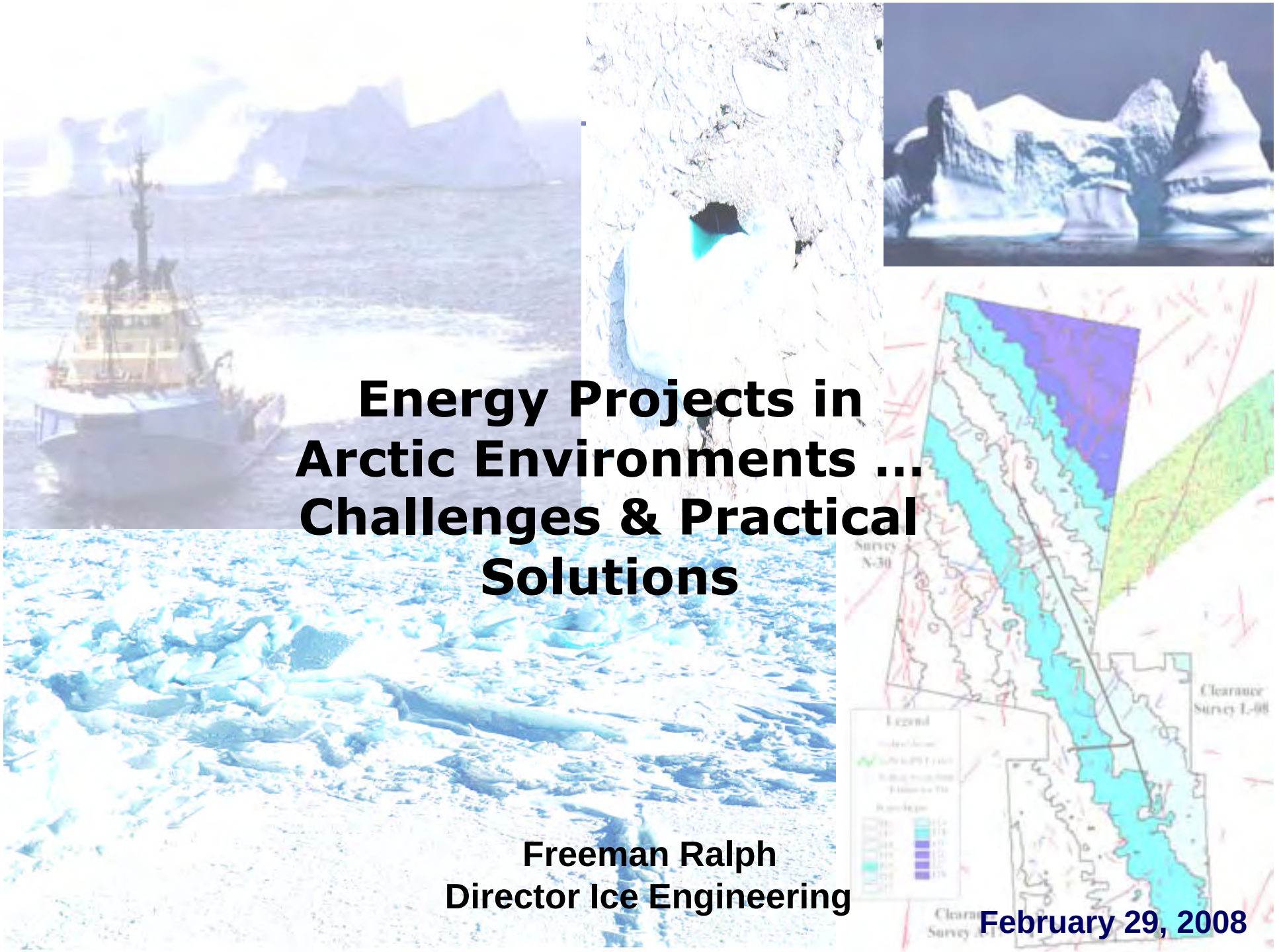

Energy Projects in Arctic Environments … Challenges & Practical Solutions

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Director Ice Engineering

February 29, 2008

Presentation Outline

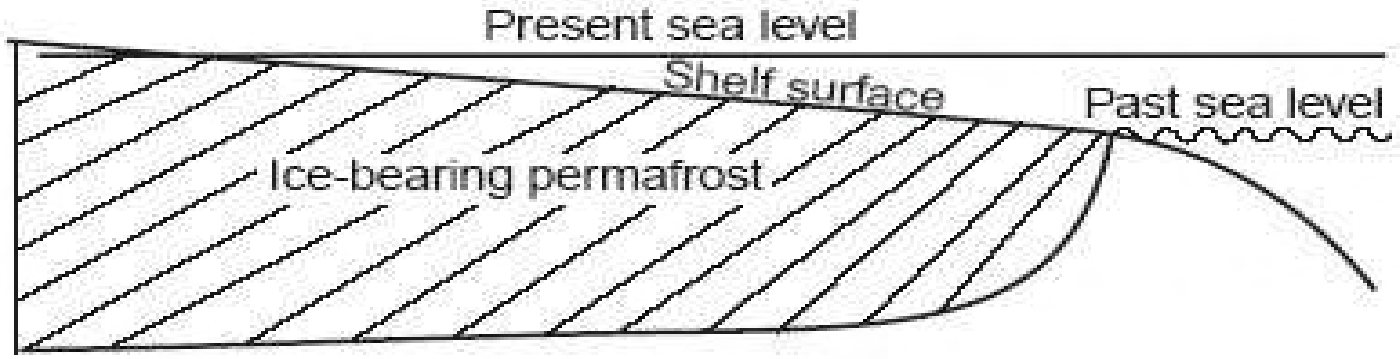
- Physical Environment in the Arctic
  - What aspects are important for design?
  - Characterization of environment
- Design considerations
  - Loads analysis methodology
  - Mitigation of environmental factors in design
  - Structural types for environmental aspects

Physical Environmental

- Geohazards
  - Permafrost
  - Gas hydrates
  - Shallow gas
  - Coastal erosion
- Ice Conditions
  - Surface occurrence, type
  - Seabed gouging
  - Water depth
- Seismic Activity
- Temperature
- Wave Conditions

Permafrost

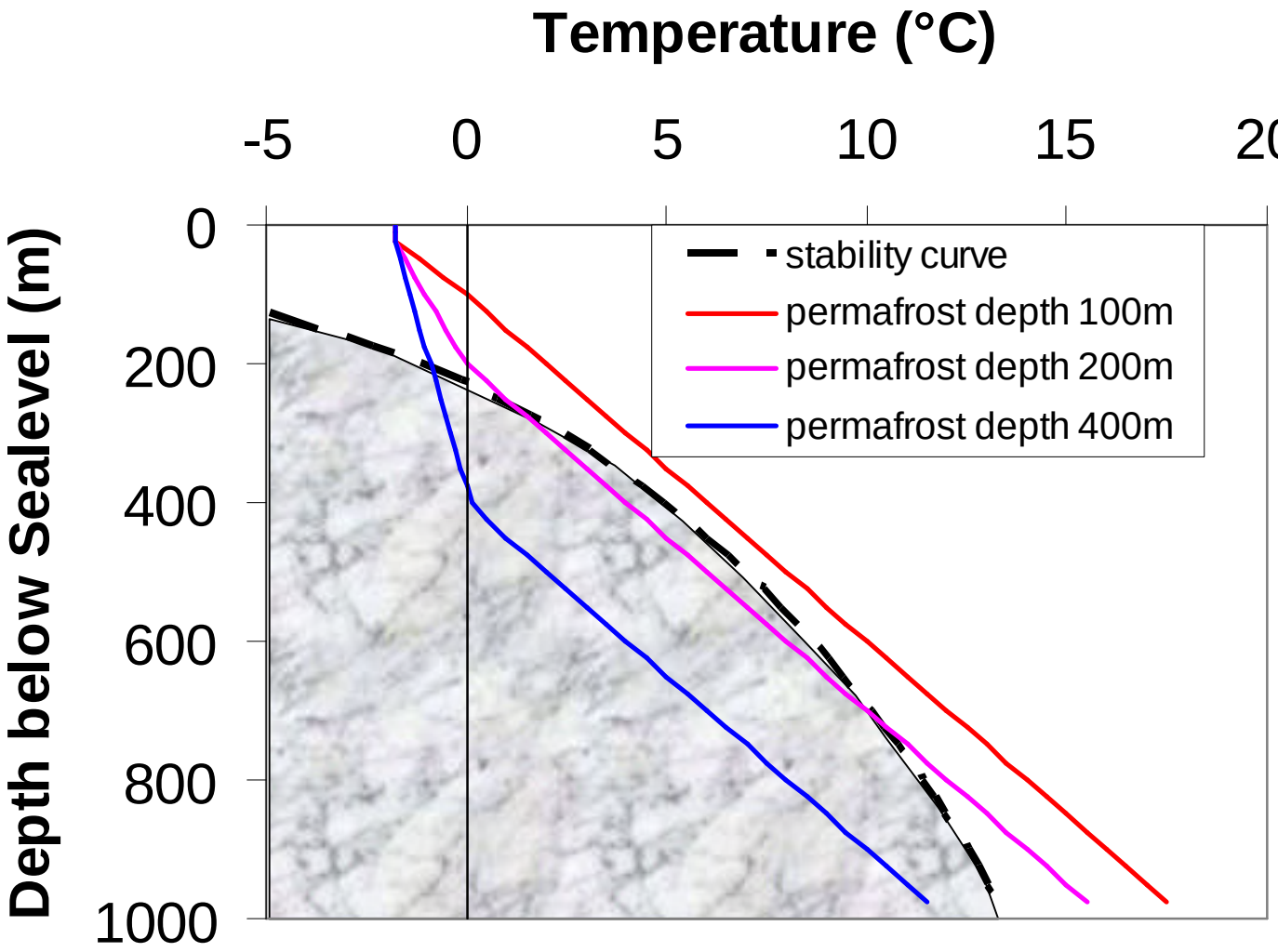
- Definition
  - Ground that remains below 0ºC for at least 2 years
  - Occurs subsea – last ice age
  - Low density, Ice content, up to 700m depth
- Design Implications
  - Settlement
    - wellcasing stability for drilling; or
    - foundation stability due to differential settlement
  - Difficulty in excavating



Gas Hydrates

- Definition
  - Gas escape structures on the seabed
  - methane gas encapsulated within an ice lattice
  - Exists within the pore space in a soil matrix, within both fine and course grained soils
  - Often found in association with permafrost
  - Potential source of energy,
  - Geohazard as a result of behaviour if destabilised

Gas Hydrates (cont.)



Assumptions:

25m water depth

2°C/100m thermal gradient

Non-saline permafrost

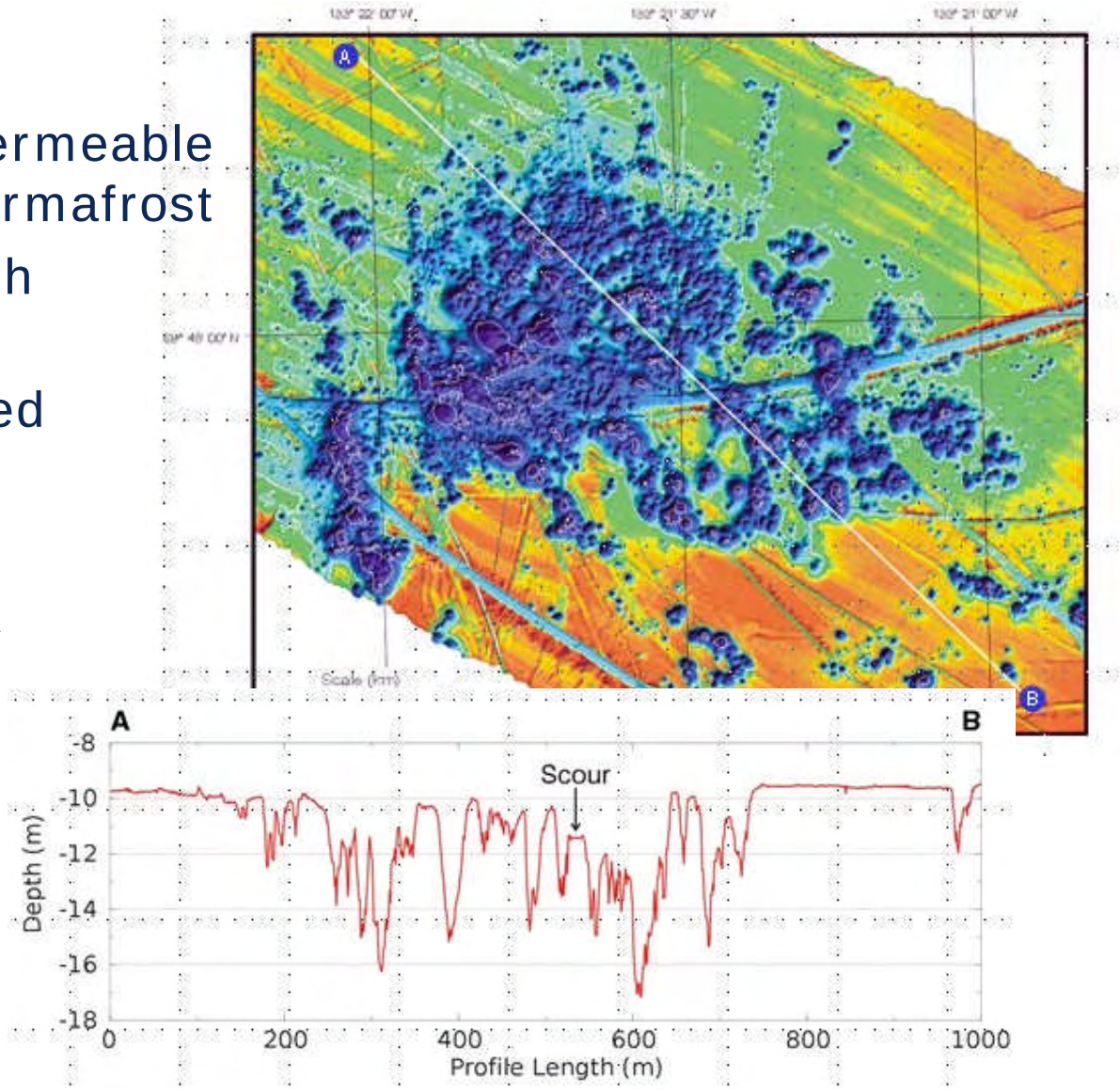
Methane hydrate

Gas Hydrates

- Design Implications
  - Increased temperature or reduced pressure can cause dissociation once the stability line is crossed resulting in release of free gas (may occur naturally as relic permafrost warms)
  - Volume increase up to 100% at 10MPa pressure (1000m depth)
  - Increased volume leads to loss soil strength
  - Can cause instability of seabed soils including slope instability

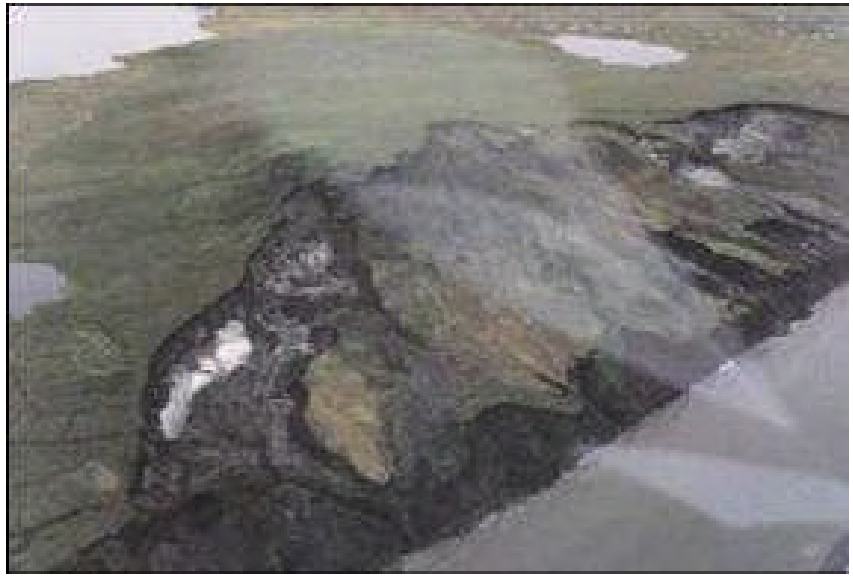
Shallow Gas

- Identification
  - Gas trapped in impermeable layers … clays or permafrost
  - Gas seepage through fissures or taliks
  - Pockmarks on seabed
- Design Implication
  - Well-casing stability during drilling
  - Foundation stability



Coastal Erosion

- Occurrence
  - Wave and ice erosion
- Design Implication
  - Protection of Pipeline approaching shore
  - Expose permafrost



Arctic Ice Conditions

- Offshore Ice Features
  - Level ice -- Hummock fields
  - Rafted ice -- Icebergs
  - Ice floes
  - Pressure ridge (linear feature)
  - Rubble pile (grounded), stamukha, Rubble field
  - Ice islands (single feature, glacial ice)

Multi Year Ridge

Ice Rubble

Iceberg in Pack Ice

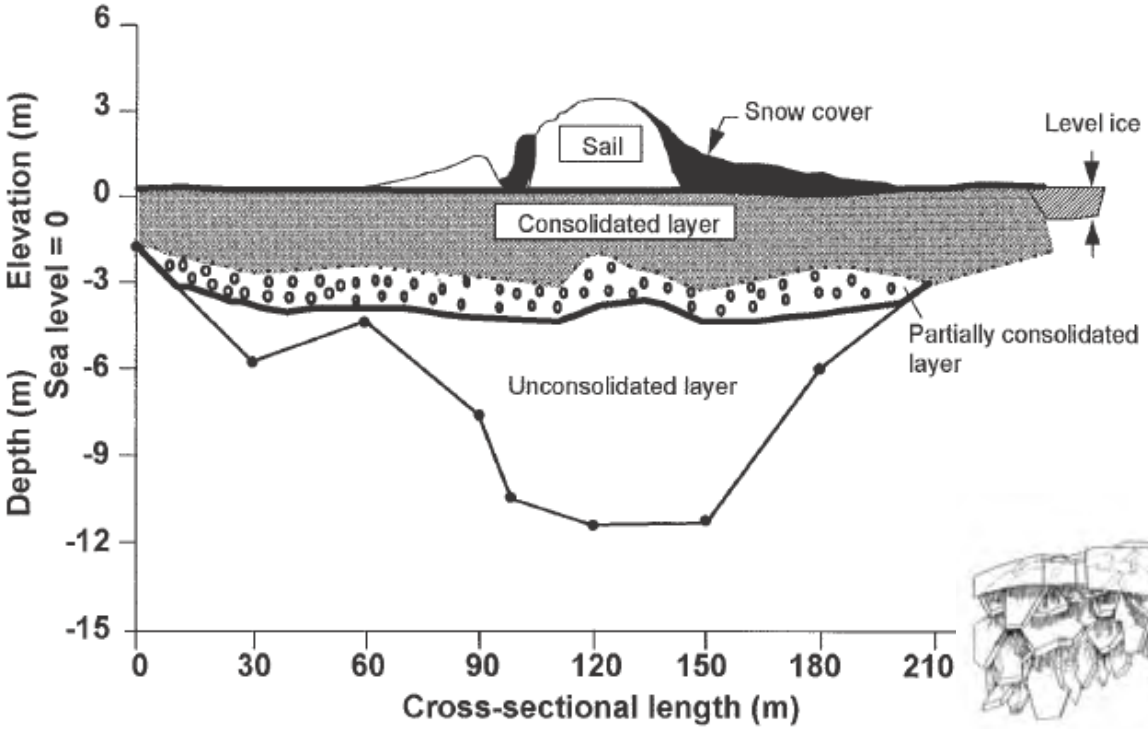
Characterization of Ice Regime

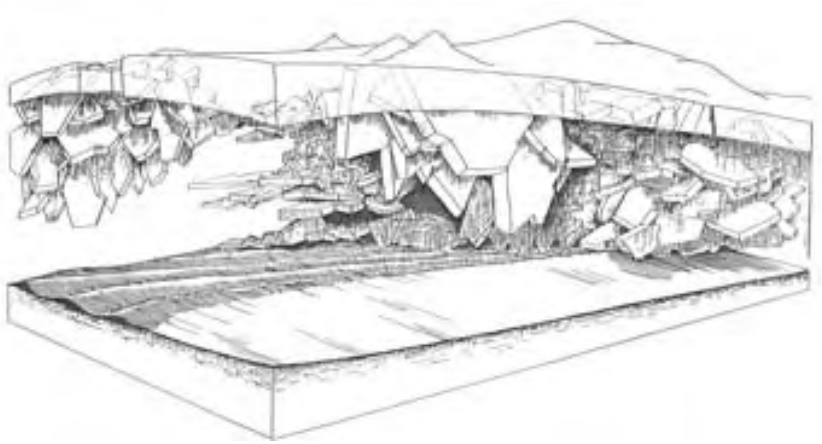
- Ice Rubble
- Hummock Field

Shoreline Ice Rubble Pile, Confederation Bridge, PEI
Source: C-CORE

Characterization of Ice Regime

- First Year Pressure Ridge

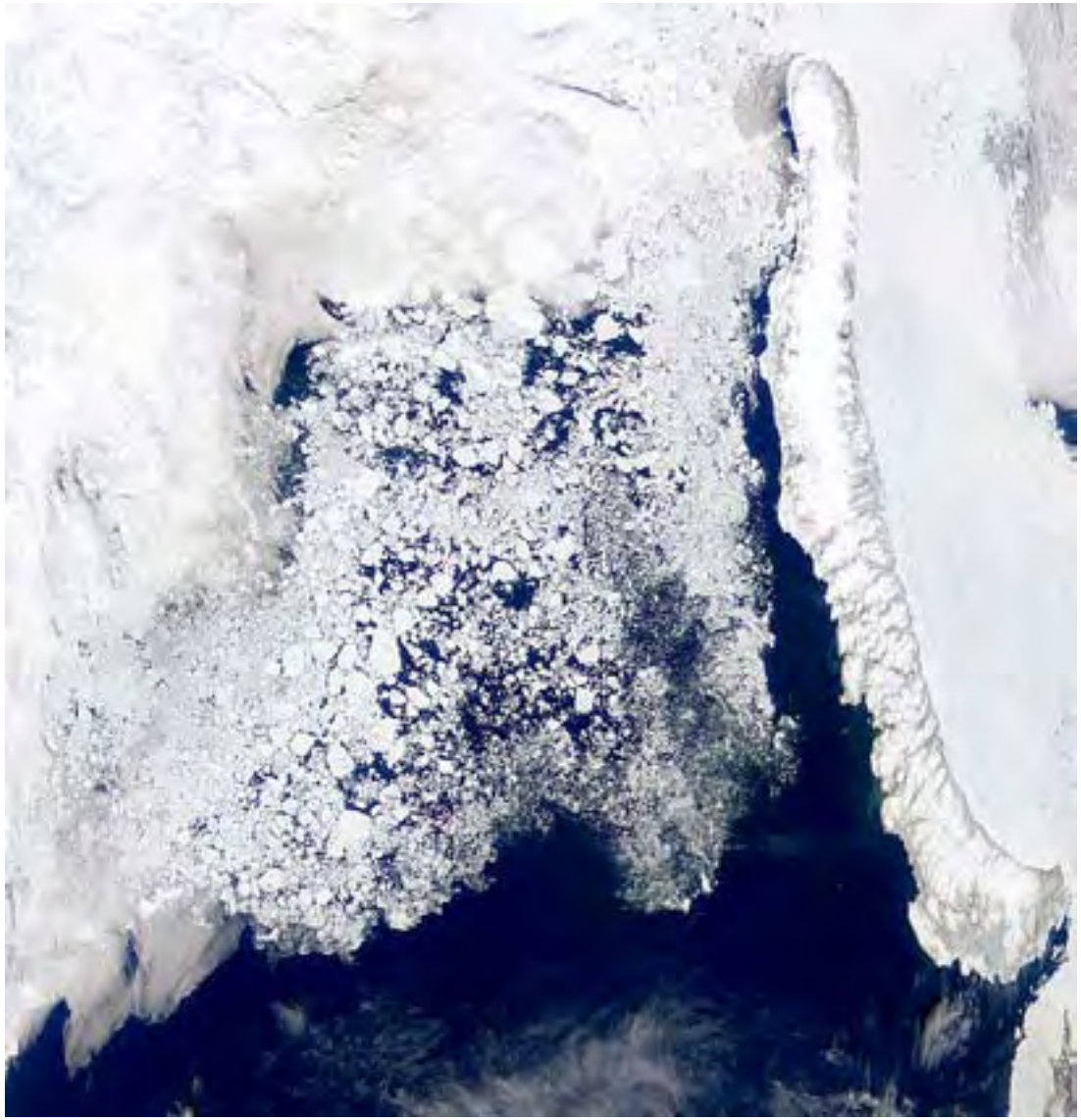




Source: Blanchet (1998), Can. J. Civ. Eng.

Characterization of Ice Regime

- Ice cover near Shtokman June 1998
- Note that ice cover near Shtokman GCF not an annual event



Source: Canadian Geographic

Characterization of Ice Regime

- Unique to each geographic location
  - Beaufort Sea
    - All ice types
  - Sakhalin Island
    - No multi-year
    - Severely ridged first year
    - Stamukha (grounded rubble)
    - Fast moving
  - Barents Sea
    - First year ice
    - Multi-year (depending on location)
    - Icebergs / ice island fragments

Characterization of Ice Regime

- Unique to each geographic location
  - Caspian Sea
    - No multi-year
    - Level ice ~ 0.5m
    - Severe rafting > 2m
    - Stamukha (grounded rubble)
    - Sudden rapid movements, directional changes
  - Grand Banks
    - Icebergs
    - Occasional Pack Ice (~1 in 5 years)

Design Methodology

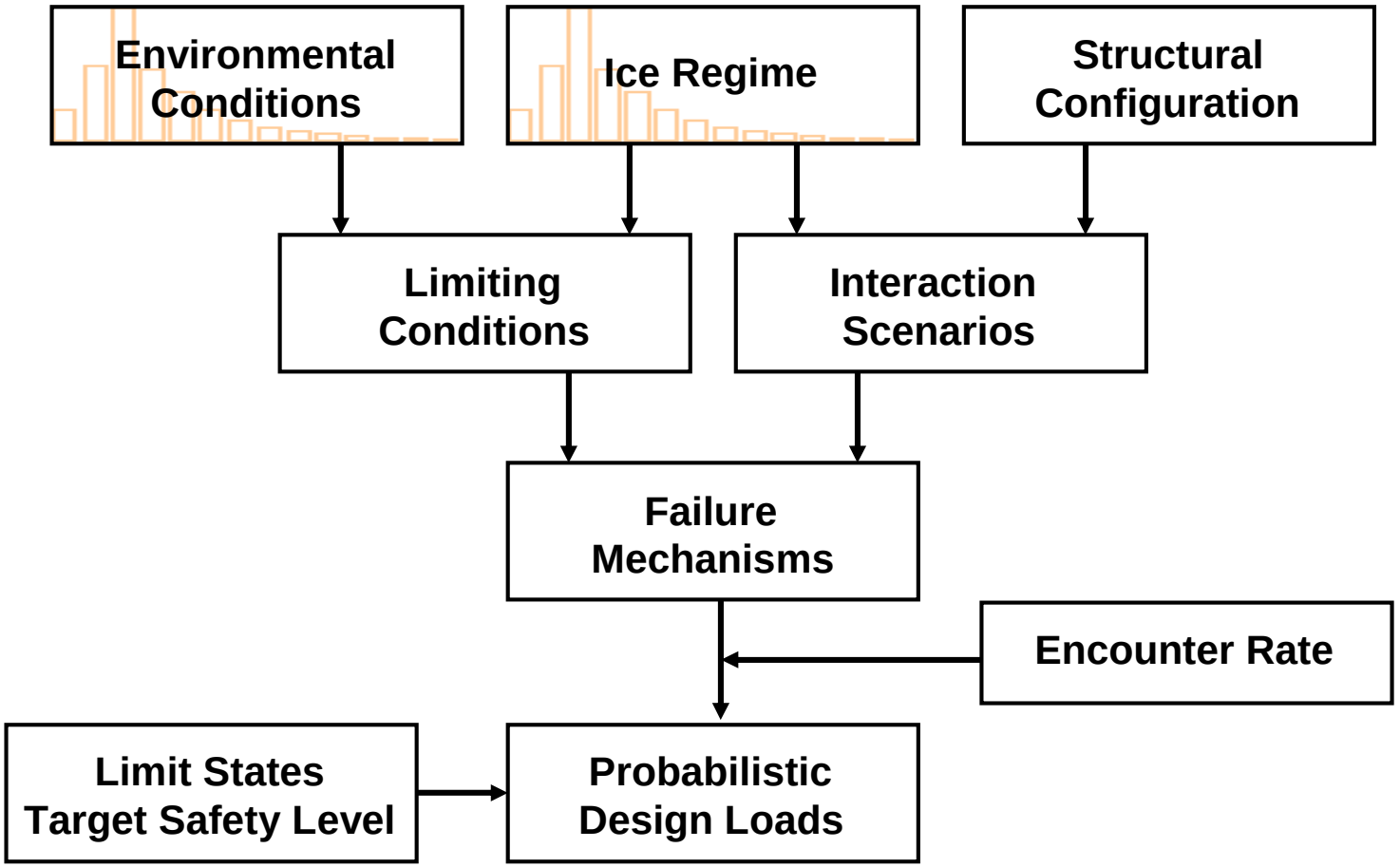
- Sea Ice Occurrence
  - Ice types, concentration, floe size, thickness, drift speed
- Ice - Structure Interaction
  - structure size & shape
  - Ice failure / clearing mechanisms,
  - Ice strength
- Risk Mitigation
  - Icebreaking
- Global Loads
  - **Limit stress** – ice failure (sheet, ridge)
  - **Limit energy** – kinetic energy in ice
  - **Limit force** – wind/wave driving force
- Local Loads
- Structure Design
  - Foundation lateral resistance
  - Foundation bearing resistance
  - Structural Integrity

Design Loads

- Design Load Methodology
  - Deterministic
    - 100 year parameter inputs into engineering models
    - Estimate of 100 year loads may not be accurate
    - Typically overly conservative
    - Good for preliminary design
  - Probabilistic
    - Same engineering models as deterministic method
    - Developed distributions for input parameters giving variability in design loads
    - Accurate 100, 1000, 10,000 year loads
    - Detailed design

Design Load

- Probabilistic Approach



Safety Considerations

- Target Safety Levels (CAN/CSA-S471-04)
  - Ice loading

Safety Classes	Consequences of Failure	Target Annual Reliability Level
Safety Class 1	Great risk to life or high potential for environmental pollution or damage	10^{-5}
Safety Class 2	Small risk to life and low potential for environmental pollution or damage	10^{-3}

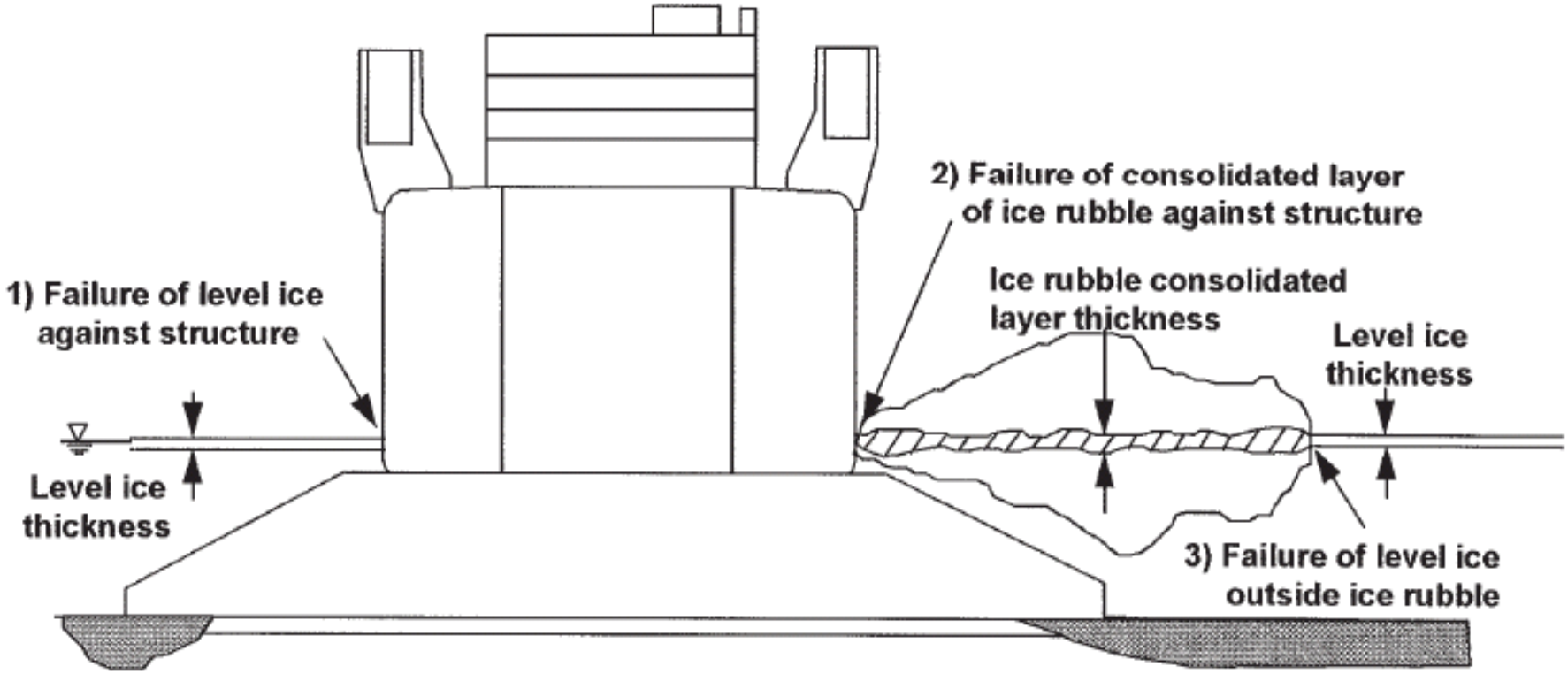
Design Loads

- Annual exceedence probabilities (CAN/CSA-S471-04)
  - Ice loading

Load Type	Safety Class 1		Structure Design Approach
	Annual Exceedence Probability p_E	Load Factor	
Specified loads, E_g based on frequent environmental events	10^{-2}	1.35	Elastic or very limited damage
Specified loads, E_r based on rare environmental events	10^{-4}	1.0	Ultimate Limit States (allow damage but require repairs)

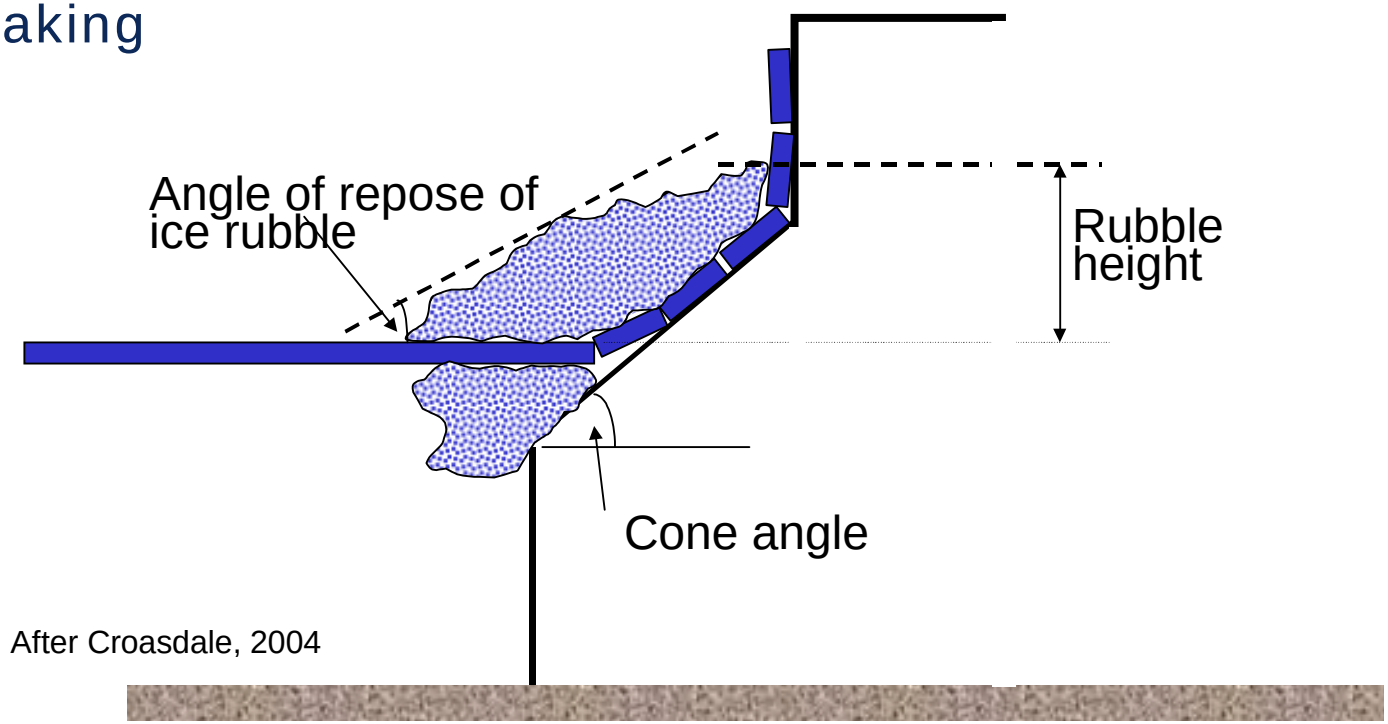
Ice Structure Interaction

- First year ice interactions



Ice Structure Interaction

- Sloping Structure
  - Upward breaking
  - level ice
  - ridge

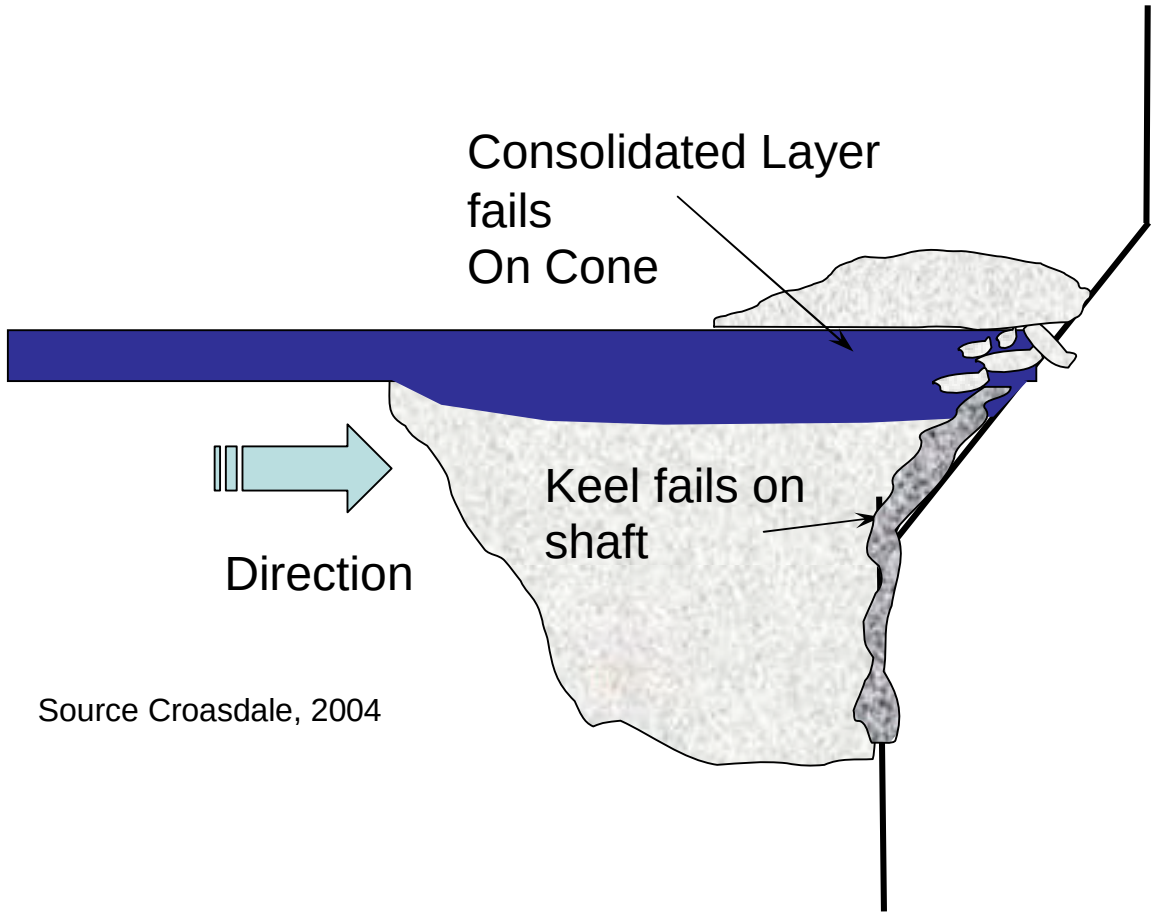


After Croasdale, 2004

- Forces
  - Flexure failure, failure of rubble, pushing through rubble, lift rubble and ride up the slope, rotate block

Ice Structure Interaction

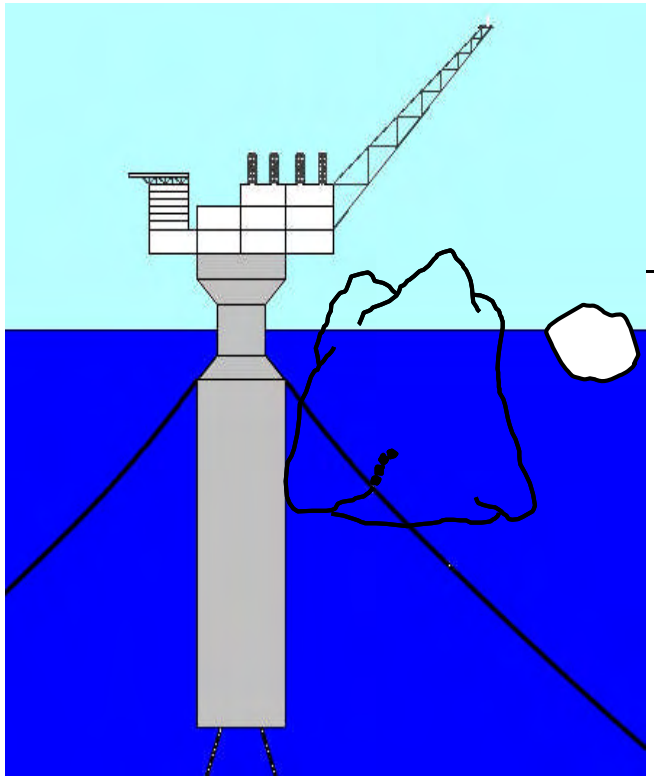
- Sloping structure
  - Ridge failure

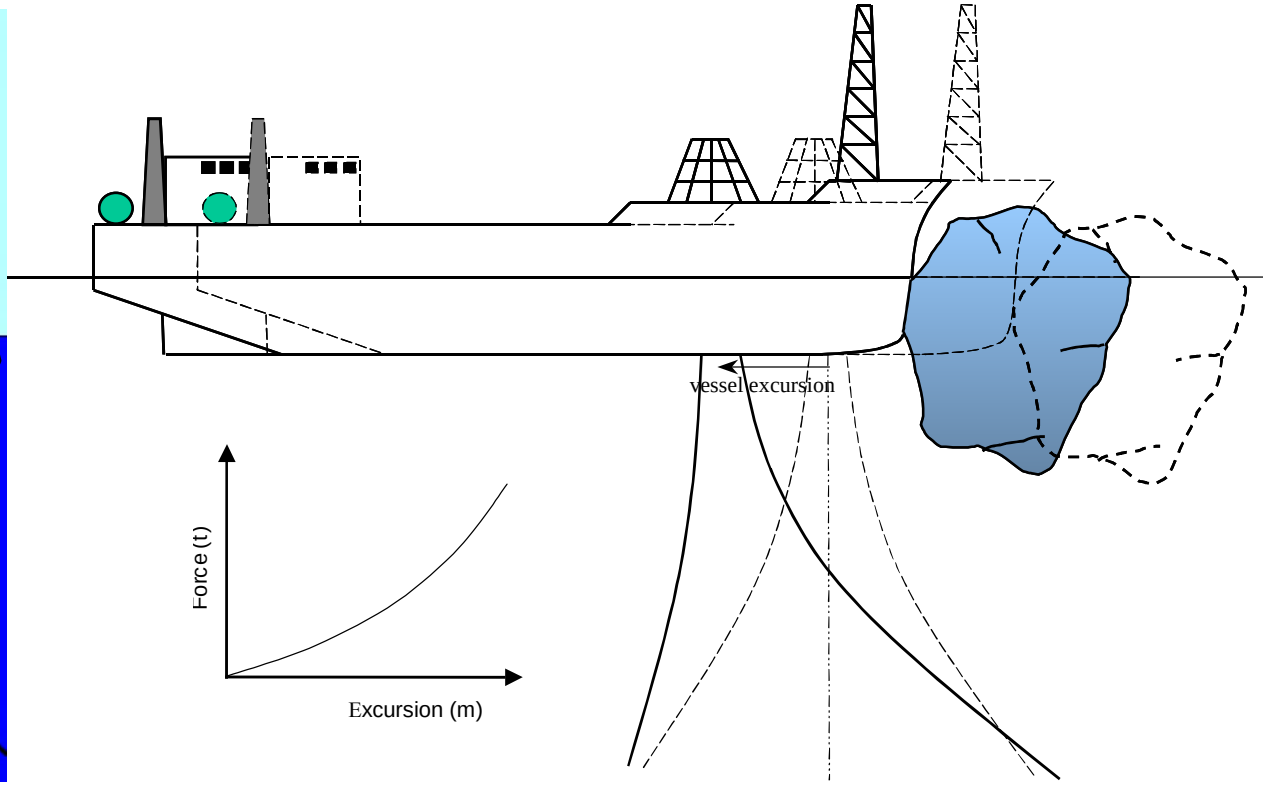


Source Croasdale, 2004

Ice Structure Interaction

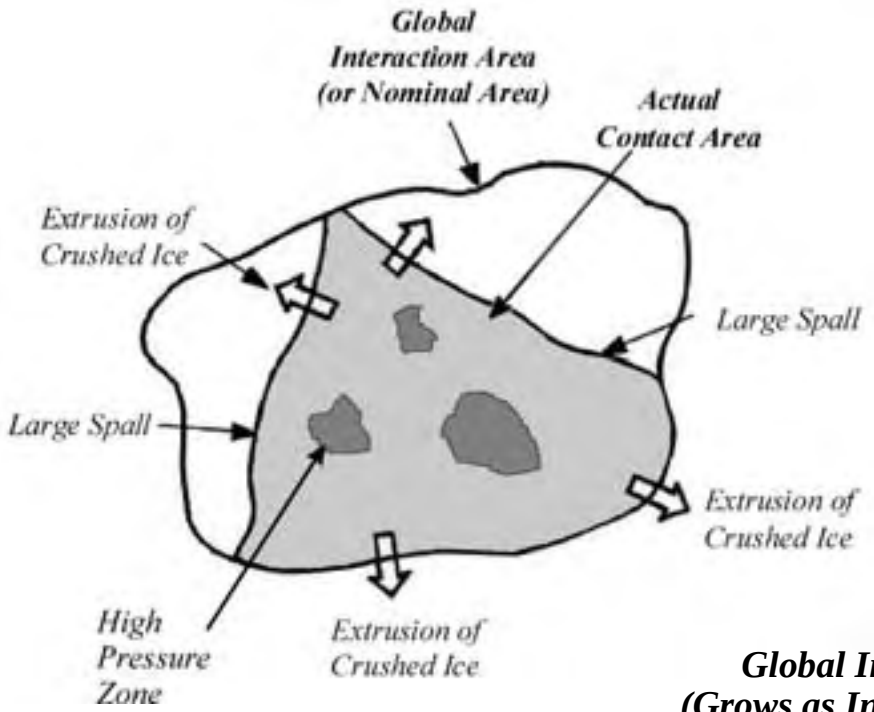
- Iceberg Impact Loads
  - Contact location
  - Localized crushing





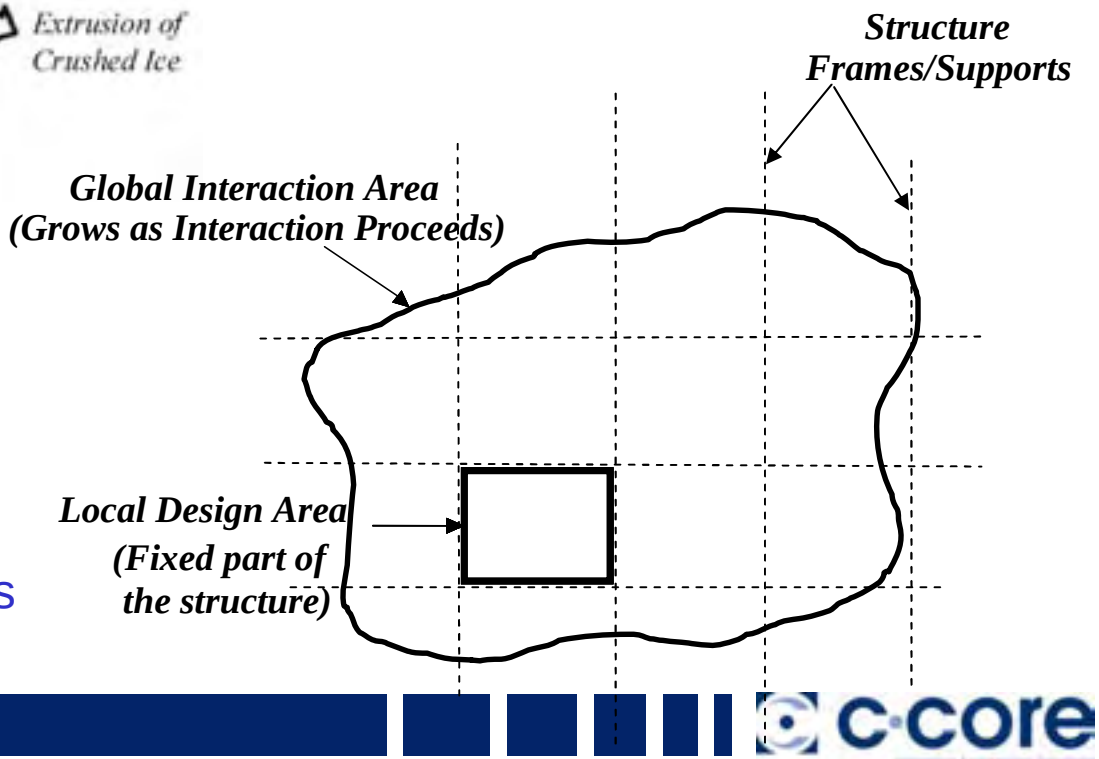
After Hydro RAO, 2007

Ice Structure Interaction



GLOBAL LOADS

- Foundation design
- Overturning moment
- Web frames



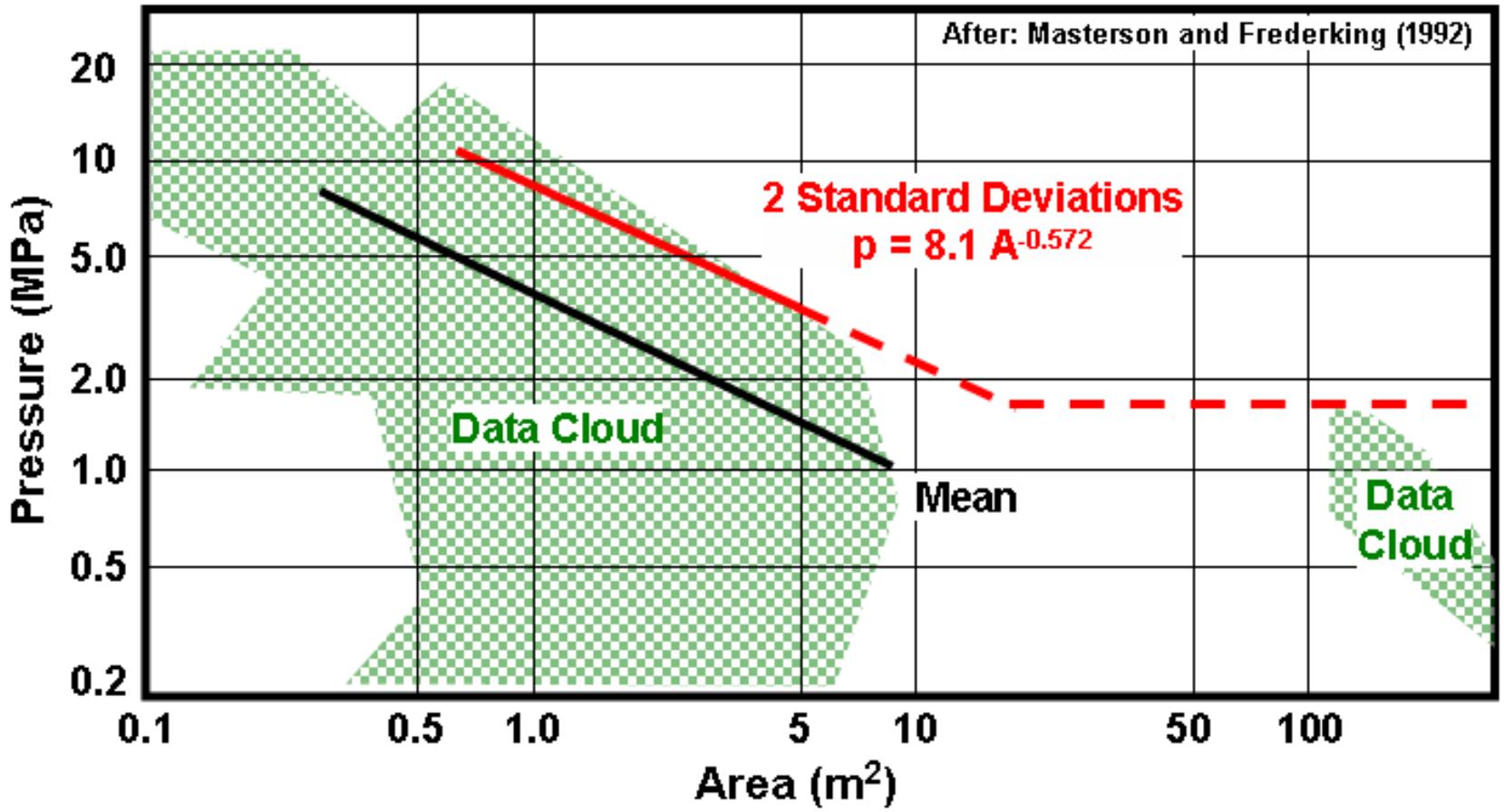
LOCAL LOADS

-Hull structure

-Shell, & stiffeners

Ice Strength

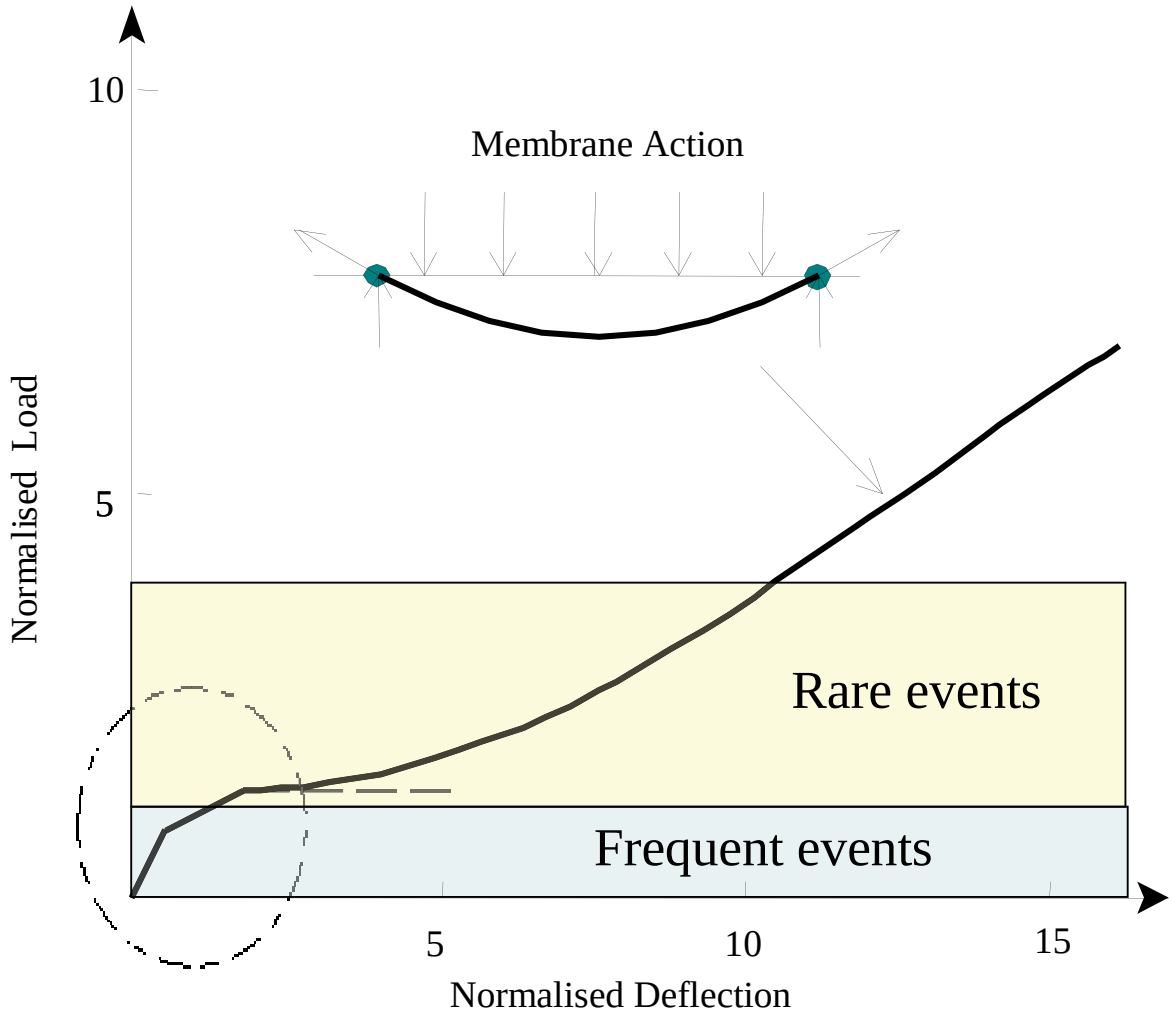
- Pressure Area Data – scale effects

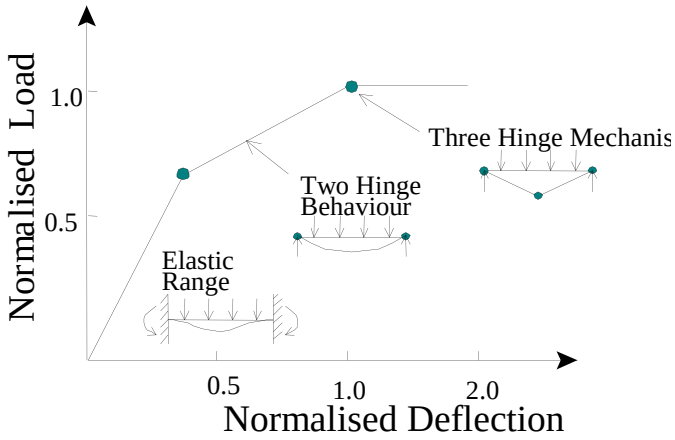


Source: Masterson and Frederking (1992)

Structural Design

- Structural Design Philosophy





Risk Mitigation

Ice detection
Icebreaking
Iceberg towing
Disconnection

Risk Mitigation - Ice Management

- Icebreaker support
  - Extend operational season of floating drill rig (i.e. Kulluk)
  - Relieve pressures in confining pack conditions
  - Push extreme features away from rigs