Future Exploration Potential Associated with Glaciogenic Carboniferous Series in the Bolivian Subandean Chaco Foreland System*

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Abstract

The glaciogenic Carboniferous series (e.g. Machareti and Mandiyuti Groups) of the Bolivian Subandean Foreland Basin are known to host significant hydrocarbon resources and are therefore considered a relative mature play. Through the completion of a regional and integrated surface/subsurface G&G study, including sedimentological and allostratigraphic analysis, the intimate stratigraphic architecture of these sedimentary units has been partially resolved at a basin scale. The results allow distinguishing an extremely strong intrinsic architectural complexity relying on the glaciogenic nature of deposits as well as the occurrences of numerous undrilled stratigraphic traps (e.g. sand-filled glacial valleys) and subsequent remaining exploration leads. Using outcrop and subsurface analogs, a dedicated geoscientific investigation workflow, the distinctive types of plays/leads were revealed. We will discuss the leads and associated risks, attempting to better address remaining and/or future exploration potential for the Carboniferous Series of Bolivian Subandean Foreland area.

Selected References


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Introduction

- In Bolivia, well developed and preserved glaciogenic rocks, « Carboniferous » aged, are hosting significant reserves of hydrocarbon (e.g. RGD, MCT, TIT ...gas fields); representing +/- 10-12% of proven GIIP resources.

- Glaciogenic deposits are among the most complex HC reservoir plays to address, especially in term of spatial heterogeneity (e.g. thickness, facies, reservoir quality, subsidiary glacial erosive surfaces (GES), nested sedimentary units ...etc...); deserving cautious interpretations and frequent disappointing E&P results.

- Recent Petroleum System results for the Llanura Chaquena seem to point out that Carboniferous series may have an attractive exploration potential (stratigraphic traps)

- This talk will try to put some lights on these glaciogenic Carboniferous deposits by presenting:
  - their sedimentological characteristics,
  - their internal stratigraphic organization
  - their subsequent prospectivity (potential plays/leads & associated risks)
Geological setting

- Paleozoic cratonic basin, shallow marine to glaciogenic settings coeval of relative quiescent tectonics
- Mesozoic unconformity, uplift of Izozog & basin borders, mainly continental setting
- NW/SE trending open folds during Late Cretaceous Paleocene
- Late Tertiary andean orogeny peripheral foreland evolution (e.g. forebulge, foredeep to foreland stages)

Llanura Chaquena Basin
- Carboniferous series
- Estructura de Izozog
- RGD-81
- Tertiary unit
Stratigraphic setting

- Glaciogenic succession dated from: Late Devonian (Late Famennian) to Late Carboniferous/Early Permian; 700 to 1200 m thick
- Complete succession made of 8 stacked formations later grouped into 2 main Groups of Formations
- At least 3 to 4 major glacial cycles ranging from Late Famennian (Devonian) to Early Permian

Paleo-icesheets configurations for Gondwana trough late Paleozoic

Synthetic log for Carboniferous glaciogenic series

Chronostratigraphic chart for Late Devonian & Permo-Carboniferous from Bolivia

Latitudinal occurrences of ice during palaeozoic (Giles, 2012)
Glaciogenic sedimentology, glacial sequence/cycle definition & complex stratigraphic architecture

- Facies model was obtained throughout an integrated sedimentological analysis of Late Devonian & Carboniferous glaciogenic deposits using:
  - Outcrop & core facies analysis + well data
  - Seismic stratigraphic & geomorphologic analysis of 3D analogs within studied area (MCT/RGD 3D cubes)

- Facies partitioning within Glaciogenic sequence, defined between 2 successive Glacial Erosive Surfaces (GES)

- Subsequent allostratigraphic subdivisions & resulting geometries

- The aim of this section relies on the description of complexity of glacial depositional setting and how to address this along HC exploration workflow
Glaciogenic depositional systems: Quaternary analogs

Glaciated basin: impact on bedrock of subglacial drainage system & glacially-cut topographies => distinctive sizes & scales of objects

Ice-streams (mega-valleys) & tunnel-valleys network on inter-ice-stream areas

North Sea shelf (late glacial maximum)

Norwegian Ice-stream

Tunnel-valley
Glacial Erosive Surfaces (GES) & glacially-cut topographies

Wherever you are looking, the base of any glacial depositional unit is marked by abrupt change in facies & high relief erosive surface of distinctive shape/size, a Glacial Erosive Surface (GES).

Valleys to valleys network of distinctive sizes/shapes:
- Narrow & locally branching valleys (tunnel valleys network)
- Mega-valley => ice-stream (> 10 km) separated by large interfluves (where tunnel valley may occur).
Facies model

- 5 facies main « atypical » sedimentary facies associations may be defined where facies ranging from subglacial, proglacial to periglacial settings

- Elementary sedimentary facies motif repetition where individual facies motif/sequence, bounded by 2 successive GES

Outcrop synthetic carboniferous section, Bermejo/Cuevas syncline, Santa-Cruz Dpmt; tied with nearby subsurface data (Rio-Seco, RSC-X6 well; ~30 km Eastwards)
Glaciogenic depositional systems

Conceptual generic model Glaciated shelf/basin

Glaciogenic depositional system is governed on 2 main controlling factors:
- Accommodation space created by « glacial » incision
- The behavior of meltwater circulation (i.e. perennial vs ephemeral), crucial for sediment nature partitioning
Glacial erosive surfaces (GES) and Glacio-tectonic units (GA1) deposited/formed as tillites, morainal banks & push-moraines

Heterolithic deposits (diamictites, breccias, conglomerates & sandstones) affected by intense glacio-tectonic deformations (push moraine ?, subglacial deformation tillites ?, tillites ?)
Subglacial glacio-fluvial depositionnal system represented by cross-bedded sandstones and conglomerates with superimposed abundant glacio-tectonic deformation (ice-recoupling phases) implying kink-folds & step-fractures.

GA2 Subglacial facies

Subglacial glacio-fluvial facies (sand-prone tractionnal deposits, subordinate debrites (diamictites) & glaciotectonic overprint) deposited beneath ice-sheets due to meltwater circulation.
Sand-prone infill of glacial valley as massive sandstones (as red/white amplitudes) filling valley envelop

Subglacial heterolithic infill of glacial valley as patch of sandstones (red amplitudes) encased within diamictites (blue amp.)

Intra Machareti surface (subsidiary GES surface) + Horizon slice-2390 ms

Inferred reservoir geometry

Raw amplitudes

1-5 km

NW SE

Intra Machareti surface (subsidiary GES surface) + Horizon slice-2480 ms

Inferred reservoir geometry

Raw amplitudes

1-5 km

Subglacial sdet Outwash sdet.

Diamictites

Base carboniferous (amalgamated surface) + Horizon slice-2480 ms

Inferred reservoir geometry

Raw amplitudes

1-5 km

Subglacial sdet Diamictites
GA3 proglacial facies: Ice-contact to Outwash fan/delta

Proglacial outwash fan /ice-contact fan sand-prone facies made of:

- high-energy long-lived sustained flows (flood-dominated; massive, cut-&-fill, climbing dunes & antidunes structures);
- subordinate diamictites

Svalbard Glacier analog; Dowsedell et al., 2015
In front of a subglacial melt-water portal (e.g. tunnel valley/channel mouth/outlet) 

Ice-contact/outwash fan (pro-glacial) modified from Deschamps et al., 2013

GA3b facies association; high density pro-glacial turbidites. A- well stratified unit of GA3a FA showing sandstone/diamictite alternations. B- detail view of a massive to supercritically climbing ripples. C- dewatering features at top individual bed. D – High energy parting lineations and pebbles at base of unit. E – Load cast structures at base of individual bed.

GA3 proglacial facies: Distal outwash fan/delta
Outwash fan / ice-contact fan sand-prone facies depositional system observed in horizon-slices from RGD & MCT 3D data

Sand-prone units formed at mouth of subglacial drainage system but of different spatial extension

Svalbard Glacier analog, Dowseell et al., 2015
GA5 Varva-like shale prone-facies; occasional dropstones and/or sandstones droplets, subordinate dilute turbiditic fine grained-beds and marine and/or lacustrine ? bioturbations such rocks if preserved from erosion are acting as efficient internal seal rocks within glaciogenic package.
Glaciogenic sequence

Use of MCT data set for definition of glaciogenic sequence based on observations of well developed cycle at base of Carboniferous (Machareti/Tupambi)

Shape of Base Carboniferous GES surface: «Tupambi» Valleys

Glacially-cut topography corresponds to a NW/SE oriented megavalley/ice-stream and ~perpendicular 3 tributary smaller valleys (tunnels)

~10 km

RMS-X1
MCT-X2
Shape of Base Carboniferous GES surface: «Tupambi» Valleys

Iquiri Ghost => Base-Tupambi
Base-Tupambi => "T2 horizon"
At early stage of infill, deposition is dominated by:
- Subglacial channels sandstones
- Subordinates diamicites

Only central ice-stream/megavalley & RMS tributary valley (tunnel) are active
Glaciogenic sequence

Early retreat phase; increase of meltwater release

During early retreat deposition is dominated by:
- Subglacial channels sandstones within tunnel valleys
- Ice-contact fan sandstones and subordinates diamictites at ice-front

Megascale glacial lineations left by rapid retreat

Main valley as well as all tributary valleys are active feeding ice-contact deposit at ice-front

Subglacial drainage system

~ 10 km
Glaciogenic sequence

Seismic geomorphological results from bolivian Carboniferous glaciogenics (MCT data) contenders of Quaternary analogs from Scandinavia

Monte-Crasto dataset

- Megascale glacial lineations
- Subglacial meltwater channels
- Grounding line sediment wedge
- ~10 km

Graham et al., 2016 Ice streel related landscape & bedforms

Late Pleistocene analogue

- Ice proximal deposits at grounding line
- Subglacial drainage system
- ~10 km

Grounding line sediment wedge

Stable marine ice margin

Notched glacier margin

Rising turbulent plume

Ice proximal deposits (IPDs)

Ice-front (grounding line)
Glaciogenic sequence

Ice-front still-stand (+/- minor pulses)

Instable still-standing ice-front

Ice-front is retreating more slowly, with minor readvancing pulses creating morainal bank. Instable ice-front triggered alternatively gravity flows dominated sequences punctuated by sandy ice-contact fans.
Ice-front recession

Ice-front final retreat, increase of clastic supply creating progading sandy outwash fan/delta despite rising glacio-eustatic sea-level. In case of non-perenial meltwater delivery diamicite-prone sedimentation may occur.
Interglacial flooding; drowning of residual topography if any; shallow marine or lacustrine setting; basin free-of-ice;
T2/Itacuami deposition (laminites/varvas; +/- rainout & dropstones; subordinate dilute fine-grained turbidites may occur; bioturbations in fully marine conditions
Glaciogenic sequence

Relatively distal glacial shelf sedimentation (diamictites, granules-rich shales) disrupted by turbidites to proglacial outwash fan deposition; corresponding to distal influences of re-advancing ice-front
Renewed ice-maximum phase

Ice and meltwater participate to the erosion of former underlying glaciogenic deposits, creating valley network and onset of infill of newly created topographies
Stratigraphic architecture resulting from multiple ice-advance/retreat cycles

- If facies partitioning for 1 single glacial cycle/sequence may be complex ...what would be the results of stacking, amalgamation and/or even imbrication of multiple glacial cycles in the rock record?
Complex stratigraphic architecture

Multiple stacked or nested glacial sequences
Exemple from RGD 3D dataset

~ 10 km
Complex stratigraphic architecture

Multiple stacked or nested glacial sequences

Exemple from RGD 3D dataset

Preserved thickness of sequence

GDE map of Macheriti Cycle 2

~ 10 km
Main erosive pathways

Isochronochore (time-thickness) of preserved 3rd Machareti glacial cycle (ms TWT)

Preserved thickness of sequence

Multiple stacked or nested glacial sequences
Exemple from RGD 3D dataset

Complex stratigraphic architecture

~ 10 km

Mandiyuti erosion

Preserved thickness of sequence
GDE map of Machareti Cycle 3
Complex stratigraphic architecture

Multiple stacked or nested glacial sequences
Example from RGD 3D dataset
Multiple stacked or nested glacial sequences
Exemple from RGD 3D dataset

Complex stratigraphic architecture

Preserved thickness of Lower Mandiyuti
GDE map of Lower Mandiyuti

Isochronochore
(time-thickness)
of preserved
Lower part of
Mandiyuti
glacial cycle (ms TWT)

~ 10 km
Complex stratigraphic architecture

Multiple stacked or nested glacial sequences
Example from RGD 3D dataset

Preserved thickness of Upper Mandiyuti

GDE map of Upper Mandiyuti

Outwash channels and sandsheets

Glacial front (in retreat) Grounding line

~ 10 km
Multiple stacked/nested cycles

Complex depositional history where multiple erosively-based cycles create a resulting composite & complex reservoir geometries relying on:

- Intrinsic nature of valley infill (sand-prone or heterolithic)
- Preservation state of reservoir geobodies
- Connectivity &/or isolation issues to address regarding HC migration and trapping
Machareti (Late Dev./Early Carboniferous)

As previously said Machareti corresponds to a composite glaciogenic rock package where at least 3 glacial cycles may be locally amalgamated.

Regional map shows 2 imbricated main directions of valley paths:
- N/S to NW/SE (1st or major phase)
- ~E/W (tributary or from other phase)
Mandiyuti Group (Late Carboniferous)

Mandiyuti corresponds a priori to a «unique» major glacial advance/retreat cycle, certainly pulsed.

Regional map shows a partly anastomosed network where:

- major large-scale valleys (>10 km wide) separated by large interfluve zones are lying on a NW/SE direction
- Tributary (linked to main network) and/or isolated smaller valleys are occupying interfluve areas

Complex stratigraphic architecture
Glaciogenic plays/leads characterization

- Mainly erosively based valley-shaped geobodies as reservoir plays; +/- discontinuous & disconnected

- Distinctive types of plays/leads
  - Structural linked to pre-andean open-folds (Late Cretaceous-Paleocene)
  - Stratigraphic: object-based pinch-out under unconformity
  - Combined

Composite Seismic line as key example for play/lead definition

Gas accumulations (proven)
Potential HC accumulations (leads)
Integration of results from first petroleum system simulation:

Most of the HC expulsion occurs before the Cretaceous (post-stratigraphic traps)

A secondary expulsion phase occurs during the late Cenozoic (Andean Phase)

Late Cretaceous/Paleocene deformation implies folding of charged Paleozoic structures/traps if existing

Basin modeling results at that preliminary stage of basin analysis gave rise to:
• the delineation of areas of preferential HC accumulations (structural closures)
• the constrain of main migration pathways.

Both will be regarded for Carboniferous leads characterization.
Structurally closed glaciogenic rock package (subglacial & outwash sands) sealed by pro- to interglacial shale-prone units within Late Cretaceous open anticlines (RGD, MCT, TIT... etc...)

Those plays have been already drilled with success except Aguila/Canada-Honda structure; such results may be possibly due to lack of significant reservoir rocks or enhanced connectivity with younger drains at structure culmination (cf. inset)
Glacial-valley (tunnels) sand-prone or heterolithic infill as “finite” object independently of structural situation; potentially sourced by simulated HC migration pathways; sealed laterally & vertically by glaciogenic mud-prone strata (or even laterally by late Devonian marine shales (only valid for older Machareti objects)

Those plays/leads rest with relatively high risks regarding reservoir presence, 3D connectivity pattern, in respect of intrinsic mode of infill (diamicrite- vs sand-prone) and stacking pattern of glacial cycles
Glacial-valley (tunnels) as object lead (example)

Carboniferous glaciogenic play sketch

Glaciogenic rock package (subglacial & outwash sands)
sealed by pro- to interglacial shale-prone unit
within (Late Cretaceous) or against open anticlinals
(structural closure)

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Amplitude anomalies/Bright spot => DHI?
Carboniferous glaciogenic play sketch

Glacial valley sandy-infill (subglacial facies) and/or glaciogenic assemblage (outwash+subglacial) truncated (»pinch-out«) by Base Mesozoic (&/or even Base-Cenozoic Unc.) capped by younger «sealing» rock unit (Ichoa heteroliths; Tertiary Yecua,...). Occur as +/- continuous belt along subcrop of Carboniferous Series.

Those plays/leads rest with relatively high risks regarding reservoir occurrence, sealing capacity of overlying formations and migration/trap formation relative timing.
Glacial-valley (tunnels) pinch-out below Mesozoic unconformity (example)

Carboniferous glaciogenic play sketch

- Shale-prone Ichoa Formation acting as regional seal
- Glacial valley pinch-out (tunnels) below Base Mesozoic

Isolated Escarpment valley shape (twt) below Base Mesozoic

Isochonochore (Twt ms) of valley object (450 to 300 ms, i.e., ~250 to 500 m)
Preliminary results of prospectivity assessment: Combined Carboniferous glaciogenic play/lead map for Llanura Chaquena.
De-risking of identified leads

Seismic lines/volumes will be converted into lithofacies volume to address in details spatial partitionning of reservoir/seals occurrences. .....with 3D seismics direct extraction of geobodies is possible.

Link between sedimentological facies, petrophysics and geophysics by electrofacies computation and seismic inversion, to obtain lithofacies and/or lithofacies + fluids.

Rousse et al., in prep. Late Ordovician deglacial sequence 3D sedimentary model: a subsurface fully-integrated approach (Wet Basin, Algeria).
Conclusions & way-forward

Carboniferous glaciogenic plays are certainly non trivial, risky & even “tricky” by many ways:

- Multiple glacial cycles each associated with their own internal complex geometries/facies partitioning
- Reciprocal geometrical relationships between cycles, as stacked and/or nested stratigraphy, lead to differential preservation states of stratigraphic elements as well as chaotic connectivity or isolation issues
- A particular typology of the associated HC exploration plays/leads

The Future of exploration for “Carboniferous” glaciogenic plays relies on:

- The rundown of uncertainties by dedicated knowledge re-enforcing (outcrop, core data)
- The follow-up and deepening of the mapping for any stacked/nested cycles at regional scale (or at least within HC potential accumulation areas) to address & delineate more leads/plays
- The accurate de-risking process for the identified/delineated plays/leads using:
  - Petroleum system assessment encompassing the existing complex reservoir/seal geometries defined
  - Petro-acoustic &/or petro-elastic analysis using nearby well data as analogs, to access spatial partitioning of facies and/or facies+fluid-content of identified exploration targets
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