PS Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts*

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Abstract

Current facies models, produced from decades of research on temperate and tropical systems, are heavily biased towards low latitude analogs. These have been successfully applied in both mature and frontier basin exploration settings. However, with increasing exploration interest in high latitudes, especially the Arctic, it is timely to examine in more detail process variability at different latitudes, and determine how facies models should be modified (or not) to include that variability. Inherent to facies models are a series of processes built on our overall understanding of sedimentary systems. By ignoring that certain processes gain or diminish in importance with changing latitude, these models, and our application of them introduce a hidden bias towards low latitude systems. As a result, using these familiar concepts and models in high latitude systems can introduce errors that are often not accounted for.

Numerous processes have been shown to be amplified and/or diminished at higher latitudes, producing variances in stratigraphic architecture from more familiar depositional “norms”. For example, Coriolis effects are stronger at high latitudes, whereas tidal forces are weaker. Extremes of seasonality at higher latitudes result in temperature and insolation effects on fauna and flora, as well as short runoff seasons and strong fluvial discharge seasonality. Some important high latitudes processes such as ice melt algal blooms have no temperate or tropical equivalent and are thus unaccounted for in established models. These differences can and do impact numerous play elements including reservoir, source, and seal quality and distribution. The main goal of this

presentation is to outline the depositional variability between high and lower latitude systems, demonstrate how such variability affects hydrocarbon play elements, and provide the needed basis for refining the established stratigraphic and sedimentary concepts, methods, and tools for use in high latitude basins.

AAPG Annual Convention & Exhibition 2014

Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts

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ABSTRACT

Current facies models, produced from decades of research on temperate & tropical systems are heavily biased towards low latitude analogs. These have been successfully applied in both mature and frontier basin exploration settings. However, with increasing exploration interest in high latitudes, especially the Arctic, it is timely to examine in more detail process variability at different latitudes, and determine how facies models should be modified (or not) to include that variability. Inherent to facies models are a series of processes built on our overall understanding of sedimentary systems. By ignoring that certain processes gain or diminish in importance with changing latitude, these models, and our application of them introduce a hidden bias towards low latitude systems. As a result, using these familiar concepts and models in high latitude systems can introduce errors that are often not accounted for. Numerous processes have been shown to be amplified and/or diminished at higher latitudes, producing variances in stratigraphic architecture from more familiar depositional "norms". For example, Coriolis effects are stronger at high latitudes, whereas tidal forces are weaker. Extremes of seasonality at higher latitudes result in temperature and insolation effects on fauna and flora, as well as short runoff seasons and strong fluvial discharge seasonality. Some important high latitudes processes such as ice melt algal blooms have no temperate or tropical equivalent and are thus unaccounted for in established models. These differences can and do impact numerous play elements including reservoir, source, and seal quality & distribution. The main goal of this presentation is to outline the depositional variability between high and lower latitude systems, demonstrate how such variability affects hydrocarbon play elements, and provide the needed basis for refining the established stratigraphic and sedimentary concepts, methods, and tools for use in high latitude basins.

PROBLEM STATEMENT

- Better understanding of depositional systems and analogs leads to better inputs for geological models and more accurate assessment of risk for plays and prospects in hydrocarbon exploration
- Most familiar facies models derive from temperate and, to a lesser extent, tropical examples. By comparison, depositional analogs from higher latitudes are sparser in number and more poorly understood.
- Numerous processes are amplified and/or diminished at higher latitudes, producing variations in stratigraphic architecture from more familiar depositional "norms"

OBJECTIVES

- Examine some latitudinal variations in sedimentary processes and environments
- Highlight departures from depositional "norms"
- Search for insights that may be useful in subsurface interpretations; or at least some "health warnings"
- Introduce Hedberg Conference "Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts"

Regardless of the global climatic state (i.e. icehouse vs greenhouse), some processes are enhanced or diminished at higher latitudes, and some are only present at certain latitudes (high or low). An non-exhaustive list would include:

- Extremes of seasonality
- Temperature and insolation effects on flora and fauna
- Types, occurrences, and effects of storms
- Wind types and patterns
- Enhanced Coriolis effect and impact on geostrophic currents
- Reduced tidal effects
- Direct and indirect effects of seasonal ice

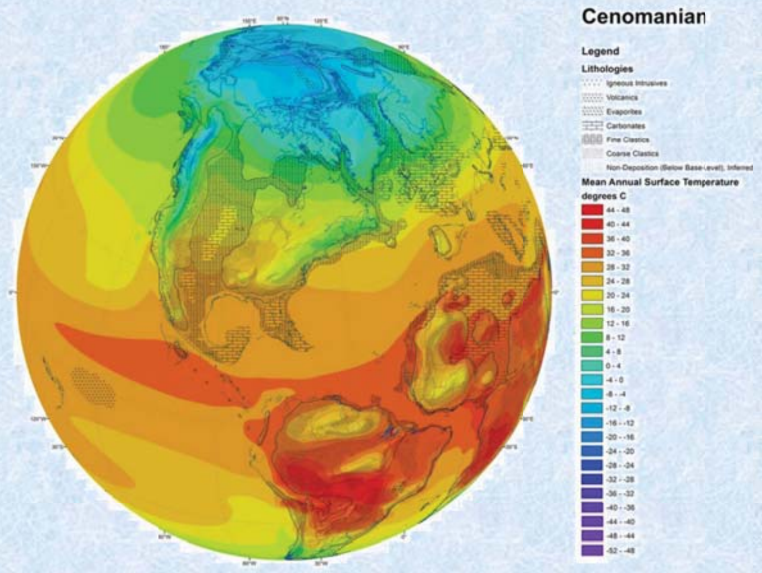
Some processes are only present/significant at high latitudes during <u>icehouse or icehouse to greenhouse transitional</u> climate states: A non-exhaustive list would include:

- "Direct" glacial deposits, e.g.,
    - Glacial loading and rebound
    - Tunnel valleys
    - Glacial outbursts
- Thermokarst (pingos, tabular ground ice, etc.)
- Permafrost
- Ice jam flooding
- Extensive sea ice
    - Deltaic overflow and underflow
    - Ice-break-up

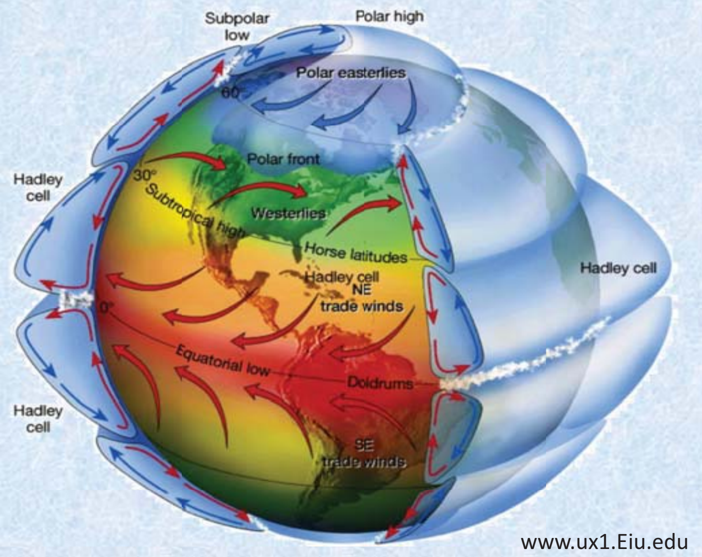
Processes Strongly Affected by Latitude I – Climate Influenced

Temperature, Precipitation, and Wind

Cenomanian Surface Temperatures



Modern Atmospheric Circulation



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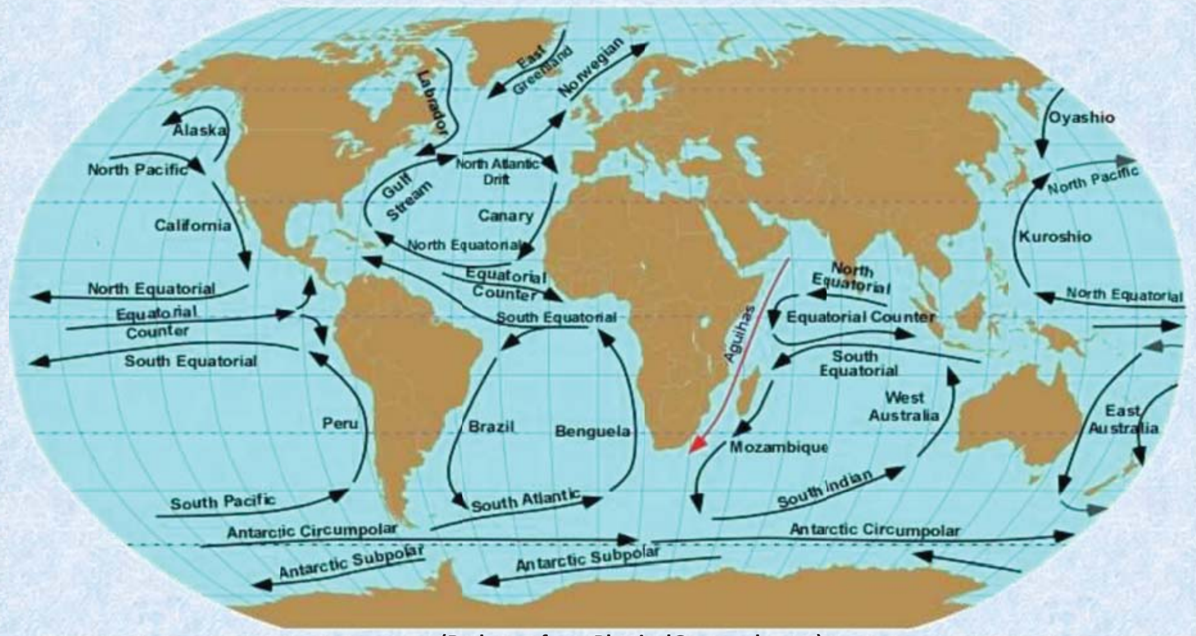
A pole to equator temperature gradient has always existed, caused by the differences in solar energy received. This Cenomanian (Late Cretaceous) Mean Annual Temperature (MAT) map (Source: Getech's Globe Earth System Modelling Programme, Cretaceous Atlas) shows how even in a hot-house world, with raised polar temperatures, a strong temperature gradient still existed. This disparity drives atmospheric circulation, which in turn controls precipitation & winds. Temperature and precipitation control weathering, runoff (degree & seasonality), erosion, vegetation cover, and ice accumulation. Winds influence waves, vegetation cover, oceanic surface currents, and storms.

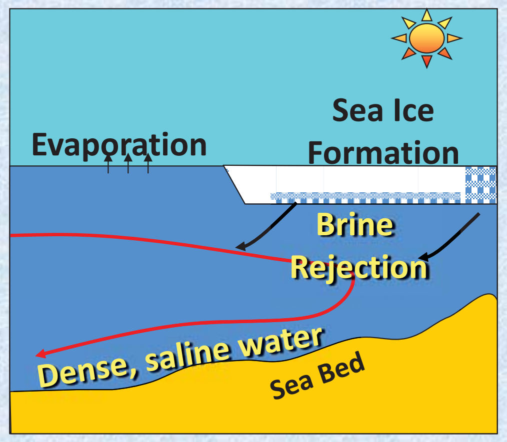
Semi-Permanent Oceanic Currents



(Redrawn from PhysicalGeography.net)

Atmospheric circulation drives the movement of ocean currents. Many of these currents affect the continental shelves of the world. Some, such as the Agulhas Current on the southeast Africa margin, shown in red, regularly impinge onto the continental shelf. Latitudinal controls are evident in the distribution and nature of the currents. In each major basin, the ocean currents form several closed circulation patterns known as gyres. A large gyre develops at the subtropics centered at about 30 degrees of latitude in the Southern and Northern Hemisphere. In the Northern Hemisphere, several smaller gyres develop with a center of rotation at 50 degrees. Similar patterns do not develop in the middle latitudes of the Southern Hemisphere, where ocean currents are not bound by continental masses.

Density Currents



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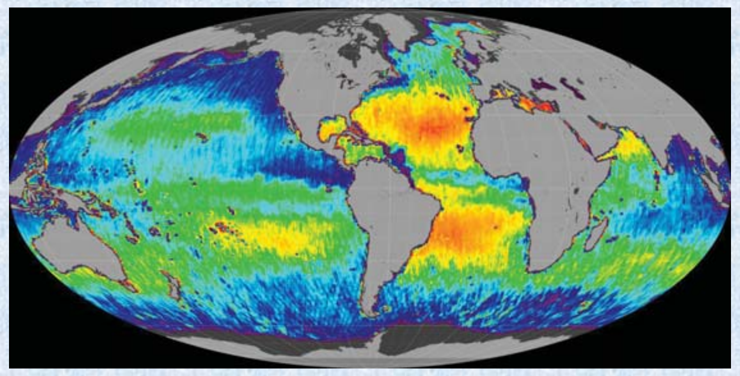
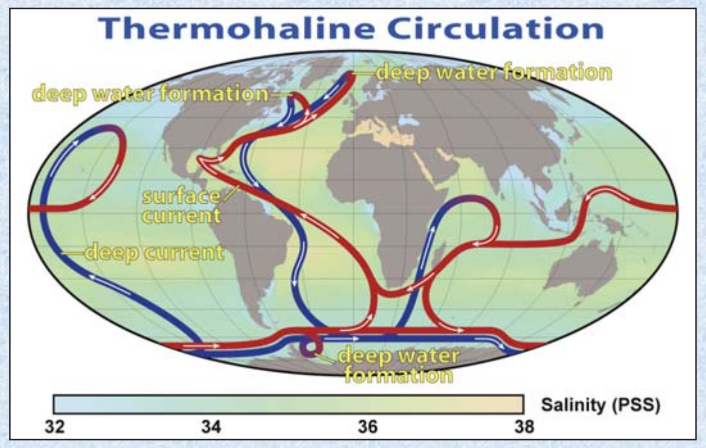
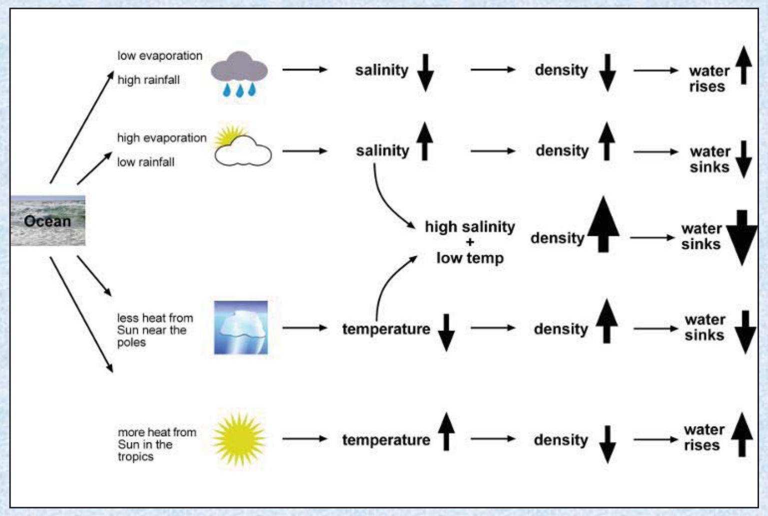


Sea surface Salinity from satellite observations . High salinity – red; low salinity - blue(NASA Aquarius)



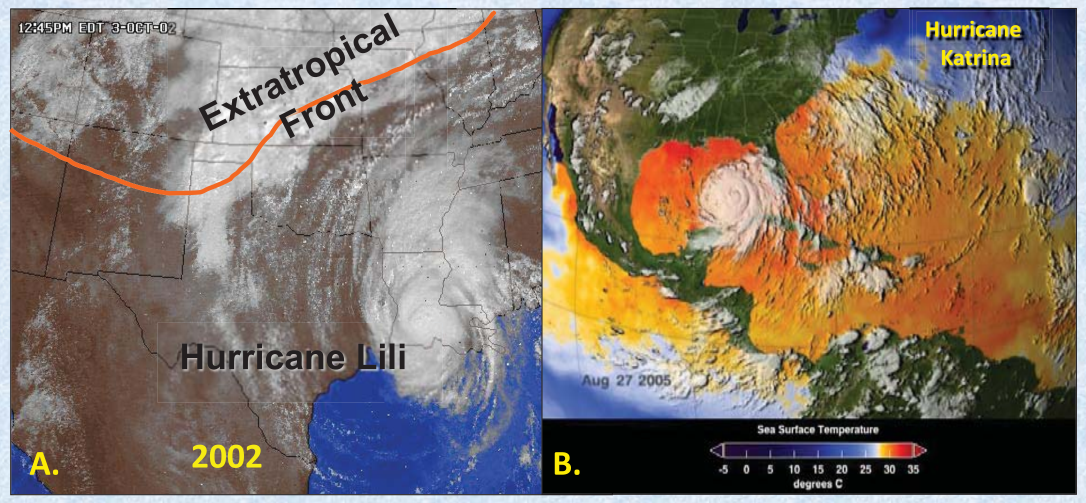
The large-scale movement of water through the oceans, called the thermohaline circulation. Blue represent deep-water currents, and red represent surface currents. (Robert Simmon, NASA Earth Obs.)

Ocean salinity is controlled by a balance between water removed (by evaporation or ice formation) and water added (by rivers, ice melt and precipitation). Salinity and density of water can be increased by brine rejection in the high latitudes. Salinity can be increased in the low latitudes by evaporation but the higher temperatures keep the density higher than high salinity water masses near the poles. These processes help drive the "Global Conveyor Belt" of Thermohaline circulation and result in water masses at different depths in the oceans. These various ocean currents are responsible for heat transfer across the globe as well as transfer & deposition of biological and sedimentological particles.

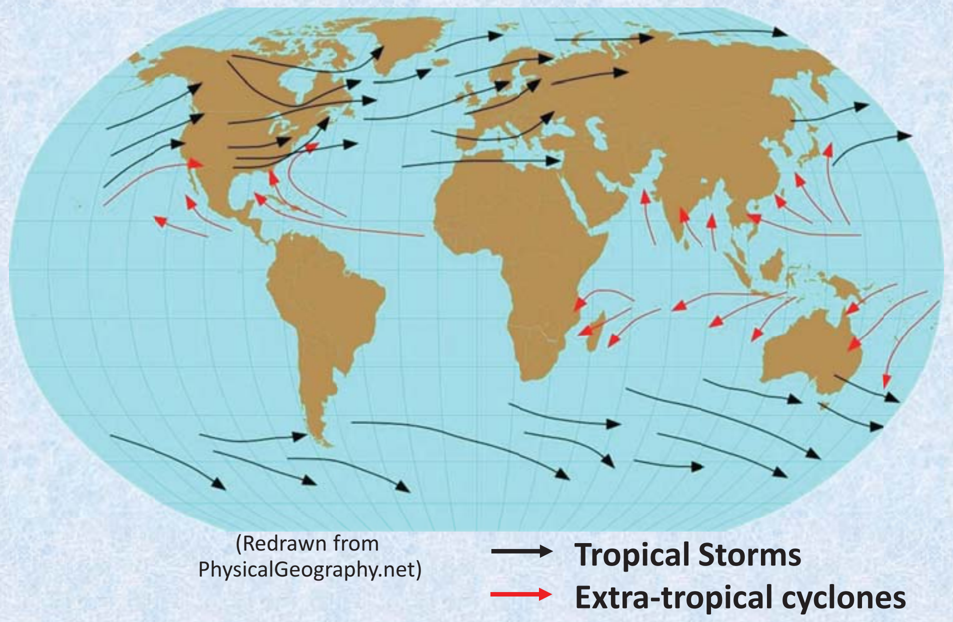


Effects of evaporation & temperature on ocean salinity & density.(From http://wwWaikatow.sciencelearn.org.nz & The Univ of Waikato

Storm Tracks



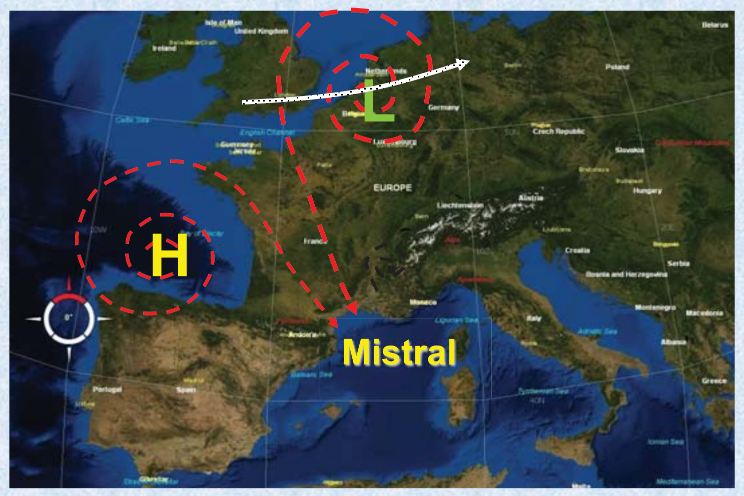
(Image: Accuweather.com) (Image: NOAA)



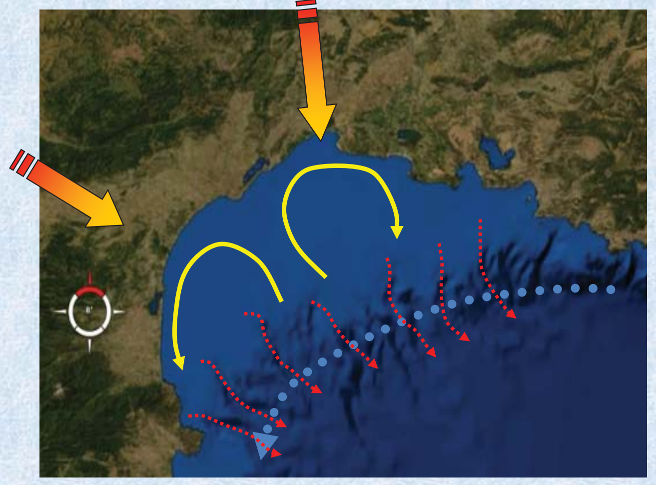
(Redrawn from PhysicalGeography.net)

Temperature and atmospheric circulation drive storm tracks, with obvious differences and latitudinal variations. Major storm systems fall into two main categories – tropical storms (hurricanes, typhoons, etc.) and extra-tropical storms. Examples are illustrated above (redrawn after Suter, 2006). The satellite images above depict two tropical storms (Hurricanes Lili (2002) and Katrina (2005) in the Northern Hemisphere, as wells as an extra-tropical cold front which occurred at the same time as Hurricane Lili. "Tropical" storms are obviously more prevalent in lower to mid-latitude areas.

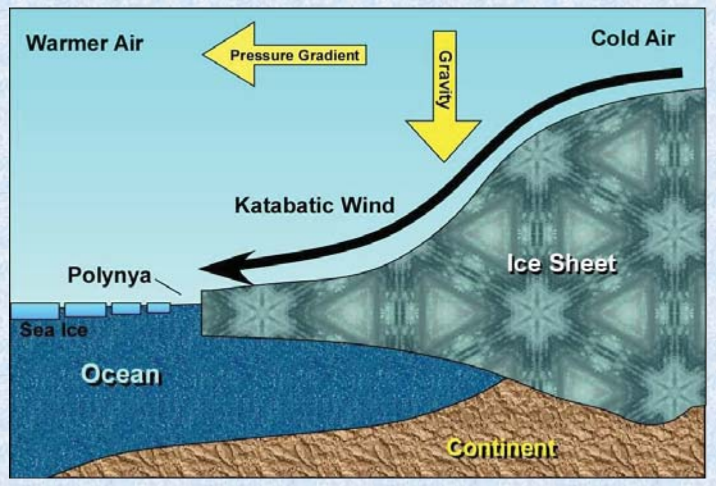
Katabatic Winds



The katabatic MISTRAL winds of the western Mediterranean are reach velocities of more than 90 km/hour, sometimes lasting over a week.



Winds generate downwelling current and ultimately density cascade, transporting sediments and organic matter offshore and into deeper water.



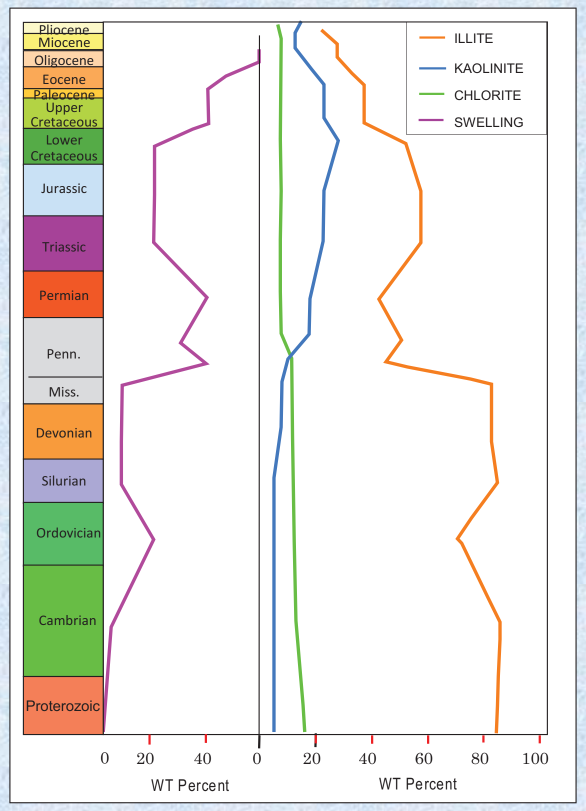
Katabatic winds develop from radiational cooling of air over an elevated regional, such as a glacier. Some katabatic winds can reach hurricane speeds, while many are of much lesser intensity. Katabatic winds are especially common at polar latitudes over major ice sheets.

Redrawn after Suter, 2008; Images: NASA Worldwind.
Currents redrawn from Palanques et al, 2006

Weathering

The nature of weathering changes with latitude , with chemical weathering generally favored by higher temperatures and greater precipitation, more typical of low-latitude regions. High latitude (and high altitude) environments tend toward mechanical weathering. In the sedimentologic record, grain size, composition, sediment flux and the existence of patterned ground all reflect this relationship.

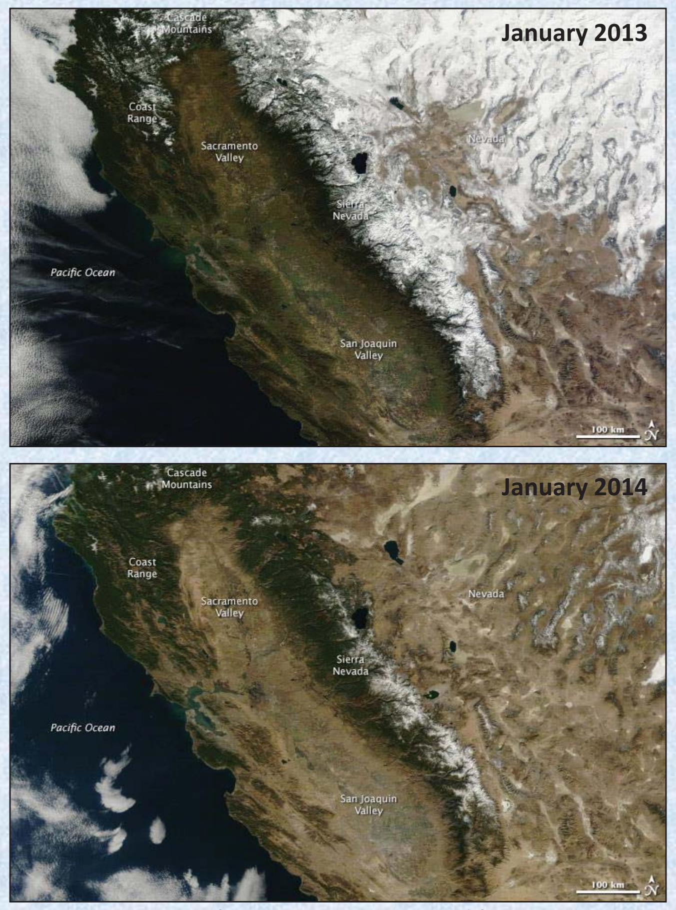
Patterned ground in the Northwest Territories, Canada. Typically found where soil undergoes intense freezing and thawing cycles. The constant change in the volume of water tends to move the coarser particles in the soil to the surface. Further frost heaving arranges the stones and rocks according to their sizes to produce patterned ground. Currently found across 20–25% of the Earth's land surface. (Image from C. Fraticelli)



Global clay mineral dominance through time. The decrease in illite minerals post-Devonian is related to the evolution of plants, which enhance chemical weathering.(Modified from Weaver 1989)

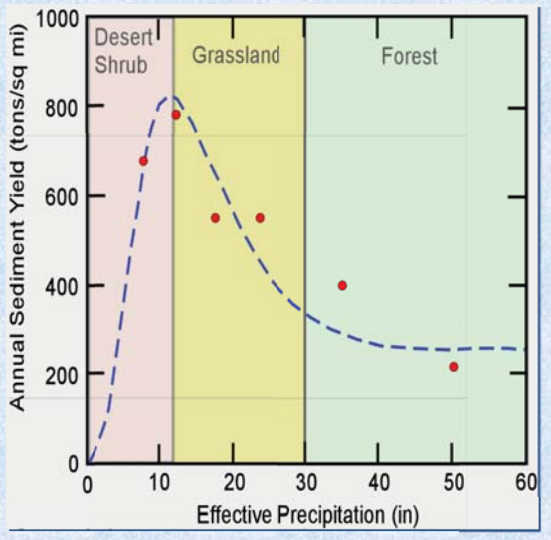
Processes Strongly Affected by Latitude II

Vegetation

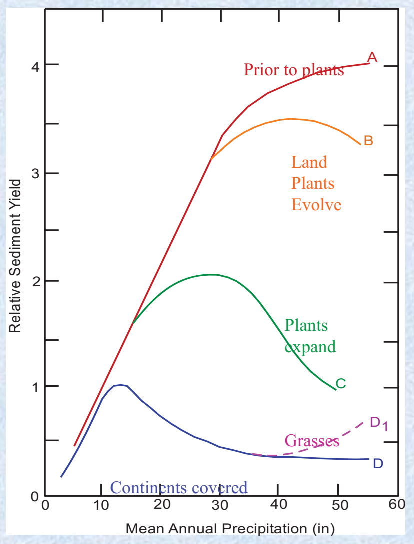


Dramatic reduction of vegetation cover over California and surrounding areas is visible in satellite images. Comparison of normal conditions (Jan 2013) and drought conditions (Jan 2014). NASA images courtesy LANCE/EOSDIS MODIS Rapid Response Team at NASA GSFC

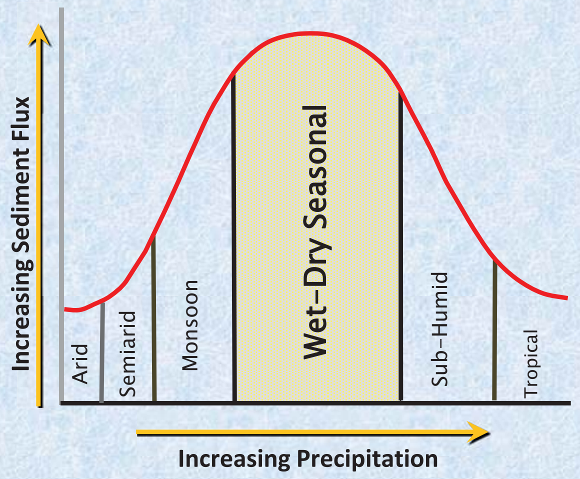
Runoff and associated sediment yield are also tied to vegetation cover, which is, in turn, a result of temperature, precipitation, and the seasonality of those processes. The role of vegetation in sediment yield was well documented by Schumm and others who described increasing sediment yield with precipitation up until the point that vegetation cover was significant enough to stabilize the soil, after which sediment yield decreases with increasing precipitation. A similar effect was hypothesized to occur across the geologic record due to the evolution of plants.

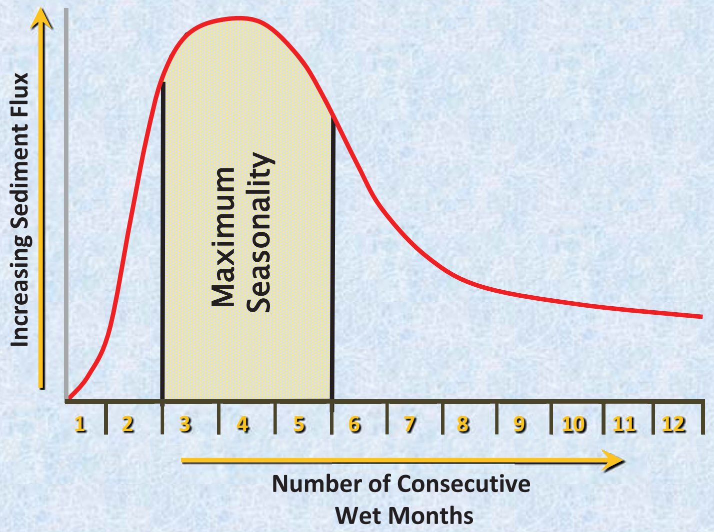


Redrawn after Langbein and Schumm (1958)



Redrawn after Schumm (1968)





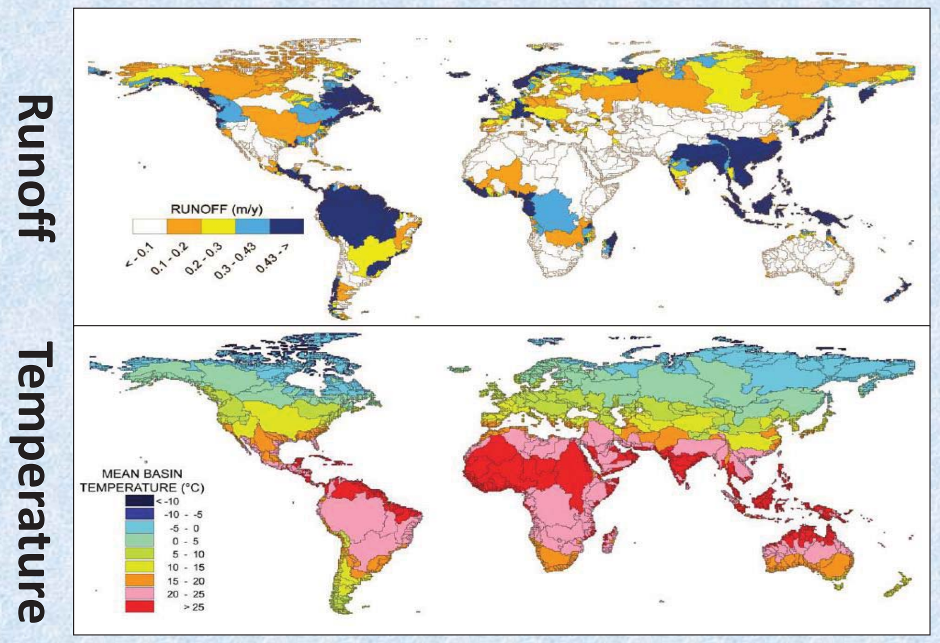
Number of Wet Months	Precipitation Regime	Seasonality
0	Arid	Aseasonal
1-2	Semi-arid	Minimal
3-5	**Dry subhumid**	**Maximum**
6-8	Moist subhumid	Medial
9-11	Humid	Minimal
12	Everwet	Aseasonal

Modified from Cecil, 1990 & 2003

Because of these vegetation relationships, annual sediment yield relates to the seasonality of precipitation – *not* annual average. In humid/tropical precipitation regimes vegetation & soil development restricts the amount of sediment available for erosion & transport. In arid regimes, there is typically not sufficient precipitation for transport of sediment. Environments in which there is significant precipitation, yet minimal vegetation are ideal for coarse sediment transport.

Maximum seasonality = maximum supply of siliciclastic sediment

Global Basin-Averaged Runoff and Temperature



(redrawn from Syvitski and Milliman, 2007)

$Q_s = \alpha B A^{3/4} R T$

Where

Qs = fluvial sediment flux

B = lithology, glacial extent, human factors, trapping

A = Drainage Area

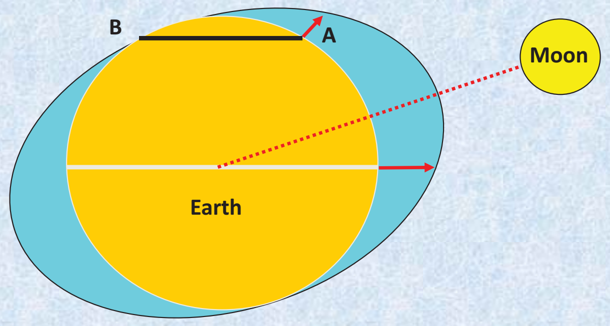
R = Basin-averaged relief

T = Basin-averaged temperature

Runoff and associated sediment yield, tied to the global temperature gradient, as illustrated by the BQART runoff model above (Syvitski and Milliman, 2007). As temperature increases, fluvial sediment flux increases. This model does not however explicitly include vegetation.

ORBITAL FORCING

Tidal Forces



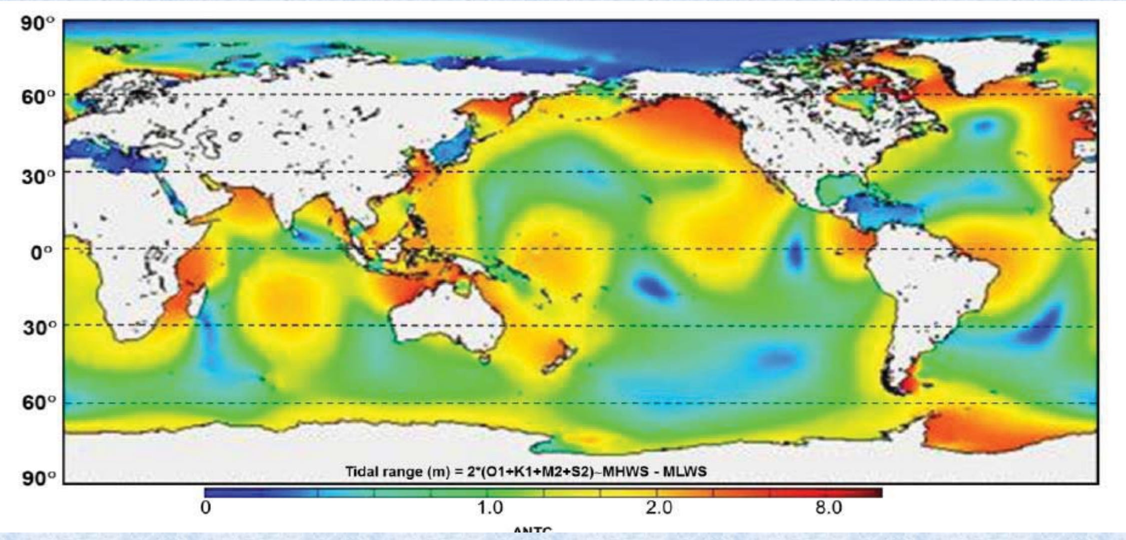
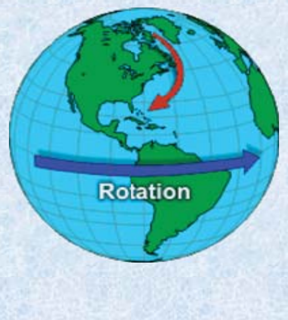
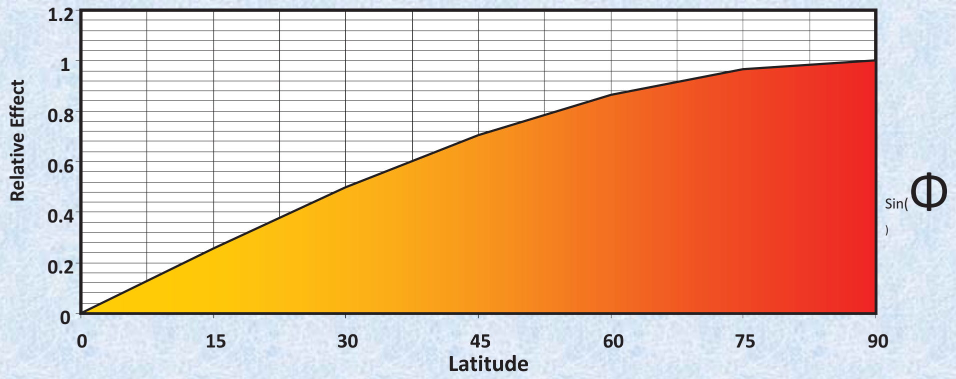


Image: National Tidal Centre, Australia

Declination of the moon with respect to the center of the earth causes successive tides to be similar near the equator, and progressively different with increasing latitude. Local resonance affects can result in higher tides in some areas of the Arctic Ocean.

Coriolis Effect





C=2mΩVsine(Φ)

Where: m = mass of object

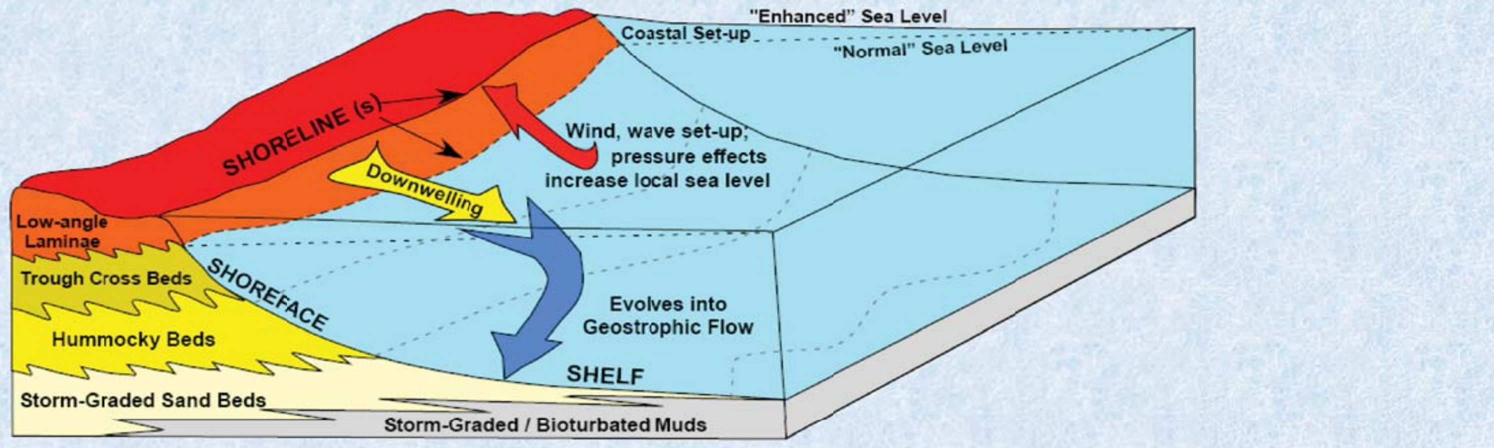
Ω = rotation

V = velocity

Φ = latitude

The rotation of the earth imparts the apparent Coriolis force to horizontally moving objects, creating a deflection that is oriented at right angles to the direction of movement. In the northern hemisphere the deflection is to the right, and in the southern hemisphere, to the left. This deflection affects offshore-flowing marine currents, causing them to veer obliquely offshore. Ultimately, should the pattern persist for sufficient time to achieve equilibrium, the offshore flow and the Coriolis deflection balance, creating an essentially shore-parallel geostrophic, or "balance of forces", current. The Corilois effect is directly correlated to latitude (Coriolis plot from Suter, 2008).

Geostrophic Currents



(Redrawn from PhysicalGeography.net)

Shoreface–shelf sediment succession formed in response to storm impact. Rip currents from the storm-enhanced surf zone along with downwelling storm currents resulting from coastal setup carry sediment offshore onto the shelf. Interaction with the Coriolis force leads to the evolution of geostrophic currents, sweeping storm-graded graded sediments obliquely offshore and alongshore. The intensity of such processes will clearly vary directly with latitude (redrawn from Swift et al, 1991).

Stratigraphic Models: Latitudinal Controls on Fluvial & Deltaic Deposits

Stratigraphic Models are dominantly based on modern depositional systems. Typically these are low to mid latitude systems. As we have shown, a number of processes known to be important in the development of these systems vary with latitude. Are these variations being taken into account when applying these models to systems from a different latitude? Are the current stratigraphic models robust enough or should they be modified to account for these differences?

Climate processes affect virtually every play element

	Temperature	Precipitation	Seasonality	Restriction	Upwelling	Runoff	Salinity	Wind Regime	Wave Regime
Siliciclastic Reservoirs	x	x	x			x		x	x
Fine-grained rocks - Source	x	x	x	x	x	x	x	x	x
Fine-grained rocks - Seal	x	x	x	x	x	x	x	x	x
Carbonates	x	x		x	x	x	x		x
Evaporites	x	x	x	x		x	x		x

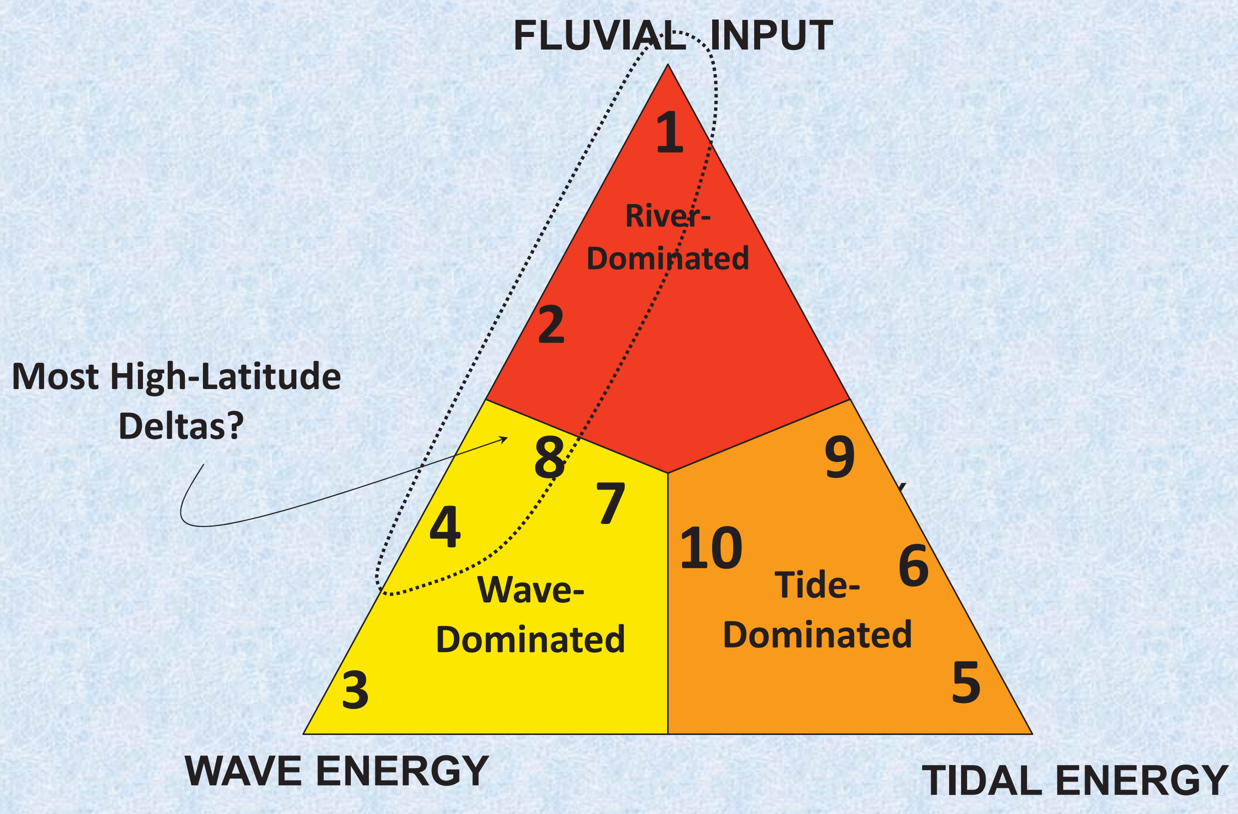
Source is controlled by biologic requirements governed by:
- – upwelling
- – ocean & land temperatures
- – continental runoff (precipitation, temperature, vegetation)
- – oceanic & atmospheric circulation

Carbonate Reservoirs are controlled by biologic requirements responding to:
- – ocean salinity
- – oceanic circulation
- – clastic influx

Clastic Reservoirs are controlled by weathering & transport processes:
- – precipitation
- – temperature

Seals are affected by weathering processes and temperature & precipitation at the depositional site

Burial & Maturation are controlled by sediment transport & surface temperatures



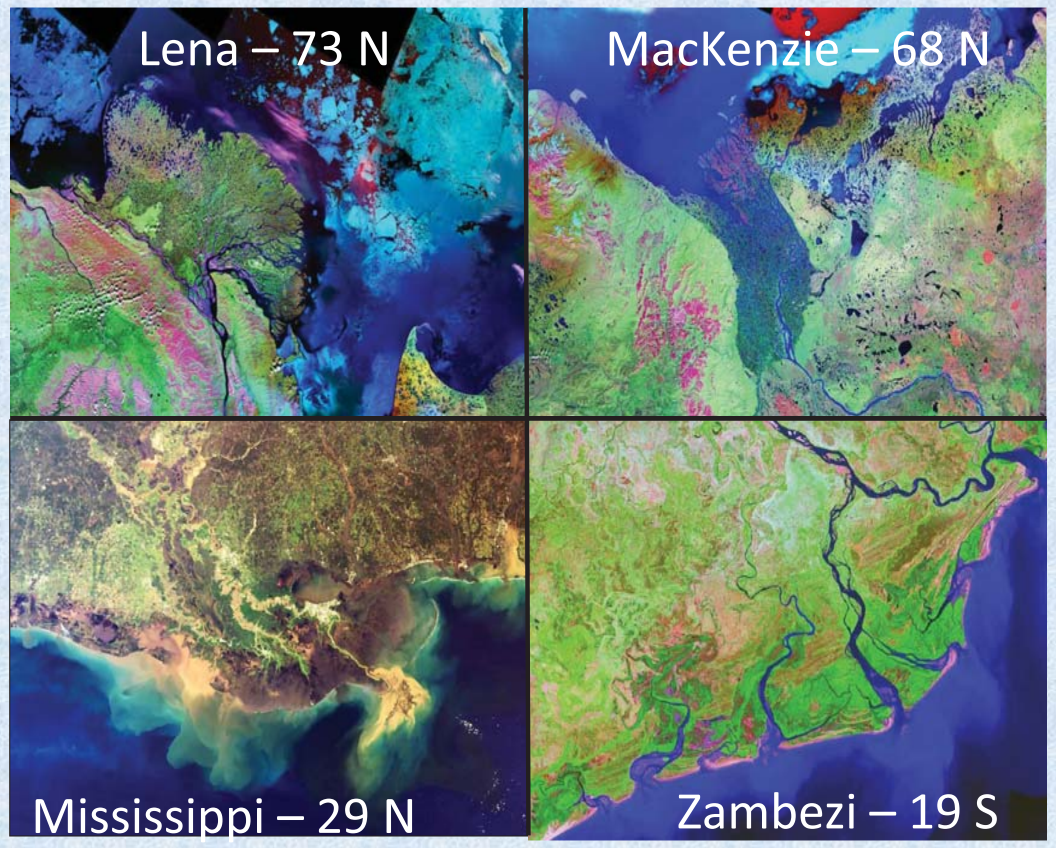
1 Mississippi	6 Ganges
2 Lafourche	7 Niger
3 Sao Francisco	8 Orinoco
4 Nile	9 Mahakam
5 Fly	10 Mekong

Deltaic Classification:

Process-Response and Delta Front Morphology

Deltaic systems have particular manifestations depending on a variety of factors (redrawn after Galloway, 1975). These include sediment supply – amount and caliber of sediments; receiving basin process – relative power of marine processes vs. fluvial input; basin bathymetry and configuration; climate, and accommodation – eustatic fluctuations; and subsidence, both tectonic and compactional. Many of these factors are functions of latitude, which leads to some interesting differences between the morphology of deltas, as shown to the right. These morphologic differences are reflected in different succession of deltaic deposits. We speculate that because of lessened tidal forces and wave energy dampening by sea and shorefast ice that higher latitude deltas are more likely to be river-dominated.

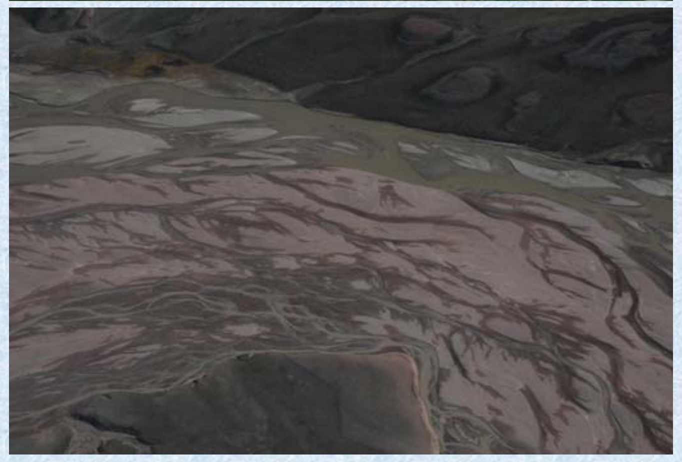
Delta Architecture and Morphology with Latitude



Images: NASA LandSat/Modis; K. Soofi COP

Deltas show interesting variations with latitude. High latitude delta plains , such as the MacKenzie and Lena deltas, show strong influence of thermokarst. Lower latitude examples , like the Mississippi and Zambezi, show dramatically different delta plains and greater influence of marine reworking. (redrawn after Suter, 2008).

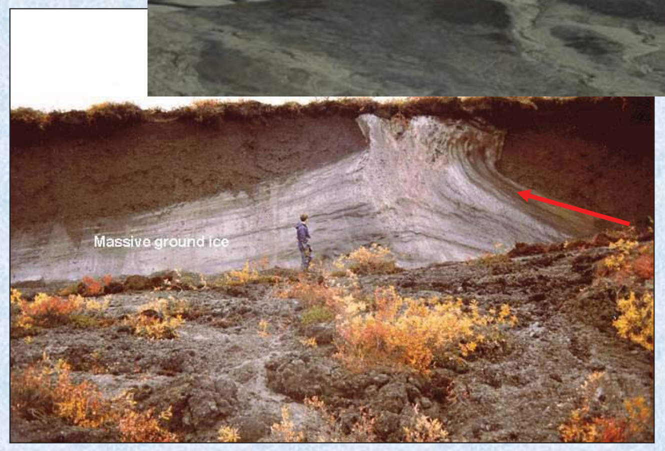
Fluvial Models



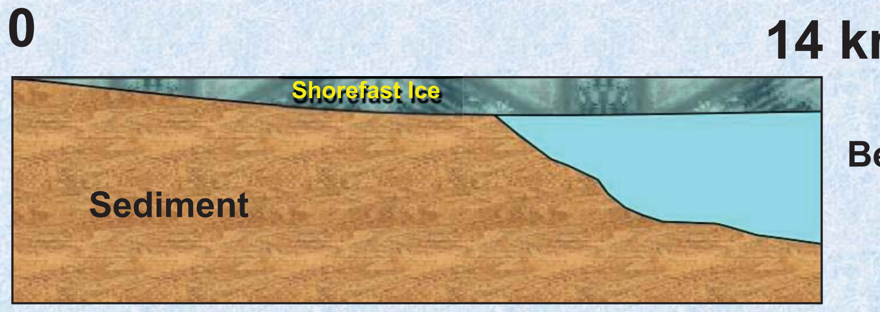
Tropical rivers, represented here by the Fly River of Papua-New Guinea (Latitude ~ 7.50 ^{0} S), typically have strongly different styles. Greater chemical weathering can lead to a higher fine-grained sediment/clay load, enhancing the sinuous nature of streams. (Image: Google Earth)

Characteristics of Cold-Climate Fluvial Systems

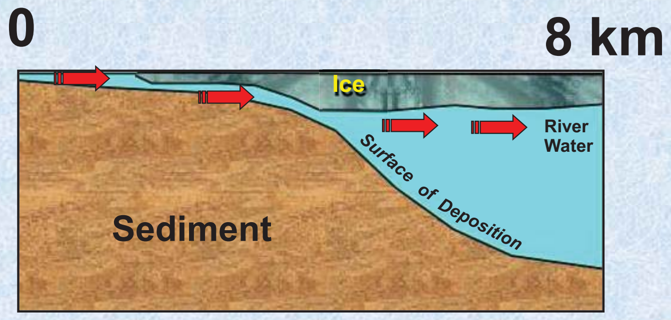
1. Strong discharge seasonality
   a. Short runoff season
   b. Disequilibrium streams?
      i. increase in floodplain sedimentation?
      ii. Tendency towards incision?
      iii. More frequent avulsions? Less frequent?
2. Some Rivers completely frozen during much of year
3. Ice jams during the spring flood
   a. increased potential of seasonal flooding of flood plains
4. Permafrost effects - thermokarst
5. Lessened vegetation – effects on channel patterns? Lower sinuousity?
6. Proglacial Rivers
   a. Variety of processes and inputs
   b. Catastrophic meltwater floods (jokulhaups)



Pingos form as permafrost development forces pore waters to be expelled. Tabular ground ice 1-30 m thick occurs in the Mackenzie Delta. How would this be expressed in cores and logs?



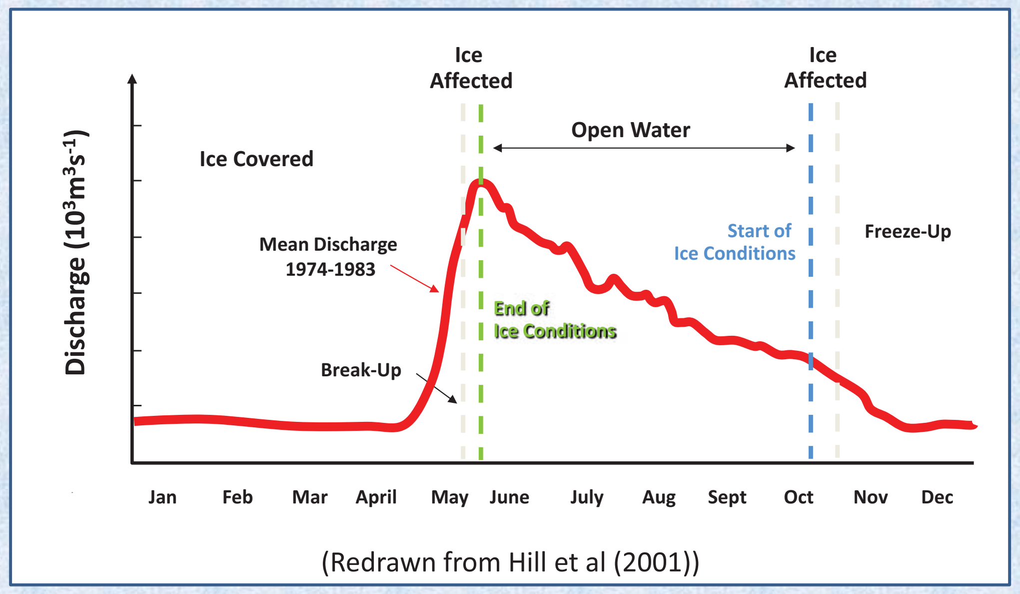
Before Break-up



One Month after Break-up:

Sediment bypasses delta front; Deposited up to 8 km offshore

Another interesting feature of higher latitude, ice-influenced deltas is shown above in this example from the Colville Delta of Alaska. Depending on the timing of flooding & sediment delivery versus timing of shoreface ice break-up, conditions of underflow vs. overflow will vary and sediments may bypass the delta front (redrawn after Reimnitz and Bruder, 1972).



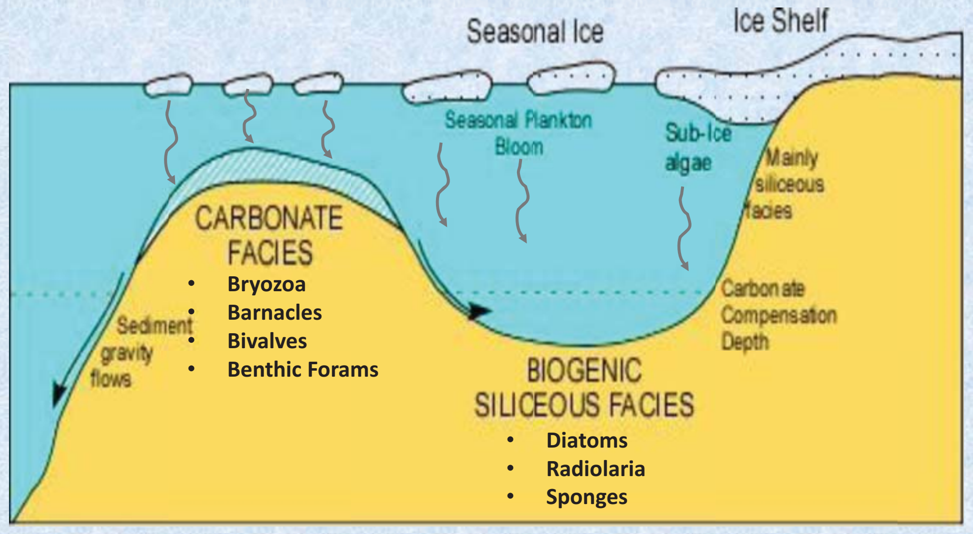
MacKenzie River Average Discharge 1974-1983

Stratigraphic Models: Carbonate Deposits

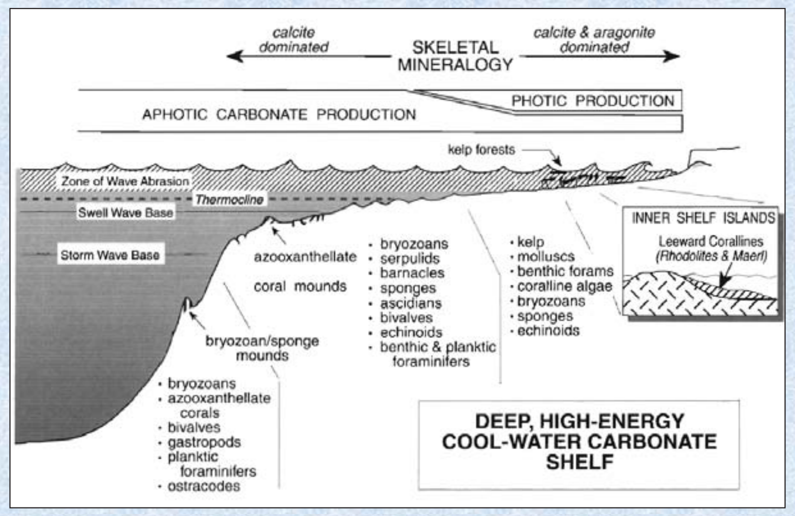
Carbonates can form at all latitudes, irrespective of water temperature, as long as the rate of terrigenous input to carbonate production is low. (e.g., Chave, 1967; Lees and Buller, 1972, James, 1998). However, the type and form of carbonate sediments and accumulations differ by latitude.

Bottom Water	Sediment Provinces	Attributes
Warm >22 C	Tropical	**PHOTOZOAN**: shallow rimmed shelves open shelves ramps reefs abundant carbonate mud marine cementation, micritization bioerosion aragonite Mg calcite mineralogies
~18-22 C	Sub-Tropical	**HETEROZOAN** + minor **Photozoan** elements: abundant coralline algae, open shelves and ramps, few reefs, minor carbonate mud, minor marine cementation, bioerosion, aragonite+calcite mineralogies
Cool ~10-18 C	Temperate	**HETEROZOAN**: open shelves and ramps, minor carbonate mud, minor cementation, no reefs, slope mounds extensive, bioerosion, maceration, calcite minerals dominant
5-10 C	Sub-Polar	**HETEROZOAN**: abundant barnacles and/or molluscs, brachiopods, open shelves and ramps, extensive maceration and boring, no cementation, calcite mineralogies
<5 C	Polar	**HETEROZOAN**: gigantism, biogenic siliceous facies, open shelves and ramps, barnacles common, no cementation, calcite mineralogies

James (1997) classified carbonate deposition into several broad attributes/categories depending on their constituents as a function of temperature = latitude. Redrawn after James (1997).



An early model for cold water carbonate shelf deposition,. Redrawn after James (1997); therein derived from Domack (1988) and Taviani et al (1993.)



One of a suite of models (James, 1997) for cool-water (Heterozoan assemblage, 10-18^0 C) carbonates.

Stratigraphic Models: Deep water Sedimentation

- Mathematical, experimental studies, and some observations lead to the prediction that deepwater channel systems will be less sinuous at high latitudes than at low latitudes
- The reported correlation of latitude-sinuousity exceeds that of sinuousity to slope.
- Higher latitude depostional events are predicted to be thicker and of smaller spatial extent than an equivalent event at lower latitudes

Are these predictions corroborated by experience and observations?

Stratigraphic Models: Mudstone and Source Rocks

Post ice melt algal bloom, Barents Sea

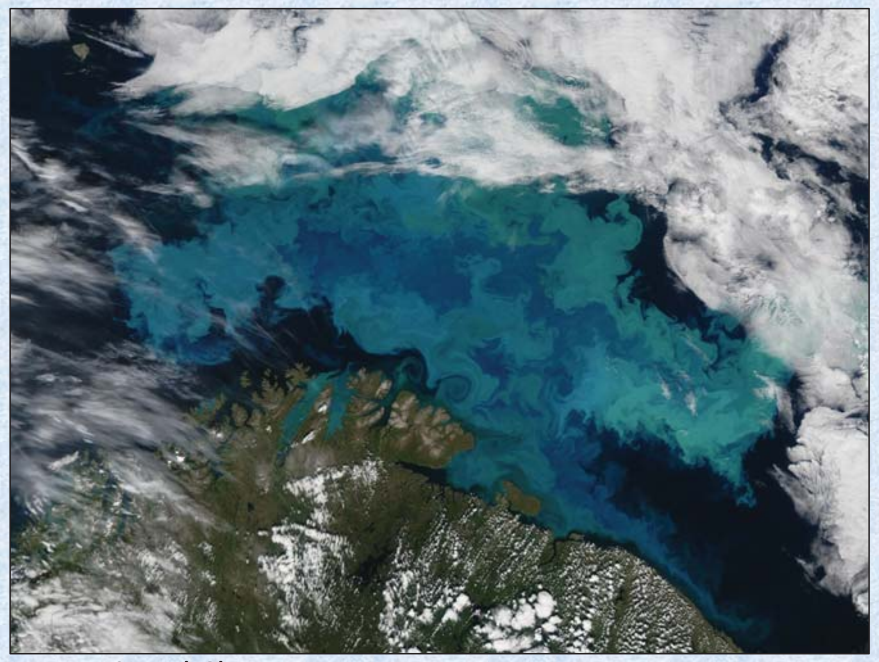


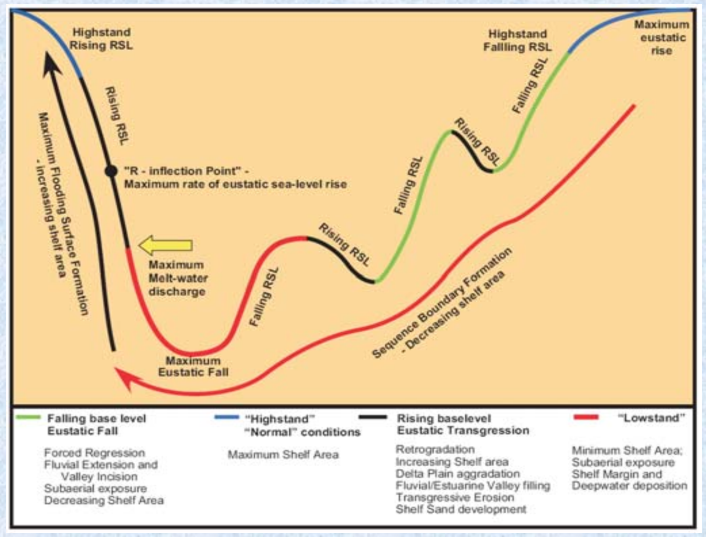
Image: NASA Earth Observatory

Sub-Ice Algae, Antarctica

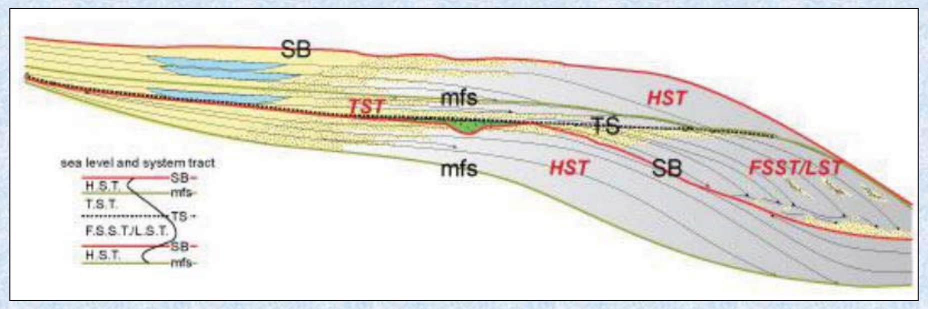
Latitudinal controls on mudstone deposition at high latitudes are poorly known relative to low latitudes. Do these processes vary with latitude in any recognizable and quantifiable ways? Here are a few speculations:

- Clearly greater chemical weathering at lower latitudes will act to enhance production of clay minerals, and should affect deposition by increasing "suspended" sediment load, as well as producing different clay mineralogy.
- Distribution of clay and organic rich sediments are controlled by the processes discussed above, in which there is a latitudinal component.
- Ichnology and early diagenesis of fine-grained and organic rich deposits is impacted by temperature.
- Primary productivity is affected by latitude,
- Is there any latitudinal control on the creation and distribution of dysoxic environments, which affects preservation of organic matter?
- Ice significantly influences sediment transport and primary productivity. High organic productivity below melting sea ice may be distribution by brine rejection and currents generated by catabatic winds, resulting in different types and distributions of organic facies.
- Algal blooms associated with annual sea ice melts have been document at both poles – is this a significant contributor to the TOC component of high latitude source rocks?

Do Sequence Stratigraphic Models Need to Account for Latitude?



Hypothetical response of to a Quaternary glacioeustatic fluctuation in the northern Gulf of Mexico (redrawn from Suter, 2006), built largely on data and examples from temperate continental shelves. Autocyclic processes and climatically driven changes in discharge and sediment load are convolved with base-level forcing, which is a function of ice-volume. Continental shelf area expands and contracts as sea level rises and falls. Various deposits are most significant in the particular systems tracts. Although no exact timing is implied in this diagram, note that the timing of significant surface formation is also a function of ice-volume driven base level changes.



At higher latitudes, due to the force of ice and the proximity to ice sheets during glacial maxima – expected behavior during systems tracts will be modified

During highstand:
- Ice sheet growth will significantly reduce/modify drainage basins for fluvial systems – likely reduction in sediment delivered to the basin as HST & LST progress
- Glacial loading will push land areas down, resulting in increased flooding of zones as glaciers advance

During lowstand:
- Sea ice likely covers the ocean, blocking sedimentary input & damping any ocean mixing
  - Likely results in condensed section or hardgrounds – not large deepwater systems

During transgression:
- Ice sheet retreat results in increases in sedimentation as flow from under and in front of the glaciers – increase can be dramatic
- Highest sedimentation rates likely in the TST
- Glacial rebound results in incised fluvial/deltaic systems and a local sea level drop
- Algal productivity associated with melting sea ice likely increase during the TST into the HST
  - Also when anoxia most likely

Incised delta, Jameson Land Greenland Image: JR Suter

Upcoming Hedberg Conference:

September 28-October 1, 2014

Banff, Alberta, Canada

Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts

As we hope we have shown in this far-from-comprehensive summary, numerous sedimentary processes are amplified or diminished depending on latitude.=, which can produce variations in stratigraphic architecture from more familiar depositional "norms." Current facies models, produced from decades of research on temperate and tropical systems are heavily biased towards low latitude analogs. These have been successfully applied in both mature and frontier basin exploration settings. However, numerous processes have been shown to be amplified and/or diminished at higher latitudes, producing variances in stratigraphic architecture from more familiar depositional "norms." For example, Coriolis effects are stronger at high latitudes, whereas tidal forces are weaker. Extremes of seasonality at higher latitudes result in temperature and insolation effects on fauna and flora, as well as short runoff seasons and strong fluvial discharge seasonality. Some important high latitudes processes such as ice melt algal blooms have no temperate or tropical equivalent and are thus unaccounted for in established models. These differences can and do impact numerous play elements including reservoir, source, and seal quality and distribution, in both conventional and "unconventional" systems. These variations need to be incorporated into subsurface interpretations to Improve stratigraphic models and probabilistic risking.

Towards this end, a joint AAPG-SEPM Hedberg Research Conference on the topic of Latitudinal Controls on Stratigraphic Models and Sedimentary Concepts has been approved to take place in September 28-October 1,2014 in Banff, Alberta, Canada. The main goal of the conference is to outline the depositional variability between high and lower latitude systems, demonstrate how such variability affects hydrocarbon play elements, and provide the needed basis for refining the established stratigraphic and sedimentary concepts, methods, and tools for use in high latitude basins. With increasing exploration interest in high latitudes, especially the Arctic, it is timely to examine in more detail process variability at different latitudes, and determine how facies models should be modified (or not) to include that variability. By ignoring that certain processes gain or diminish in importance with changing latitude, these models, and our application of them introduce a hidden bias towards low latitude systems. As a result, using these familiar concepts and models in high latitude systems can introduce errors that are often not accounted for.

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