PS Identification of a Neoproterozoic Shelfal Suprasalt Carapace and Correlation to a Tapered Composite Halokinetic Sequence at Patawarta Diapir, Central Flinders Ranges, South Australia*

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Abstract

Stratigraphic and facies analysis of the Neoproterozoic Wonoka Formation and Patsy Hill Member of the Bonney Sandstone that surround Patawarta allochthonous salt sheet permit identification of an isolated suprasalt carapace section of the Wonoka Fm that is condensed and lithologically distinct from the correlative minibasin section. The two sections are spatially separated by a 3.8 km wide zone of outcropping Callana Group in the Patawarta diapir.

The Wonoka Fm carapace section displays a uniform 14 m thickness of parallel strata over a distance of 2.5 km and lies unconformably above the Patawarta salt sheet. The lower 7 m comprises upper-shoreface to foreshore silty lime mudstone and the upper 7 m comprises debris-flow facies interbedded with peritidal sandstone and shale capped by lagoonal stromatolitic mudstone. Debris-flow clasts were derived from older Wonoka Fm units and the Callana Grp. Equivalent strata in the adjacent minibasin comprise outer-shelf to upper-shoreface lime mudstone, siltstone and shale with minor sandstone. These strata form the bulk of a tapered composite halokinetic sequence (CHS) that thins (975 m to 117 m) and turns upward (<86 degrees) toward the diapir over a distance of 457 m. The uppermost shale unit in the minibasin contains 12 thin, sandy, pebble conglomerate beds, also sourced from older Wonoka Fm units and the Callana Grp, that display a progressive unroofing sequence.

The carapace and correlative minibasin section record the highstand systems tract (HST) of a 3rd-order depositional sequence. The transgressive systems tract (TST) and early HST formed by the lower Wonoka Fm units in the minibasin are not preserved in the carapace section. The top of the Wonoka Fm carapace is a sequence boundary (SB) that correlates to a SB in the minibasin formed at the contact between the Wonoka Fm and overlying Patsy Hill Member of the Bonney Sandstone.

The debris flow facies in the Wonoka Fm carapace and the correlative conglomerate beds in the minibasin are interpreted to be locally derived from strata that were originally deposited atop the ramping Patawarta salt sheet between the carapace and the minibasin. We infer that during the process of salt sheet breakout, the tip of the Patawarta sheet became a zone of diapiric inflation forming a local topographic high in the margin area, which was eroded during the later part of the HST and shed clasts onto both the carapace and the minibasin.

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Stratigraphic and facies analysis of the Neoproterozoic Wonoka Formation and Patsy Hill Member of the Bonney Sandstone that surround Patawarta allochthonous salt sheet permit identification of an isolated suprasalt carapace section of the Wonoka Formation that is condensed and lithologically distinct from the correlative minibasin section. The two sections are spatially separated by a 3.8 km wide zone of outcropping Callana Fm. in the Patawarta diapir.

The Wonoka carapace section displays a uniform 15 m thickness of parallel strata over a distance of 2.5 km and lies unconformably above the Patawarta salt sheet. The lower 7 m comprises upper-shoreface to foreshore silty lime mudstone and the upper 7 m comprises debris-flow facies interbedded with peritidal sandstone and shale capped by lagoonal stromatolitic mudstone. Debris-flow clasts were derived from older Wonoka units and the Callana Formation. Equivalent strata in the adjacent minibasin comprise outer-shelf to upper-shoreface lime mudstone, siltstone and shale with minor sandstone. These strata form the bulk of a tapered composite halokinetic sequence (CHS) that thins (975 m to 117 m) and turns upward (<90 degrees) toward the diapir over a distance of 450 m. The uppermost shale unit in the minibasin contains 12 thin, sandy, pebble conglomerate beds, also sourced from older Wonoka units and the Callana Formation, that display a progressive unroofing sequence.

The carapace and correlative minibasin section record the highstand systems tract (HST) of a 3rd-order depositional sequence. The transgressive systems tract (TST) and early HST formed by the lower Wonoka units in the minibasin are not preserved in the carapace section. The top of the Wonoka carapace is a sequence boundary (SB) that correlates to a SB in the minibasin formed at the contact between the Wonoka Formation and overlying Patsy Hill Member of the Bonney Sandstone.

The debris-flow facies in the Wonoka carapace and the conglomerate beds in the minibasin are interpreted to be locally derived from strata that originally overlay the margin of the ramping Patawarta salt sheet between the carapace and the minibasin sections. We infer that during the process of salt sheet breakout, the tip of the Patawarta sheet became a zone of diapiric inflation forming a local topographic high in the margin area, which was eroded during the later part of the HST and shed clasts onto both the carapace and the minibasin.

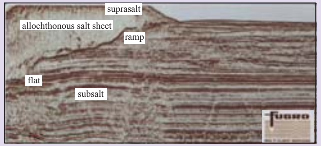
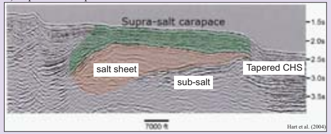


Figure 1:
-Advancing allochthonous salt sheet; forms ramps and flats
-Suprasalt is located above salt sheet
-Subsalt is located below salt sheet
-Suprasalt or subsalt minibasins are depocenters for sediment

Introduction

Carapace Defined by Hart et al. (2004)

a) Supra-salt Carapace



b) Carapace vs. Halokinetic Sequences

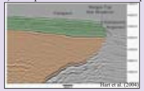


Figure 2a & b:
-Hart et al. (2004) proposed the use of the term "carapace" for a very specific type of supra-salt section
Criteria:
1) "sequences of strata that are deposited in sub-parallel layers over salt-induced sea floor highs, and which lie semi-conformably atop diapiric salt or its relic weld"
2) strata are relatively condensed sedimentologically and are lithologically distinct from coeval and overlying basin-fill assemblages
3) excludes sediments deposited onto autochthonous salt, syn-post kinematic salt not deposited on a topographic high

-Hart et al. (2004) makes distinction that carapace deposited within the intra-slope depositional environment will consist primarily of:
1) pelagic to hemi-pelagic mudstones and marls exhibiting high faunal and floral diversity
2) hemipelagic shales, high microfossil concentrations, and numerous hiatal surfaces, thinner, less sand-prone, condensed carbonate intervals
3) if sand exists, often in the form of turbidite packages

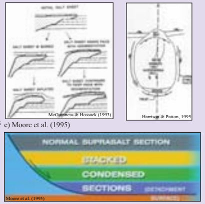
History of Carapace

Figure 3a-c:
-The concept of sediments being deposited above allochthonous sheets was first introduced by McGuinness and Hossack (1993) as a thin veneer of mud that protects the salt sheet from dissolving and translating laterally during extension

-Harrison and Patton (1995) interpreted these sediments to form in deep-water settings as condensed shale sections deposited on bathymetrically-high salt sheets that are rafted by spreading salt glaciers downdip

-Moore et al. (1995) also contributed to the carapace terminology by calling the sediments "supra-salt stacked condensed sections"
1) stacked condensed sections conformably deposited upon and coupled to the salt; 2) stacked condensed sections that have decoupled from, and extended along, the top of the salt
3) coupled or decoupled normal thicknesses of individual sequences resting conformably upon the salt
4) coupled or decoupled normal sequences that are significantly youngerthan the surrounding salt flank intervals, suggesting subaqueous erosion, nondeposition, or over thrusting

a) McGuinness & Hossack (1993) b) Harrison & Patton (1995) c) Moore et al. (1995)



Halokinetic Sequences

a) Wedge HS not forming carapace, pre drape-fold

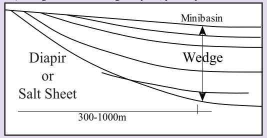


Figure 4a:
-Individual wedge halokinetic sequence before drape-fold deformation caused by subsidense and salt rise (modified from Giles and Rowan, 2011).

b) Wedge HS forming carapace, post drape-fold

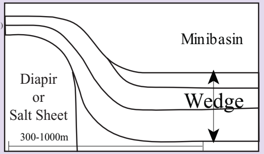


Figure 4b:
-Individual wedge halokinetic sequence after drape-fold deformation caused by subsidense and salt rise (modified from Giles and Rowan, 2011).

c) Composite HSC

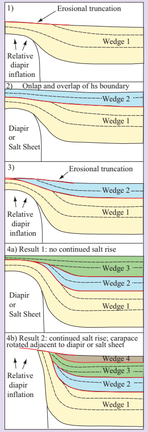


Figure 4c:
-Progressive development of Tapered CHS
-If there is no continued salt rise or advance, carapace stays on top of diapir
-If there is continued salt rise or advance, carapace is rotated adjacent to diapir
- (modified from Giles and Rowan, 2011).

Models for Advance of Allochthonous Salt

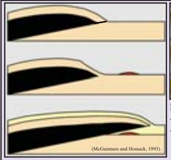


Figure 5: *Slumped-carapace model* (McGuinness and Hossack, 1993)
-Scarp relief increases during times of slow sedimentation
-Slumping of carapace creates debrite at toe of scarp; subsequently overridden as salt advances

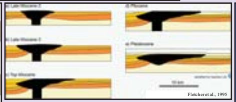


Figure 6: *Salt-glacier model* (Fletcher et al., 1995)
-Salt extrudes laterally at sea floor
-Buried by sediment once growth stops

Figure 7: *Basal-shear model* (Harrison et al., 2004)
-Well data show disrupted zones with anomalous dips and ages (rubble zone)
-Interpreted as shear zones formed during emplacement of salt and/or basinward translation of overburden plus salt

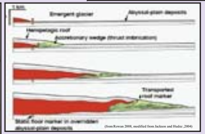


Figure 8: *Thrust Advance/Accretionary-wedge model* (Hudec and Jackson, 2006, 2009)
-Imbricate thrusts in front of sheet
-Folding of salt and advance on roof thrust results in subsalt accretionary wedge

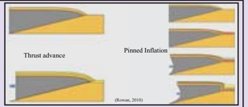


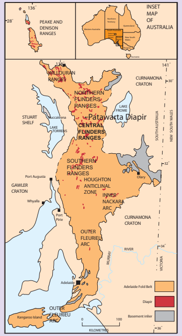
Figure 9: *Combined Model: Thrust Advance associated with Pinned Inflation* (Rowan et al., 2010)
-Interplay between lateral salt supply rate vs. sediment accumulation rate
-Salt supply driven by subsidence of suprasalt minibasin and gravity spreading

Objectives of Study

- Document facies distribution, stratal geometry and structure of suprasalt and subsalt Wonoka Formation adjacent to Patawarta salt sheet
- Correlate shelfal suprasalt and subsalt stratigraphy within a depositional sequence stratigraph ic and halokinetic sequence stratigraphic framework
- Evaluate models for salt sheet advancement of emplacment
- Hypothesize differences in Proterozoic shelfal carapace vs. Phanerozoic shelfal carapace

Geologic Setting of the Flinders Ranges, South Australia

Location of Field Area

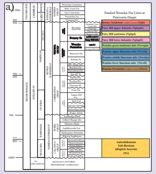


(after Preiss, 2000; modified by Giles, 2003)

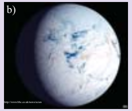
Figure 10:
-Patawarta Diapir is one of more than 120 exposed diapirs in South Australia (Preiss, 1987)
-Adelaide Geosyncline forms a north-south trending fold belt 600 km long and 200 km wide
-Stratigraphy deposited late Proterozoic-early Cambrian and is over 20,000 m thick in a rift basin between the Gawler and Curnamona cratons (Sprigg, 1952a; Preiss, 1973b)

General Stratigraphy and Snowball Earth

a)



b)



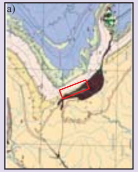
c)

Figure 11b & c:
-Artist depiction of 'Snowball Earth' and plate tectonic approximately 600 million years ago
-These environmental conditions allowed for only stromatolites to be recorded in the rock record
-Stromatolites lived on topographic highs created by shefal diapirs and incised valleys adjacent to barrier bars created by diapirs

Figure 11a:
- Neoproterozoic Adelaidean Callanna Group represents the basal strata (evaporite-bearing) of the Adelaide Geosyncline and rests unconformably above Archean and Paleoproterozoic metamorphic and igneous basement rocks (Rowlands et al., 1980).
- The Neoproterozoic Adelaidean Warrina Supergroup includes the Callanna and Burra groups which are overlain by the Heysen Supergroup divided into the Umberatana and Wilpena groups which contains the Wonoka Formation and Bonney Sandstone(Preiss, 2000)
- The informal members defined are apart of the Wonoka Formation and Patsy Hill Member of the Bonney Sandstone

Previous Maps of Patawarta Area Including Interpreted Carapace

a)



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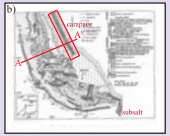

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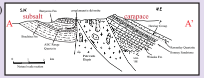

Figure 12a & b:
-Area mapped by Coats (1973), Hall (1984), by Baker (2009)

Figure 12c:
-The carapace was previously interpreted as a thrust fault of section by Lemon (1988)

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Geologic Map of Patawarta Diapir and Adjacent Neoproterozoic Strata

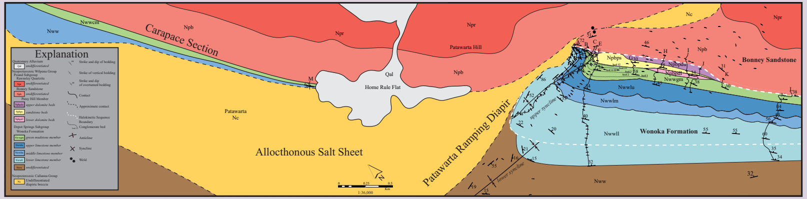


Figure 13:
-The Wonoka Formation and Patsy Hill Memeber of the Bonney Sandstone deposited locally as a suprasalt carapace section and subsalt section
-The Wonoka Formation and Patsy Hill Member for one tapered-composite halokinetic sequence

Interpretation of Depositional Environments

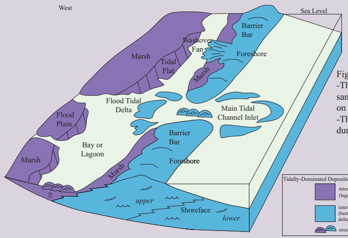
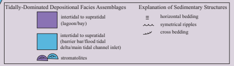
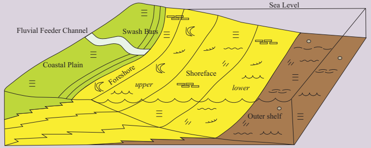


Figure 31:
-The Patsy Hill Member (lower limestone, sandstone, and upper limestone beds) form on a tidally-dominated shelf
-The Patsy Hill Member was deposited during the Lowstand Systems Tract



Stratigraphy		Map Unit	Depositional Environments	Depositional Sequence Stratigraphy	Halokinetic Sequence Stratigraphy
Bonney Sandstone		Undifferentiated	middle shelf lower shoreface	Transgressive Systems Tract *Transgressive Surface*	*Sequence Boundary*
Bonney Sandstone	Patsy Hill Member	Upper dolomite beds	lagoon/bay	Lowstand Systems Tract	Tapered CHS
		Sandstone beds	barrier bar flood tidal delta		
		Lower dolomite beds	main tidal channel inlet	*Sequence Boundary*	
Wonoka Formation		Green mudstone mbr	flood plain	Highstand Systems Tract	
		Upper limestone mbr	upper shoreface foreshore		
		Middle limestone mbr	lower to upper shoreface foreshore		
		Lower limestone mbr	outer shelf lower shoreface	*approx. Maximum Flooding Surface*	*Sequence Boundary*

Figure 32: Compilation of depositional environment, sequence stratigraphy, and halokinetic sequence stratigraphy



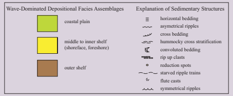


Figure 30:
-The Wonoka Formtion (undifferentiated, lower limestone, middle limestone, upper limestone, and green mustone member) form on a wave-dominated shelf that shallows to a coastal plain depositional environment
-The Wonoka Formation was deposited during the Highstand Systems Tract

Fence Diagram and Photographs of Wonoka Formation and Patsy Hill Member of Bonney Sandstone

Figure 15: hummocky cross stratification; wave-dominated lower shoreface

Figure 16: flute casts; wave-dominated lower to upper shoreface

Figure 17: stromatolitic dolomite; lagoon/bay/barrier bar

Figure 18: bi-modal arkosic sandstone; barrierbar or flood tidal delta

Figure 19: conglomeratel and crypt algal laminae; main tidal channel inlet

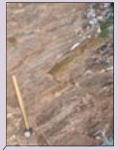
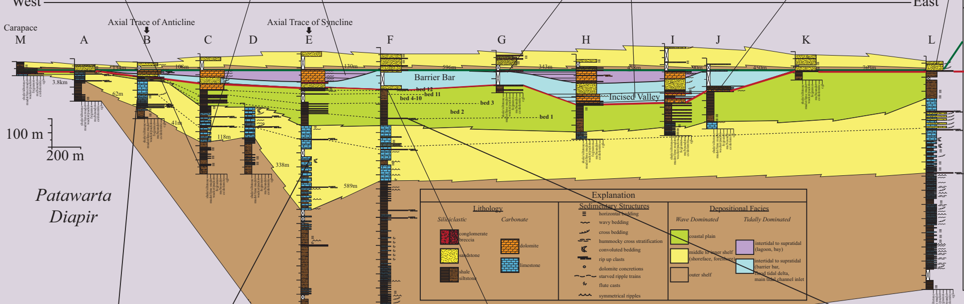


Figure 20: black shale and dolomitic concretions; main tidal channel inlet

Figure 21: low angle cross bedding; lower shoreface



Map Units			Depositional Sequence Stratigraphy
Bonney Sandstone		undifferentiated (Npb)	Transgressive Systems Tract *Transgressive Surface*
Bonney Sandstone	Patsy Hill Mbr	upper dolomite (Npbpd)	Lowstand Systems Tract
		sandstone (Npbps)	
		lower dolomite (Npbpdl)	*Sequence Boundary*
Wonoka Formation		Green Mudstone Mbr (Nwwgm)	Highstand Systems Tract
		Upper Limestone Mbr (Nwwlu)	
		Middle Limestone Mbr (Nwwlm)	
		Lower Limestone Mbr (Nwwll)	
		Wonoka undifferentiated (Nww)	

Figure 14:
-The Wonoka Formation forms the highstand systems tract of a 3rd order depositional sequence
-The Patsy Hill Member of the Bonney Sandstone forms lowstand systems tract of the overlying 3rd order depositional sequence
-The sequence boundary between the two sequences forms an incised valley cutting into the Green Mudstone Member which is filled by the Patsy Hill Member

Figure 22: hummocky cross stratification; wave-dominated lower to upper shoreface

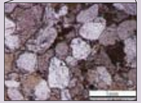


Figure 23: quartz arenite; wave-dominated lower to upper shoreface

Figure 24: soft-sediment deformation; foreshore

Figure 25: litharenite; foreshore

Figure 26: soft-sediment deformation; foreshore

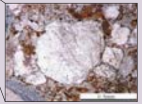


Figure 27: quartz arenite; foreshore

Figure 28: mud drapes, horizontal laminae; coastal plain

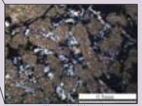


Figure 29: litharenite; coastal plain

Identification of a Neoproterozoic Shelfal Suprasalt Carapace and Correlation to a Tapered Composite Halokinetic Sequence at Patawarta Diapir, Central Flinders Ranges, South Australia

Kernen R.A.(rachellekernen@gmail.com), Giles K.A., Rowan, M.G., Hearon, T.E. IV

Correlating Suprasalt Carapace to Subsalt Stratigraphy

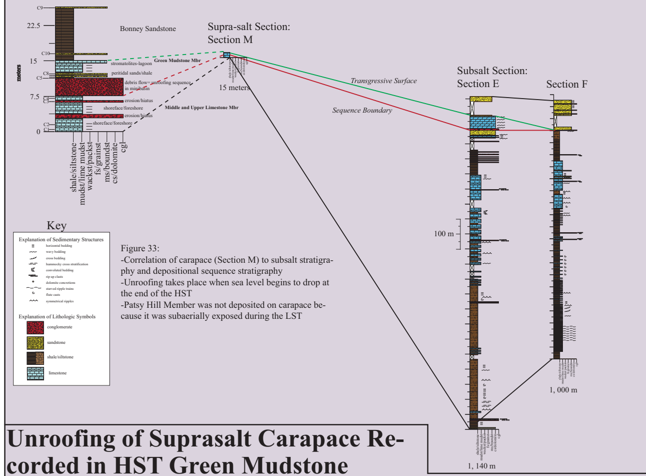


Figure 33:
-Correlation of carapace (Section M) to subsalt stratigraphy and depositional sequence stratigraphy
-Unroofing takes place when sea level begins to drop at the end of the HST
-Patsy Hill Member was not deposited on carapace because it was subaerially exposed during the LST

Unroofing of Suprasalt Carapace Recorded in HST Green Mudstone Member in Subsalt Stratigraphy

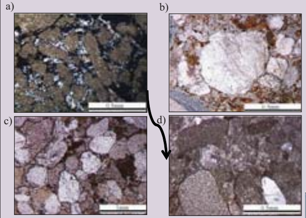


Figure 34a-d:
a) litharenite carapace; b) quartz arenite in green mudstone mbr;
c) quartz arenite carapace; d) litharenite in subsalt minibasin

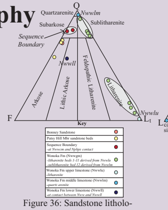


Figure 36: Sandstone lithologies in minibasin stratigraphy

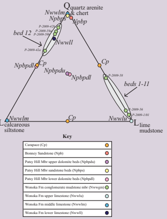


Figure 37: Composition of litharenite in specified members

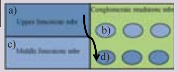


Figure 35:
-Schematic diagram of unroofing sequence

Correlating Subsalt Sequence Stratigraphy to Carapace Section

Correlation Chart

Stratigraphy		Carapace	Minibasin	Depositional Sequence Stratigraphy	Halokinetic Sequence Stratigraphy
Bonney Sandstone		Undifferentiated	Undifferentiated	Transgressive Systems Tract *Transgressive Surface*	*Sequence Boundary*
	Patsy Hill Member	Depositional Hiatus	Upper dolomite beds	Lowstand Systems Tract	Tapered CHS
			Sandstone beds		
			Lower dolomite beds	*Sequence Boundary*	
Wonoka Formation		Unroofing Sequence	Green mudstone mbr	Highstand Systems Tract	
		Upper limestone mbr	Upper limestone mbr		
		Middle limestone mbr	Middle limestone mbr		
		Depositional Hiatus	Lower limestone mbr	*approximate maximum flooding surface*	*Sequence Boundary*

Figure 38:
-Suprasalt vs. subsalt stratigraphy

Correlating Sequence Stratigraphy

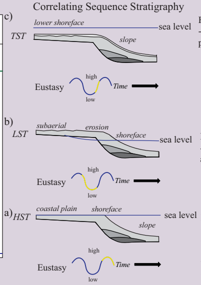


Figure 39c:
-Transgressive systems tract buries carapace

Figure 38b:
-Lowstand erodes carapace thus creating a hiatal surface

Figure 38a:
-Highstand systems tract on a regular depositional profile
-Envision depositional profile as allochthonous salt sheet
-Carapace section deposition

Pinned Inflation and Unroofing: Mechanism for Allochthonous Salt Advancement

Progressive pinning of salt

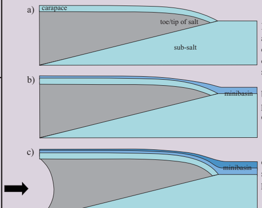
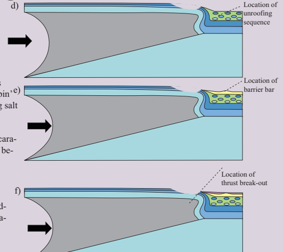


Figure 40:
a) High sedimentation rates during the HST begins to 'pin' down the toe/tip of ramping salt sheet
b) Only during the HST is carapace deposited on the shelf because rising sea level
c) High percentange of sandstones are preserved on carapace



d) As sea level drops during latest HST, unroofing of carapace is deposited in green mudstone member

e) Barrier bar forms in front of ramping salt sheet creating a topographic high

f) Thrust break out occurs after deposition of upper dolomite beds above HSB due to a drop off in sedimentation rates

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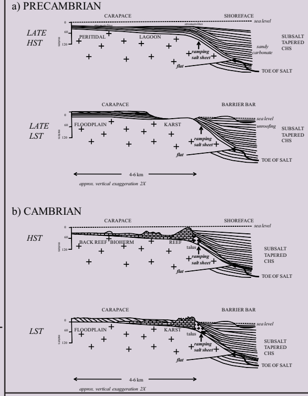
Proterozoic vs. Phanerozoic Carapace



c) Precambrian vs. Cambrian Shelf Carapace and Allochthonous Salt Advance

Characteristic	*Precambrian (Patawarta Diapir)*	*Cambrian (Wirrealpa Diapir)*	*Exploration Significance*
Carapace facies	sandy carbonate and calcareous floodplain	reef, back reef, bioherm	different source, reservoir, or seal composition
Subsalt facies	unroofing of carapace as	reef debris as talus	drilling hazard in subsalt plays
Halokinetic sequence style	wedges dominate	wedges and hooks	drilling hazard in subsalt plays
Overall lithology	siliciclastic dominated	carbonate dominated	different source, reservoir, or seal composition
Structural response above toe of salt	folding (drape-fold monocline)	faulting (grabens)	trap mechanism, drilling hazard
Sequence stratigraphy during HST	highly dependent on sediment supply; more accommodation space	carbonate producers keep up with sea level; less accommodation space	difference in source, reservoir, or seal thickness

Figure 41:
a) depositional model for Proterozoic carapace
b) depositional model for Phanerozoic carapace
c) chart comparing Proterozoic vs. Phanerozoic shelfal carapace

Conclusions

-Correlation of suprasalt and subsalt sections (14 m carapace vs. 975 m subsalt)
-Suprasalt section is 'carapace' according to Hart et al. (2004) defined list of attributes
-Shelfal carapace primarily formed during late highstand systems tract and was exposed and eroded during lowstand systems tract, and forms during transgressive systems tract
-Allochthonous break-out by pinned inflation at the tip of the salt sheet associated late highstand erosional thinning of carapace permitted by break out
-Proterozoic carapace great analog for Gulf of Mexico because lacks carbonate producers and reef builders

Comparison of Intra-slope and Shelfal Carapce

Characteristics	*Intra-slope (Hart et al., 2004)*	*Shelfal (Kernen et al., 2011)*
Lithology	pelagic to hemi-pelagic mudstones and marls	litharenite sandstones, debris flows, silty carbonate
Stratigraphic significance	hiatal surfaces, thinner, less sand prone, condensed carbonate intervals	hiatal surfaces, significantly thinner (14 m vs. 975 m), more sand prone
Exploration significance	provides a great seal for stratigraphic traps	due to high sand content may leak hydrocarbons; no seal

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