A Neoproterozoic Rock Sample Suite:
Evidence for the Snowball Earth

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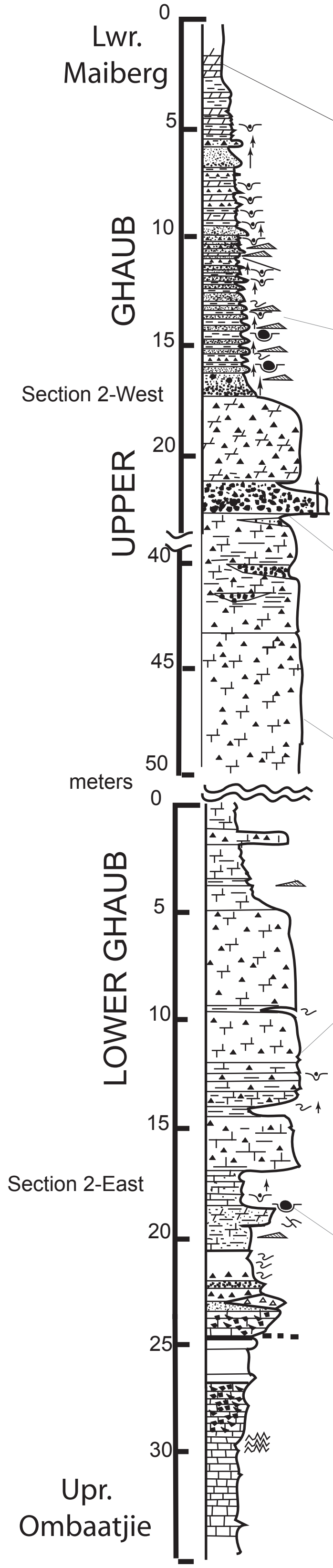
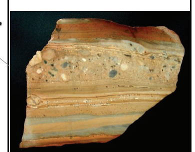
Table of Contents



Sample	Characteristics	Depositional Context
TS-1 	Fine-grained carbonate laminite.	Marine “cap” carbonate deposited directly above the Ghaub glacial formation, suggests rapid environmental change.
TS-3 	Stratified carbonate mud with sediment gravity (debris flow) deposits and significant ice rafted debris.	Represents a major deglaciation event at the end of the global Marinoan glacial.
TS-12 	Stratified carbonate mud diamictite with sediment gravity debris flow deposits and ice rafted debris.	Interbedded diamictite and sediment gravity debris flows, deposited as ice receded from the continental shelf.
TS-15 	Massive clast-rich diamictite.	Basal tillite deposited in direct contact with glacial ice.
TS-7 	Stratified carbonate diamictite with sediment gravity flow and ice rafted debris.	Implies slope instability and intense ice-rafting in response to glacial advance.
TS-20 	Carbonate mudstone with calcitic dropstone.	Records the onset of the Marinoan glaciation represented by dropstones in the Ghaub formation.
AB-1 	Fine grained carbonate laminite (lithologically similar to TS-1 of the Lower Maiberg formation).	“Cap” carbonate from the sequence directly overlying the older Cryogenian glacial event, represented by the Rhastoff formation.

Namibia TS-1

Kielberg Member of the Maiberg 'cap' carbonate succession

Carbonate laminite bounding the Ghaub glacial units

Namibia TS-1 is a thinly bedded to laminated allodapic (turbidite) dolostone that lies in sharp contact with the upper member of the Ghaub. formation. Namibia TS-1 directly overlies the Ghaub glacial deposits. The sharpness of the contact of the upper member of the Ghaub with the Kielberg cap carbonate implies a rapid transition between glacial and marine deposition. There is limited evidence for seasonal cyclicity in the Kielberg member, although it's interpretation as being a rhythmite has not been ruled out.

Sample TS-1 In the Field

What are Cap Carbonates?

(Taken from www.SnowballEarth.org)

Cap carbonates are continuous layers of limestone ($CaCO_3$) and/or dolostone ($Ca_{0.55}Mg_{0.45}CO_3$) that sharply overlie Neoproterozoic glacial deposits, or sub-glacial erosion surfaces where the glacial deposits are absent. They are typically 3-30 m thick and occur on platforms, shelves and slopes world-wide, even in regions otherwise lacking carbonate strata. Sturtian (~700 Ma) and Marinoan (635 Ma) cap carbonates are lithologically distinct, and both have unusual traits (e.g., thick sea-floor cements, giant wave ripples, microbial mounds with vertical tubular structure, primary and early diagenetic barite, $BaSO_4$) that distinguish them from standard carbonates. Marinoan cap carbonates are transgressive (i.e., inferred water depths increase with stratigraphic height) and most workers associate them with the flooding of continental shelves and platforms as ice sheets melted. Most Sturtian cap carbonates were not deposited until after post-glacial flooding had taken place. The preservation of cap carbonates and related highstand deposits after isostatic adjustment (or post-glacial "rebound") implies substantial erosion and/or tectonic subsidence during the glacial period. Post-Marinoan (Ediacaran and Phanerozoic) glaciations lack cap carbonates, or they are poorly developed.

Namibia Sample TS-3
Upper Member of the Ghaub Formation

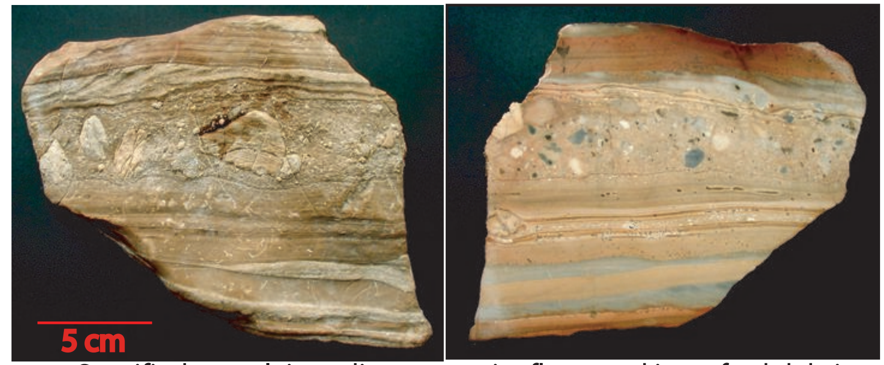
Stratified waterlain debris flows and diamictite with
'cap' carbonate transition

Namibia TS-3 represents the transition out of the Ghaub glaciation and was deposited as a marine-based ice sheet receded from an outer shelf. It lies stratigraphically above the massive basal tillite of the middle member of the Ghaub formation and directly below the Kielberg "cap" carbonate unit. The upper member of the Ghaub formation is associated with fluidized sediment gravity flows, ice-rafted debris, and a sharp contact with the overlying 'cap' carbonate of the Kielberg formation. This sample is primarily composed of fine carbonate muds interbedded with diamictite debris flows. Debris flows are dominated by stomatolitic boulders covering all size ranges.

The very thin to thickly laminated dolomitic (ferrugineous) sandstone shows current ripple cross-lamination, indicating flow direction during the time of deposition. The abrupt transition from glaci-marine turbidity current deposition into the pink "cap" carbonate unit suggests that the transition out of the Ghaub glaciation was rapid.

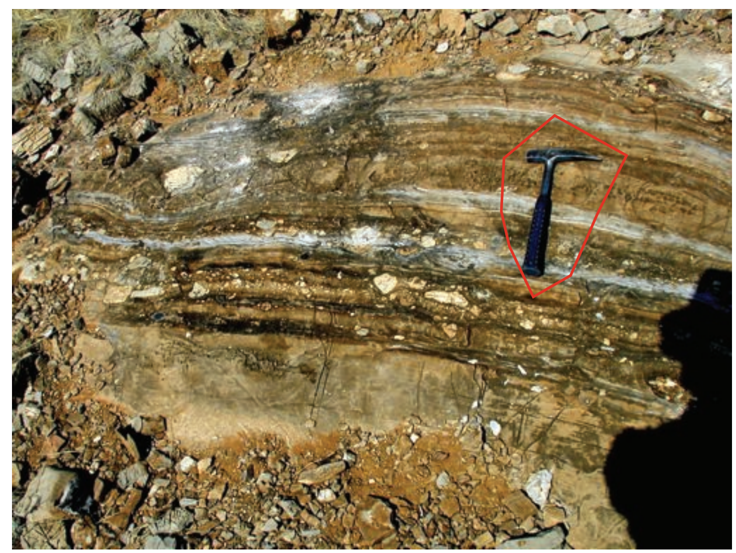
Sample TS-3 in the field

Namibia TS-12
Upper Member of the Ghaub Formation



Stratified waterlain sediment gravity flows and ice rafted debris

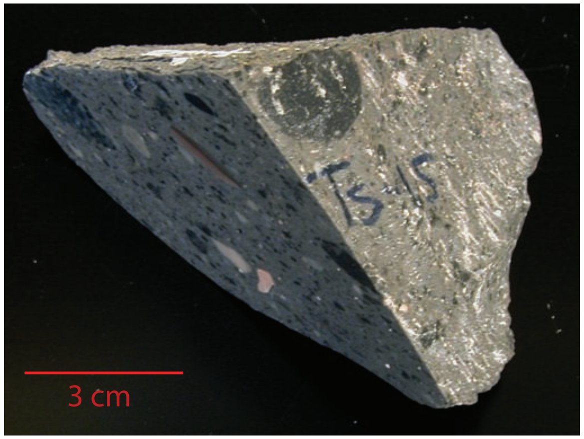
Namibia TS-12 is composed of interbedded, thinly bedded to laminated sandstone, calcareous argillite, and thin diamictite. The compositional banding is diffuse and elongate with distinct layering most likely deposited in response to local sediment supply and slope instability. Current ripple cross laminations (reference) in the ferrugineous sandstone bedding indicate the direction of transport and deposition during the Ghaub glacial recessional event. Periods between sediment gravity flows are marked by fine-grained hemipelagic carbonate mud layers with ice-rafted debris.



Sample TS-12 in the field

Namibia TS-15

Middle Member of the Ghaub Formation



Massive Clast rich carbonate basal tillite (diamictite)

TS-15 represents the middle member of the Ghaub formation, it is a poorly stratified to structureless diamictite, with a mostly gray limestone matrix. Clasts within the diamictite are unsorted and show evidence of significant lateral strain. Clasts are primarily composed of carbonate and quartz with evidence for intense silica recrystallization.

TS-15 is interpreted as being a basal tillite (diamictite) composed of unsorted carbonate debris supported by a calcitic limestone matrix that was eroded from the underlying Otavi platform as a result of ice motion.

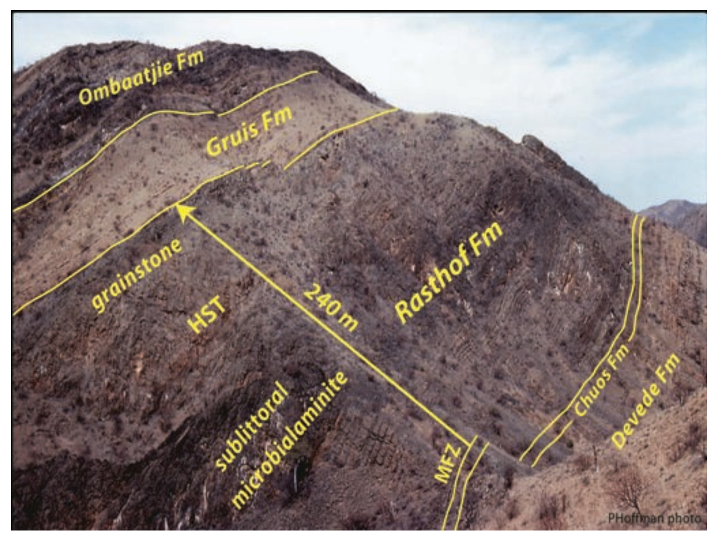
TS-15 in outcrop on the Fransfontein ridge Northern Namibia

Namibia AB-1

Rhastoff Formation

Namibia AB-1 is gray and tan carbonate laminite from the Rhastoff formation. This is a sample of the cap carbonate (typically deposited in shallow warm marine environments) unit that directly overlies the Chuos formation (interpreted as distinctly glacial in origin).

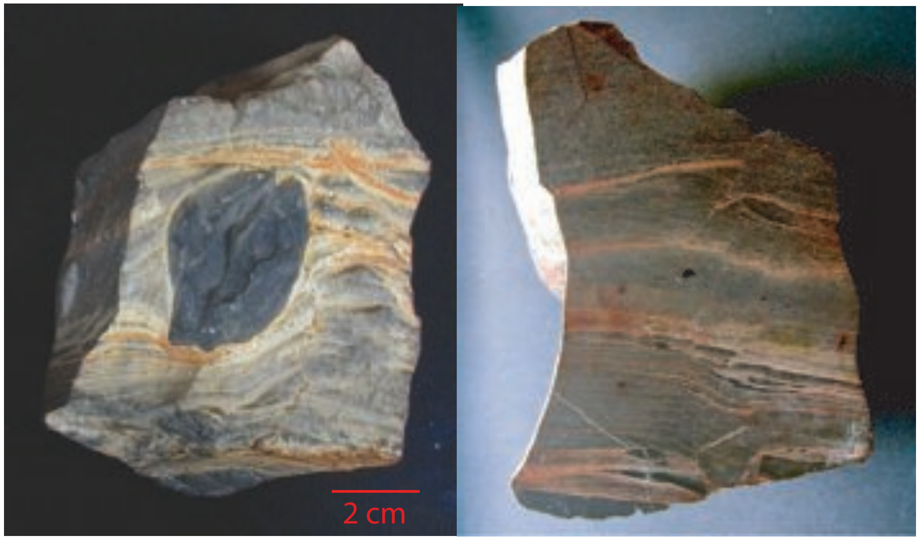
The Chuos formation represents the deposition that occured following the older, Sturtian glaciation around 710 million yrs. ago. The laminations lack any significant evidence of being influence by seasonal cyclicity and are interpreted as allodapic (turbidite) in origin.



Rhastoff Cap Carbonate Sequence, Northwestern Namibia

(Diagram courtesy of www.Snowballearth.org)

Namibia TS-20
Lower Member of the Ghaub Formation



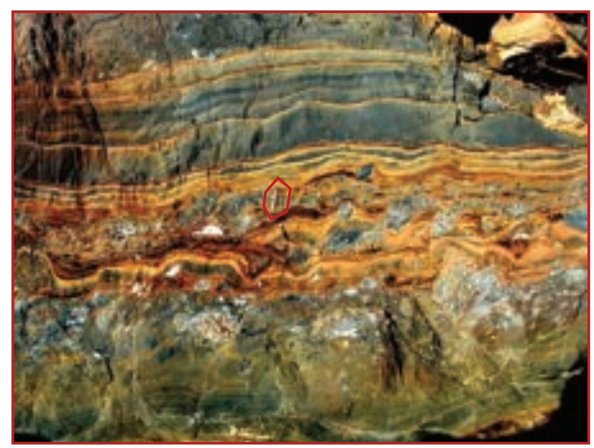
Stratified waterlain carbonate mudsone with ice-rafted dropstone

Namibia TS-20 is composed of finely stratified mudstone and ferrugineous dolostone with coarse sand grains scattered throughout. The fine grained primary bedding lacks any significant evidence of cyclicity suggesting TS-20 was deposited by turbidity currents in an ice distal environment. The sedimentary bedding bounding the two centimeter wide calcitic clast clearly indicates that this is a dropstone deposited by the rain-out of ice-rafted debris. Evidence for ice rafting is derived from the lateral continuity of layers bounding the calcitic clast; layers directly beneath the clast are deformed and appear impacted by the clast's emplacement, whereas, the layers directly above the clast appear draped and un-deformed-implying that their deposition was after that of the clast.

Ice rafting and soft sediment deformation in the lower member of the Ghaub

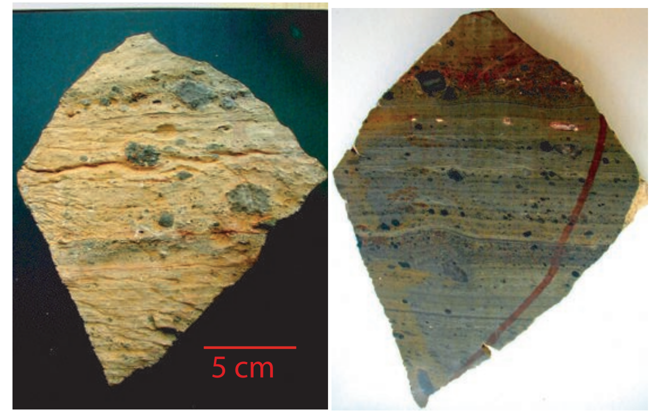
The polished surface of TS-20 reveals deformed bedding layers that suggest soft-sediment deformation occurred at some point after deposition of the lower member of the Ghaub. The excessive weight that would have exerted itself on the underlying sediments during the Ghaub glaciation more than adequately accounts for this deformation.

Dropstones like the one in TS-20 occur repeatedly throughout the thin stratified unit of the lower member of the Ghaub formation. The lower member makes a gradational transition into the much thicker and more massive unit of unstratified carbonate diamictite that makes up the middle member of the Ghaub formation. The transition between the lower member (clast-poor, stratified waterlain diamictite) and middle member (clast rich, massive basal till) of the Ghaub represent ice sheet advance, and possibly the onset of a Snowball event.



Namibia TS-7

Lower Member of the Ghaub Formation

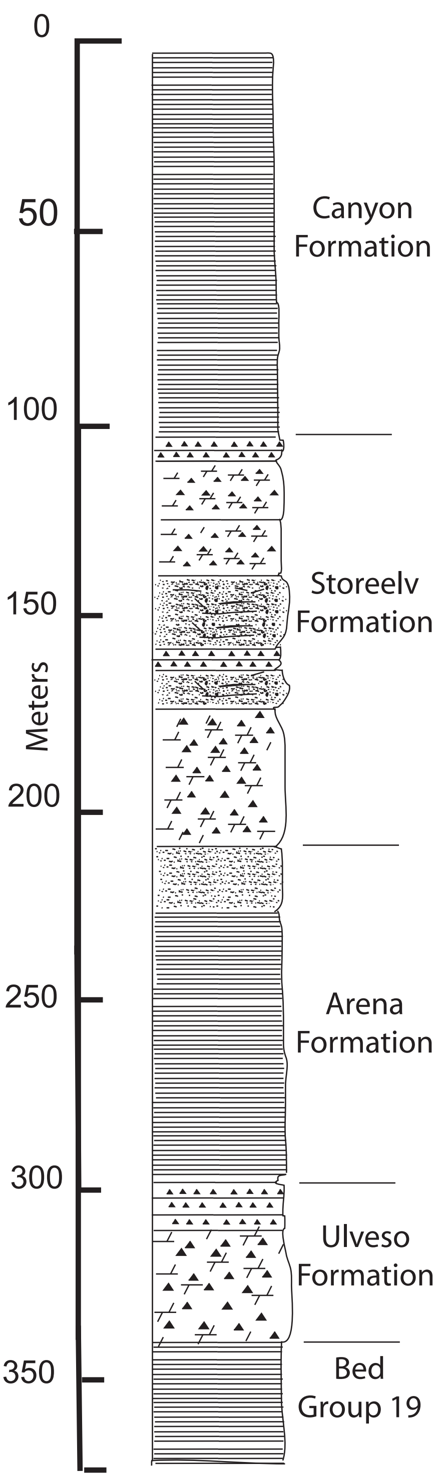


Stratified waterlain progradational tillite (diamictite)

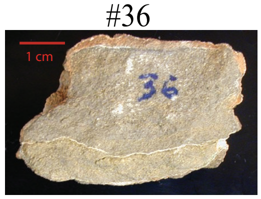
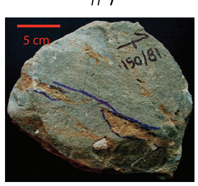
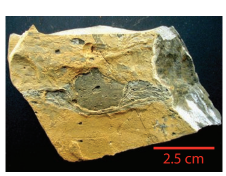
Namibia TS-7 is composed of thinly bedded to laminated dark gray limestone and very thinly bedded diamictite with large dropstones in the dolomitic interbeds. Impacted bedding structures clearly indicate stratigraphic up and current ripple cross stratification indicates the flow direction (left to right). TS-7 is indicative of a period of glacial progradation during which soft sediment remobilization occurred as carbonate material was eroded from the Otavi platform and redeposited by advancing glacial ice.

Namibia TS-7 in the field

Idealized stratigraphic column of East Greenland Neoproterozoic glacial succession.
(Derived from Hambrey and Spencer, 1987)



The East Greenland Suite
8 Samples

Sample	Characteristics	Depositional Context
#22 	Finely laminated carbonate mudstone from the Canyon formation.	This is the "cap" carbonate that lies in sharp contact with the Storeelv formation and indicates a rapid shift in sedimentary deposition, from glacial to marine in origin.
#17 	Striated and faceted stone embedded in sandy diamictite matrix from the Storeelv formation.	This stone probably became faceted and striated by transport in basal debris during ice advance
#50 	Stratified siltstone with ice rafted dropstone from the Storeelv formation.	Indicates that ice rafting was occurring in a glaci-marine environment.
#36 	Cross laminated sandstone from the Arena formation.	Indicates a period of dry windy conditions that may have occurred during the residence of continental ice.
#29 	Massive clast rich ferruginous diamictite from the Storeelv formation.	This another type of basal tillite found in the East Greenland succession.
D-6 	Massive clast rich diamictite from the Ulveso formation.	Interpreted as a basal tillite that was deposited in direct contact with overriding ice.
#7 	Massive clast-poor sandy diamictite from the Ulveso formation.	Sheared reactivation surfaces within this basal tillite suggest that glaciers were at least partially wet based.
#38 	Carbonate mudstone from Bed Group 19 with ice rafted dropstone.	Flow patterns surrounding the dropstone in this sample indicate bottom current movement at the time of deposition.

East Greenland # 36
Arena Formation

Cross laminated sandstone composed primarily of well rounded coarse sand grains

East Greenland #36 is a tan sandstone from the base of the Ulveso formation, which has been interpreted as an immature aeolian deposit, with a proglacial subaerial origin. Sample #36 may have been deposited during a period of dry windy conditions preceding the growth of a continental ice sheet. As ice accumulated (growing from high interior elevations and expanding toward the continental margin), marine margin facies (beach sand) became remobilized and was deposited further down the continental slope by the onset of glacial ice.

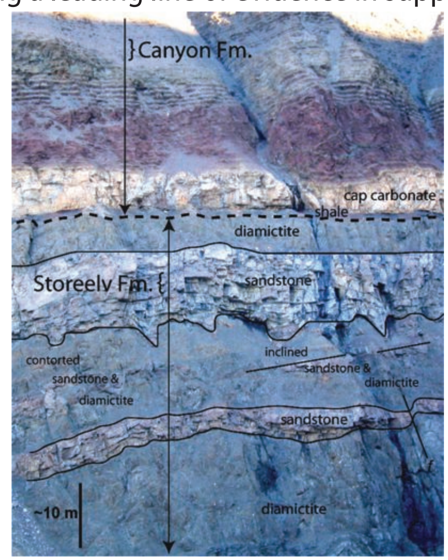
Sample #36 in the Field

East Greenland #22
Canyon Formation

Finely laminated cherty dolostone

East Greenland # 22 is a finely laminated buff yellow cherty carbonate mudstone (dolostone). This sample is taken from the unit that directly overlies the Storeelv formation glacial deposits. The sharpness of the contact between the Storeelv glacial succession and the overlying cap carbonate implies a rapid transition of depositional environments.

Isotopic ratios recorded in the carbonate rocks bounding nearly all Neoproterozoic glacial deposits record excursions that represent significant fluctuations in our planets reservoirs of natural carbon. The isotopic data gathered from the cap carbonate units is rapidly becoming a leading line of evidence in support of a snowball Earth.



Field outcrop of contact between the Storeelv and Canyon formations

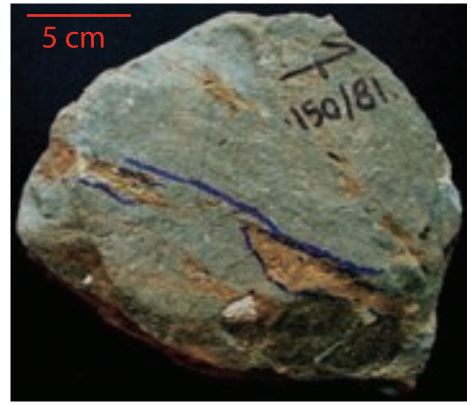
East Greenland # 17
Storeelv Formation

Faceted and striated pebble imbedded in sandy basal tillite (diamictite)

#17 is a striated and faceted stone that is embedded in a sandy diamictite matrix. The erosional surfaces of the pebble suggest that it was in direct contact with mobile basal ice. The flattened (faceted) surfaces of the pebble were formed as the pebble scraped along the bedrock beneath the moving basal ice. The striations that appear as parallel grooves etched into the faceted surface of the pebble record the direction of ice movement.

Ice grooved surface within the Storeelv Formation

East Greenland # 7
Ulveso Formation



Massive clast-poor basal tillite (diamictite)

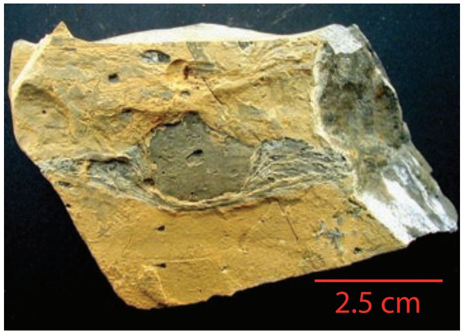
East Greenland # 7 is a massive gray to tan clast-poor sandy basal tillite (diamictite) from the Ulveso formation in East Greenland. Compositional banding is diffuse and disturbed by distinct lenses of diamictite including sandy and conglomeratic deposits.

The sandy deposits in this otherwise massively bedded sample are interpreted as melt-water washed horizons deposited in a fluctuating sub-glacial environment. The sheared sandy lenses represent a reactivation surface that formed in response to temperature changes or flow resumption in the basal ice.

The sandy horizon was probably originally deposited in cavities exposed by melting basal ice during a period of increased warmth and sediment discharge. This deposit was subsequently eroded (sheared) by basal ice-contact during glacial flow.

Sample # 7 in the field

East Greenland #38
Bed group 20

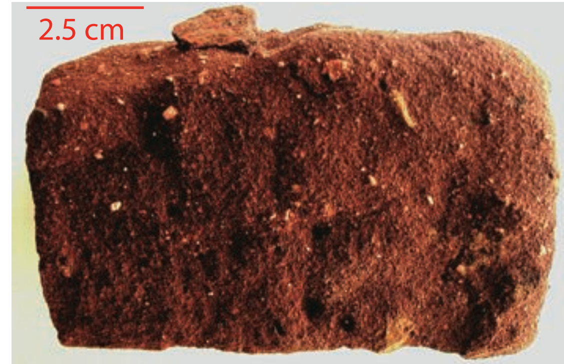


Waterlain carbonate mudstone with imbedded dropstone

East Greenland #38 is a gray carbonate mudstone from Bed Group 20 with a green weathered surface containing granule and pebble dropstones deposited in an ice-distal glaci-marine environment. The deformation of the sedimentary layering around the largest dropstone implies that significant ice-rafting must have been occurring during the period of deposition. The contrast between the sedimentary layering beneath (impacted and deformed) and above (draped and undeformed) the dropstone is typical of ice-rafted deposition. #38 comes from the unit just below the Tillite Group, suggesting there was a period of climatic deterioration during prior to glacial advance.

The whispy structures surrounding the dropstone suggest that it was placed prior to the deposition of the overlying sediment, during a period of increased water flow that created the eddy type flow pattern around the pebble.

East Greenland # 29
Storeelv Formation

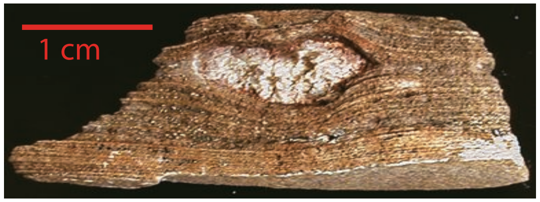


Ferrugineous clast rich basal tillite (diamictite)

#29 is a massive clast rich ferruginous diamictite. The clasts are of similar composition to those in East Greenland Sample D-6, although the matrix #29 is rich in fine grained terriginous minerals that give this basal tillite it's ferruginous color.

Greenland # 29 in the field

East Greenland #50



Stratified sandy siltstone with an ice rafted dropstone

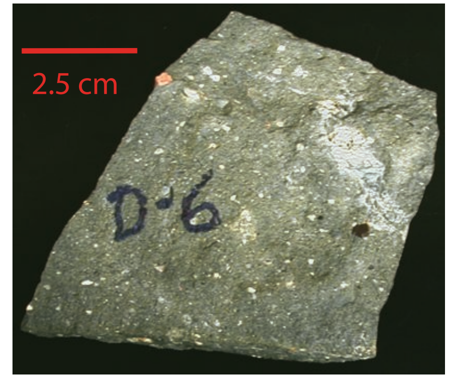
East Greenland #50 is a finely laminated reddish sandy siltstone embedded with an ice-rafted dropstone. The deformation of the sedimentary layers bounding the dropstone imply deposition in an open water glaci-marine environment. Dropstone structures like the one in sample #50 are typically found in deposits that represent transitional glaci-marine environments. The thickness of layers rich in ice-rafted debris record the rapidity of glacial advance and retreat.

Antactic Sound, East Greenland 8/10/04

The Process of Dropstone Deposition

1) Erosional debris (composition similar to that of diamictites) is entrained by advancing glacial ice and transported to the ice margin (marine ice front).
2) Glacial fluctuation causes calving to occur at the ice margin, releasing debris laden icebergs into an open water environment (typically marine or proglacial lacustrine).
3) Prevailing currents transport icebergs leaving a trail of rain-out debris as the warm open water environment melts the ice.

East Greenland D-6
Ulveso Formation



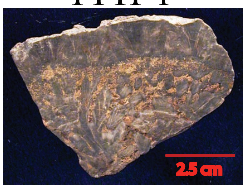
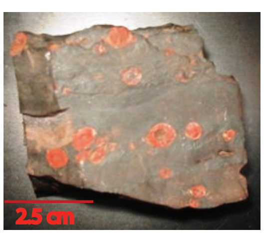
Massive clast-rich basal tillite

D-6 is a massive gray clast rich basal tillite (diamictite) from the Storeelv glacial unit. The matrix is primarily composed of coarse sand. Within the sample, clast sizes range from <1 mm to 1 cm. Clast composition and size are similar to East Greenland Sample #29, although the matrix composition is distinctly different.

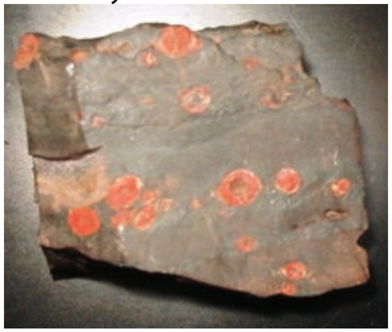
This sample probably formed in direct contact with basal ice. The massive matrix and unsorted clasts of this tillite (diamictite) were derived directly from underlying sediments and rocks eroded by the movement of basal ice during the Storeelv glacial event.

Sample D-6 in the Field

Unique Mineral Fans from Canada's Mackenzie Mountains and Mauritania, West Africa

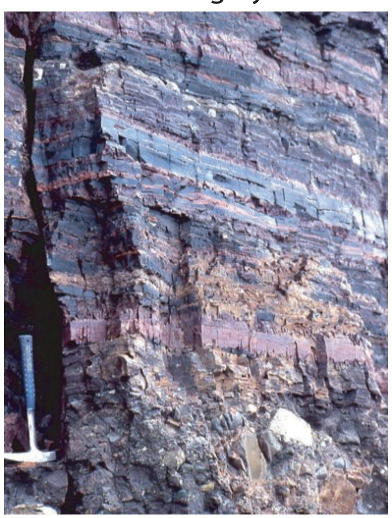
Sample	Characteristics	Depositional Context
PFH-1 	Cap dolostone with supratidal early diagenetic barite.	Mineral fans formed under anoxic ocean conditions created by global ice cover. -
PFH-2 	Cap dolostone with sea-floor barite.	Mid ocean layer deposition in anoxic Snowball ocean.
PFH-3 	Pseudomorphosed aragonite fans (sea floor cement) in calcimicrite.	Precipitated in highly alkaline conditions related to the super saturation of oceans with CaCO3 during rapid deglaciation and hot-house aftermath of a Snowball event.
PFH-4 	Banded iron formation with ice rafted debris.	Deep ocean stratigraphic equivalent of Ghaub diamictites, indicate highly anoxic oceanic chemistry.
P101A 	Peloidal cap dolostone.	Deposited in response to very rapid $CaCO^3$ precipitation during the hot-house aftermath of a Snowball Event.

Northwest Canada PFH-4
Syunei Formation



Iron formation containing hematite, jasper, and siderite

Sample PFH-4 is a banded iron formation (hematite-grey; jasper-red; siderite-buff) from the Mackenzie Mountains in Northwest Canada. Banded iron deposition requires that oceanic conditions be anoxic enough to allow for the precipitation of reduced iron (magnetite). Localized hematitic spotting is interpreted as the result of oxidation by dropstone deposition during the deep-freeze stage of a Snowball event. PFH-4 is viewed as the stratigraphic equivalent of units like the Ghaub diamictite, however was deposited in a much deeper oceanic basin during periods when ice cover prevented oceanic mixing and waters were highly anoxic.



Banded iron formation with ice-rafted debris and redeposited diamictite from the older Cryogenian (Sturtian) glaciation (Sayunei Formation, Rapitan Group) in the Mackenzie Mountains, northern Canadian Cordillera (Photo by Paul Hoffman).

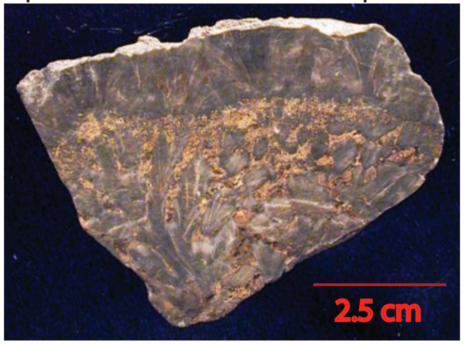
Northwest Canada P10A
Ravensthroat Formation,

Peloidal cap dolostone,

Sample P10A is a laminated peloidal cap dolostone. The graded and reverse graded peloids exhibit low-angle cross laminations easily visible with the naked eye. Peloid deposition reflects conditions in which calcium carbonate precipitation is occurring rapidly and has been associated with the hot-house aftermath of a Snowball Earth event.

Sample P10A in the Field. (Photo by Paul Hoffman)

West Africa (Mauritania) PFH-1
Amogjar cap dolostone, Jbeliat GroupTaoudeni Basin



Supratidal diagenetic barite

Sample PFH-1 comes from the Amogjar cap dolostone in West Africa. The barite fan records barium sulfate remobilization that occurred during a rapid shift in oceanic chemical conditions. Barium sulfate is insoluble in oxygenated water but under anoxic conditions it will dissolve in the manner seen here. PFH-1 records unusual oceanic chemical conditions and a short lived chemical disturbance.

In terms of a Snowball Earth, barite mineral fans like this one are believed to have formed during the rapid deglaciation and hot-house aftermath of a Snowball event. PFH-1 and PFH-2 are interpreted as having been deposited as anoxic oceans (created by ice cover that prevented mixing between the atmosphere and ocean water), once again became oxygenated with the resumption of the hydrologic cycle in the aftermath of a Snowball event.

Northwest Canada PFH-2
Sea-floor barite in cap dolostone in upper Ravensthroat Formation

Northwest Canada PFH-3
Hayhook Formation

Pseudomorphosed aragonite crystal fans (sea-floor cement) in calcimicrite

PFH-3 is an aragonite crystal fan from the Mackenzie Mountains in which the aragonite has been partially replaced by dolomite and calcite minerals. The sample records several intervals of fan growth and truncation that have been associated with the rapid deglaciation and hot-house aftermath of a Snowball event. The precipitation of aragonite occurs under highly alkaline oceanic conditions, like those created in the calcium carbonate super saturated ocean of a Snowball Earth. PFH-3 is interpreted as having been deposited during a period of short-lived, unusual climatic conditions during the rapid deglaciation and warming of $CaCO^3$ saturated waters at the end of a Snowball event. According to the Snowball Earth hypothesis, these super saturated conditions are the compound result of cold ocean waters (colder water favors higher $CaCO^3$ solubility) created during glaciations, and, increased $CaCO^3$ weathering of terrestrial rocks with the resumption of the hydrologic cycle during the rapid shift from ice-house to green-house conditions.

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