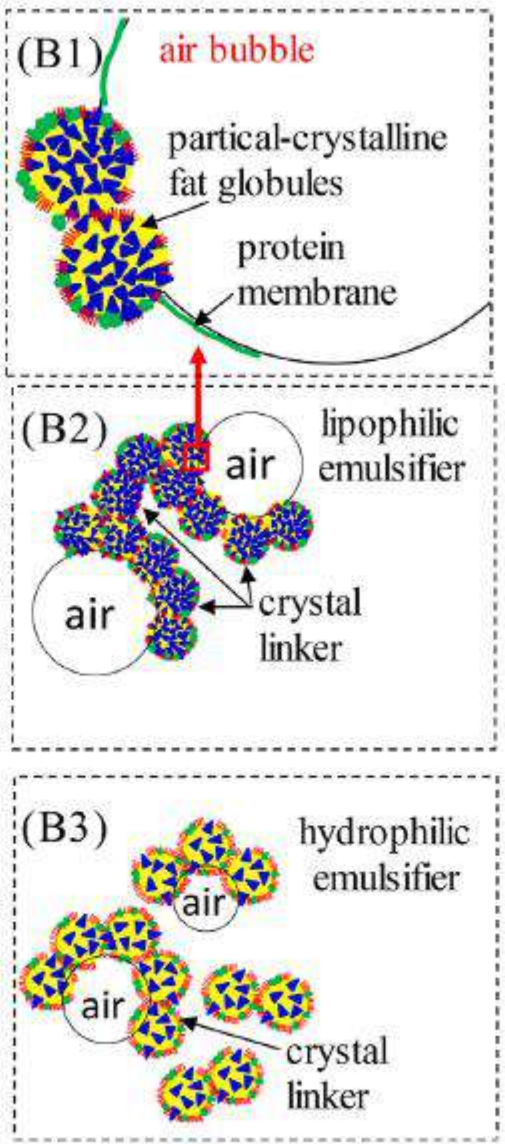


Shrinkage mechanisms in theory

- (In)stability of air phase

- Air/water interface
  - Protein, LMWS, fat networks, fat globules, mixed surfactant system..?
  - Thickness, elasticity, stability of interface

- Serum phase
  - Viscosity, osmotic pressure, etc.
  - Ability to maintain the dispersed air phase



Jiang et al. (2019)

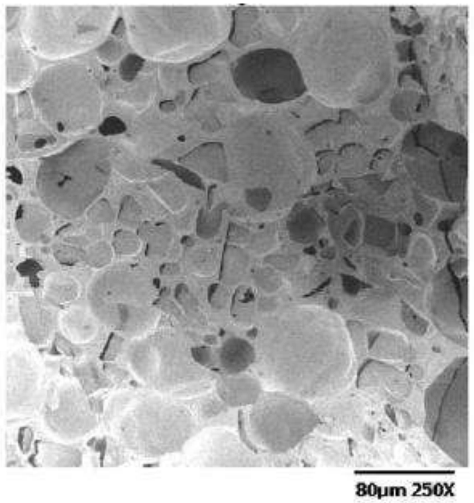
Shrinkage mechanisms in history

- Hankinson and Dahle (1944)
  - 3 forces contribute: gravity, air volume changes from T fluctuations, P change created by change in volume as water freezes to ice
  - Sinking of product due to gravity and expansion at air interface, but doesn’t fully explain shrinkage related to coarsening of air cells

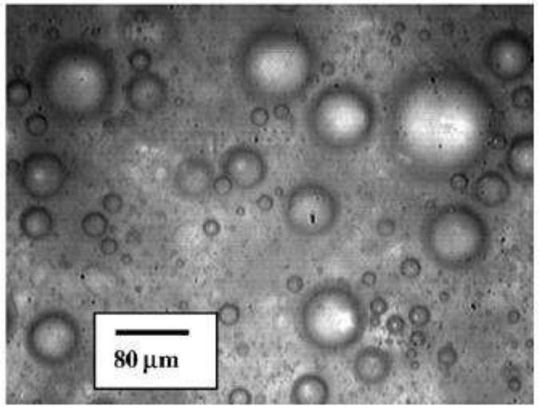
- Turan and Bee (1999)
  - Shrinkage is two-stage: first air cells form channels, then matrix collapses and loses volume
    - Channels form by disproportionation or coalescence to create a sponge matrix, which collapses due to gravity
  - Channels promote gas diffusion with exterior but are not affected by external pressure changes

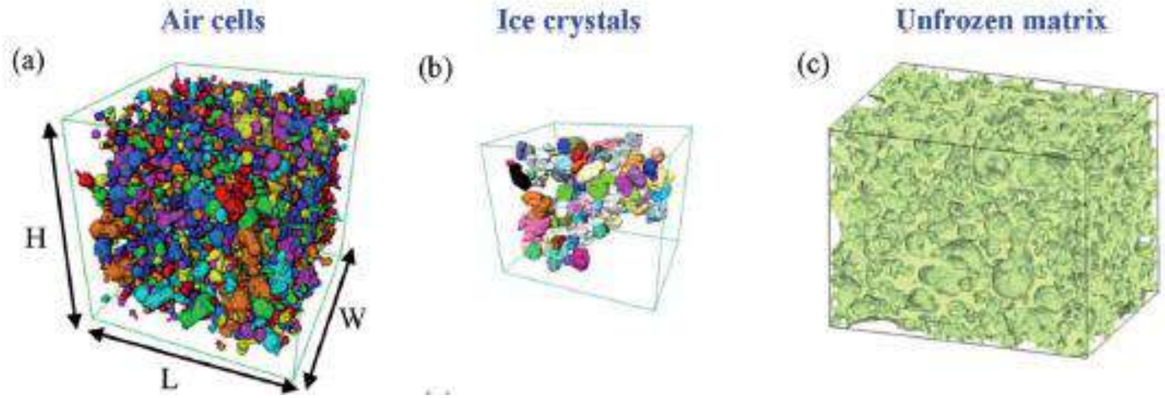
Visualizing air cell instability

- 2D measurements
  - Optical (light) microscopy
  - Cryo-EM
- 3D measurements
  - X-ray tomography
- Pressure responses
  - Transducers



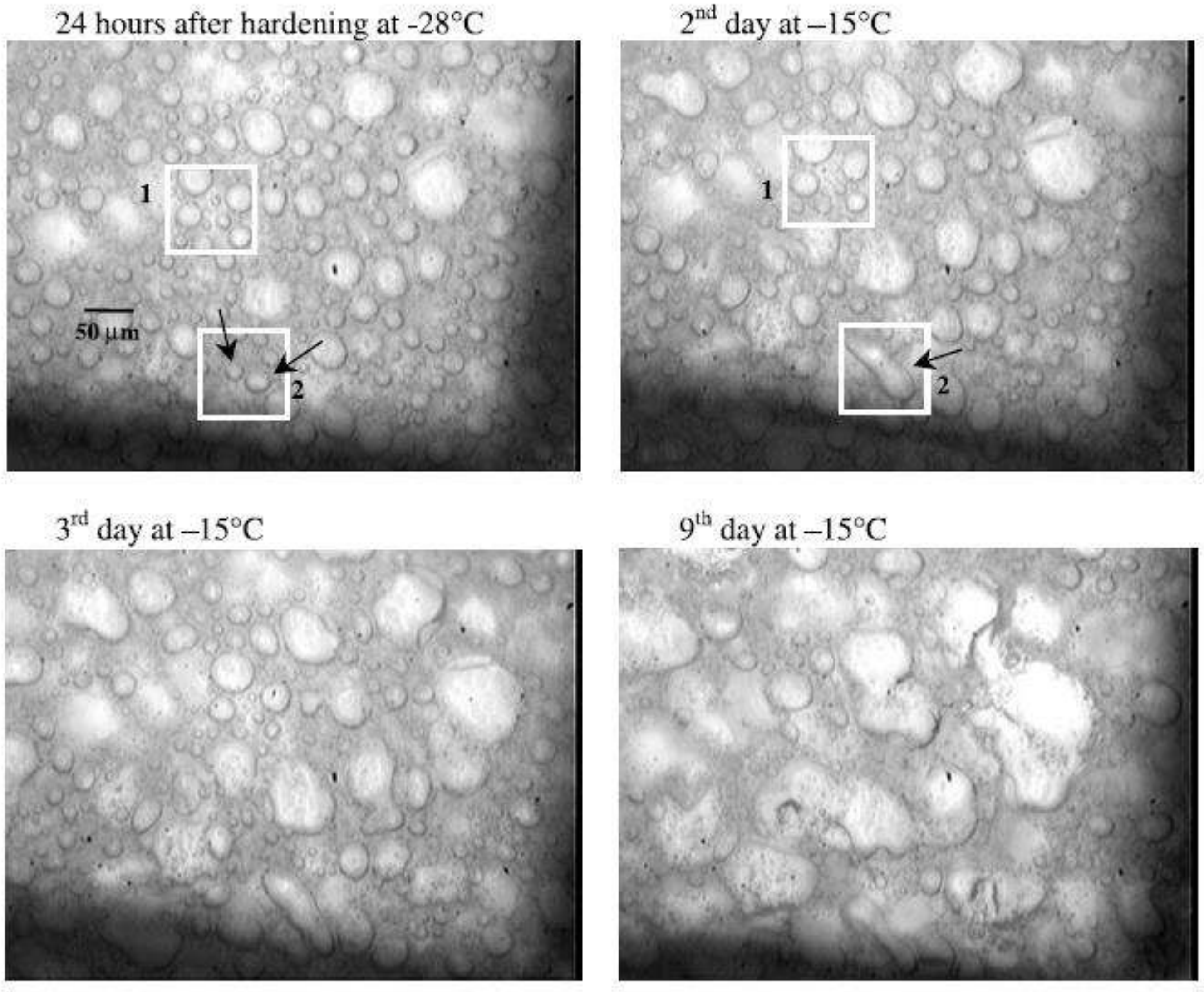
Chang and Hartel (2002)





Guo et al. (2017)

Air cell instability



Chang and Hartel (2002)

Air cell instability

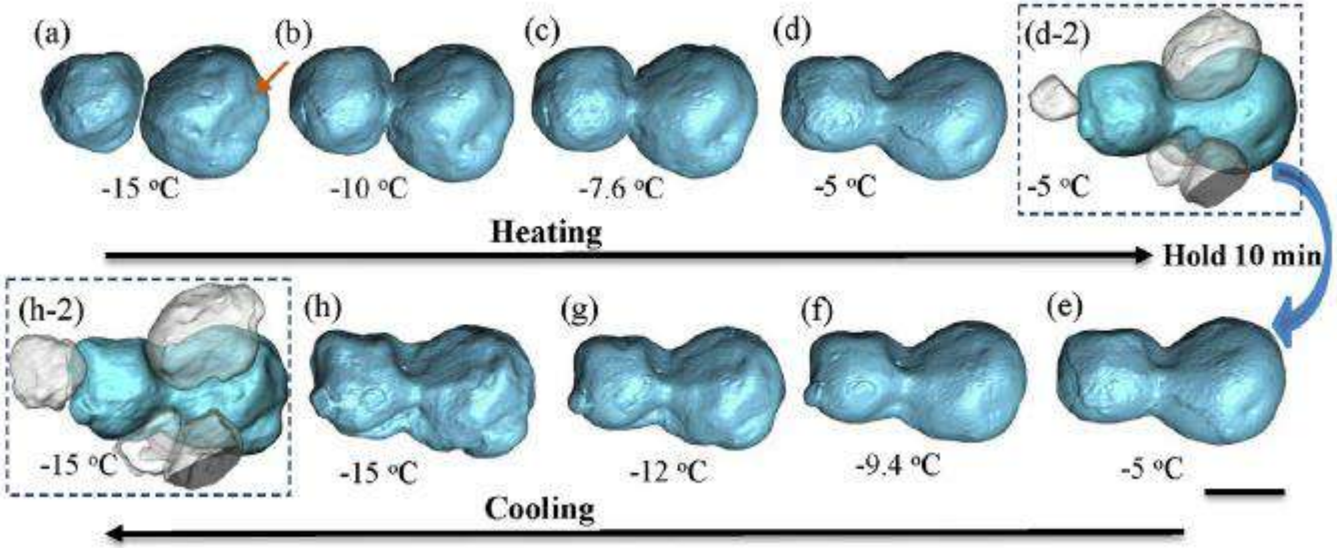
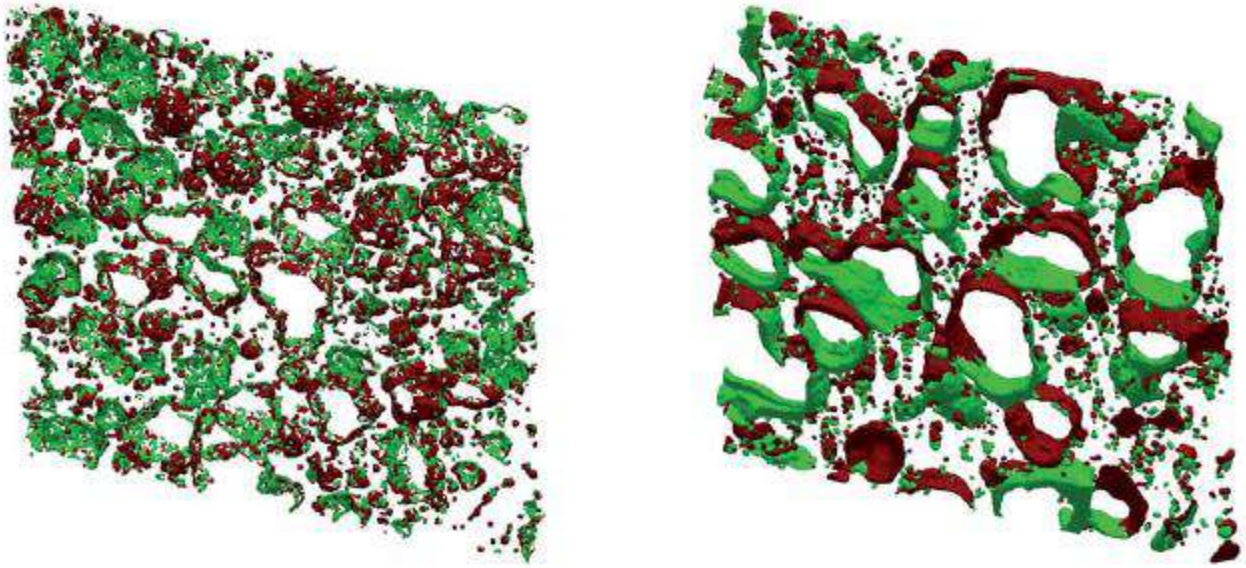


Fig. 9. Coalescence of two air cells during the heating stage (a–d) and cooling stage (e–h) of a thermal cycle. (d-2) and (h-2) show the morphological relationship between the surrounding ice crystals and the air cell at −5 °C and −15 °C, respectively. Scale bar 100 μm for all images.

Guo et al. (2018)

Air cell instability



(a) changes in air phase at the cold temperature

(b) changes in air phase at the high temperature

Fig. 9 Changes in the air phase between subsequent scans, derived from the images shown in Fig. 8. Voxels marked green represent appearing air phase and voxels marked red represent disappearing air phase. (a) For low temperatures, the bubbles remain mostly stable, which is reflected by the little changes occur during the 4 h between the scans. (b) At high temperature, there are significant changes, the growth/ablation pattern results from both moving bubbles and deforming bubbles.

Pinzer et al. (2012)

Channeling

- Cannot visualize well – 2D optical microscopes and cryo-EM don’t capture fully
- X-ray tomography has shown evidence of channel formation
- Channeled air cells do not respond to external pressure changes
- Channeling does not always lead to shrinkage

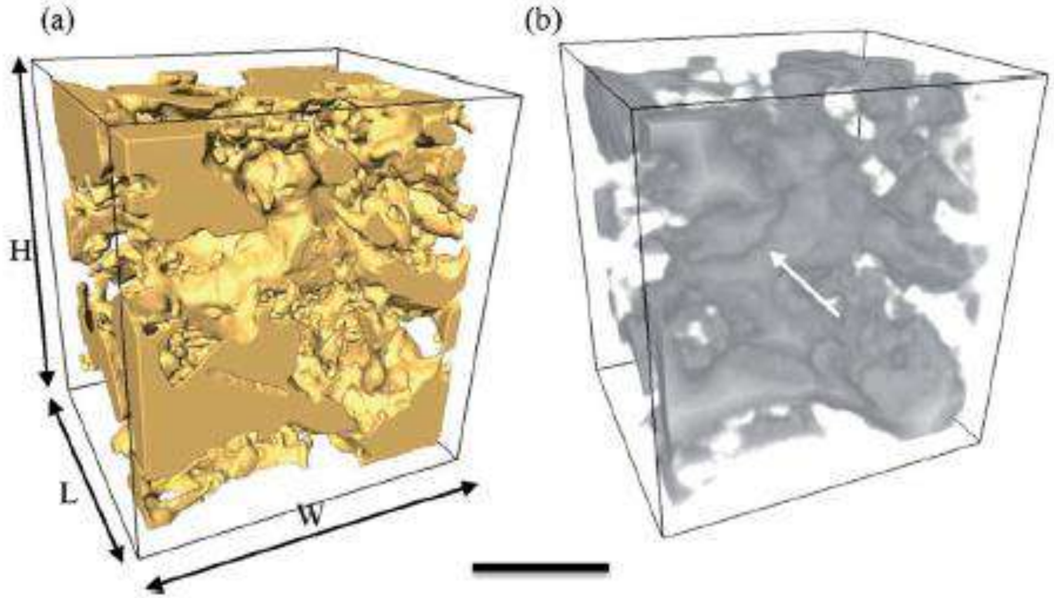
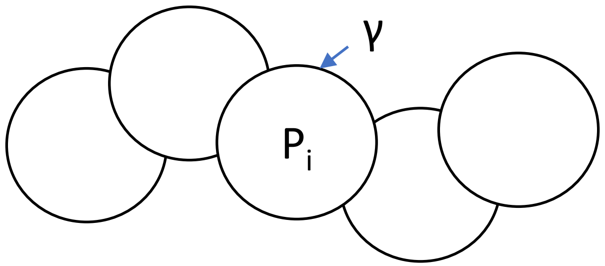


Fig. 8 3D image of an air cell channel in the C_{14} ice cream sample: (a) isosurface 3D rendering, (b) skeleton of the air cells showing a channelling feature. Volume box size is 545 × 416 × 499 ($H \times L \times W$) μm^3. Scale bar is 200 μm for both images.

Guo et al. (2017)

Modeling changes in frozen foams

- Partial coalescence
  - Balance of internal pressure and interfacial tension
  - Surfactant location and activity



- Ice recrystallization
  - Ice crystal growth mechanisms are similar to those of air phase destabilization – coalescence, disproportionation
  - Some evidence that the same peptides that can prevent recrystallization can prevent shrinkage (Cox et al. 2009, Duquenne et al. 2016)

- Melting behavior

Summary

- High protein, high sugar, high overrun promote shrinkage
- Most important ingredient: protein
- Reduce temperature (and pressure) fluctuations

- Volume displacement measurement technique recommended
- No clear mechanism
- Study frozen desserts as frozen foams
- Utilize other measurable changes during storage (especially ice recrystallization) to better understand the air phase stability

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Thank You

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