Proppant Prospects for Bauxite

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Global Head of Research, Industrial Minerals
Industrial Minerals

Since 1967, from mine to market: global non-metallic minerals intelligence
Outline

1. Proppants & hydraulic fracturing snapshot
2. Evolution of fracturing
3. Fracturing process
4. Proppant types
5. Ceramic proppants & raw material feedstock
6. Market demand trends
7. Summary & conclusions
Bauxite & alumina supply chain context

Source: Hill & Sehnke 2007
Bauxite & alumina supply chain context

Source: Hill & Sehnke 2007
Proppants & Fracturing Snapshot
Drilling for oil and gas – unconventional deposits

Proppants & Fracturing Snapshot
Drilling for oil and gas

Source: API
Source: Geological Society London
Proppants & Fracturing Snapshot

Drilling for oil and gas

- Propping agent = “proppant”
- Props open fracture
- Permits oil/gas flow (conductivity)

Hydraulic Fracturing

Hydraulic fracturing, or “fracing,” involves the injection of more than a million gallons of water, sand, and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer, in this case the Marcellus Shale, to crack. These fissures are held open by the sand particles so that natural gas from the shale can flow up the well.
Evolution of fracturing
1860-1970: early days, small volumes proppant

1860s “oilwell shooting”

1947 Harris/Clark Stanolind Oil & Gas Co., Hugoton, KS 20,000 lbs sand

mid-1950s more patents; 3,000 wells/mth; 400 lbs sand, 20/40 mesh

1968 1st 1.5m lb frac, Pan American Petroleum Corp.

1930s “well acidizing”; “pressure-parting”

1949 patent filed; excl. lic. Halliburton, Stephens OK, Orchard TX; 100-150 lbs, 332 wells; 75% up in output

mid-1960s water as standard; additives; higher volume proppants, & coarser
Evolution of fracturing
1980-present: technology matures, larger volumes

- **1981** George Mitchell Barnett Shale, TX
- **1984** First resin coated proppant
- **1983** First ceramic proppant used
- **1990-99** Mitchell Energy perfected use of proppants + water in horizontal wellbores
- **2000** ceramic and resin coated proppants to exceed 1bn lbs/yr
- **2008+** >50,000 frac stages completed worldwide, 8-40 frac stages/well; US oil production increased by est. 30% and gas 90%; average 60,000 gal, 100,000lbs sand/well, to >1m gal and 4-6m lbs proppant/well
Evolution of fracturing
Past

17 March 1949
Duncan, OK
1st fracturing by Halliburton for Stanolind Oil Co.

Source: Montgomery & Smith 2010
Evolution of fracturing
Present

Source: Baker Hughes
Evolution of fracturing

Present
Evolution of fracturing

Present
Fracturing process
Porosity & permeability in target formations

Source: Claude Cooke 2012
Fracturing process
Operational depth perspective

Drinking water aquifer<br>&lt;1,000 ft (305 m)

8,000 ft (2,438 m)

Target rock formation<br>10,000 ft (3,048 m), fractures extend '00s ft

Source: Baker Hughes
Fracturing process
Several methods of fracturing

Source: Claude Cooke 2012
Fracturing process

Summary

Typical fracturing treatment involves:

• acid stage
• pad stage
• proppant stage
• flush stage

• start at 5-8lb/gal, end with 20lb/gal
• horiz. well could be 1.6km, take a month
• fracturing can take 1dy-1wk
• pumping – hydraulic horsepower (hhp) was 75hhp now >1,500hhp sometimes >10,000hhp
• oil prod rate was 2-3 bbl/min, to 20 bbl/min in 1960s, now >100 bbl/min
Fracturing process
Typical pad or frac fleet
Fracturing process
Example: Priobskoe oilfield, Western Siberia

Largest fracturing treatment = 661,500lbs ceramic proppant @ 10,000HP
Fracturing process
Fracturing fluid typical components

Source: Talisman Energy
Fracturing process
Fracturing fluid typical components

<table>
<thead>
<tr>
<th>Component</th>
<th>Water (%)</th>
<th>Propy (%</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline silica</td>
<td>94.59684%</td>
<td>9.82941%</td>
<td>89.50915%</td>
</tr>
<tr>
<td>Hydrochloric Acid</td>
<td>0.60824%</td>
<td>0.06320%</td>
<td>0.67144%</td>
</tr>
<tr>
<td>Distillates (petroleum), hydrotreated lig</td>
<td>0.41782%</td>
<td>0.04341%</td>
<td>0.46123%</td>
</tr>
<tr>
<td>Alcohol ethoxylate C-10/16 with 6.5 EC</td>
<td>0.05223%</td>
<td>0.00543%</td>
<td>0.05766%</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.03300%</td>
<td>0.00343%</td>
<td>0.03643%</td>
</tr>
<tr>
<td>Ethane-1,2-diol</td>
<td>0.02846%</td>
<td>0.00296%</td>
<td>0.03142%</td>
</tr>
<tr>
<td>Organic Phosphonate</td>
<td>0.02212%</td>
<td>0.00230%</td>
<td>0.02442%</td>
</tr>
<tr>
<td>Sodium salt of aliphatic amine acid</td>
<td>0.02156%</td>
<td>0.00224%</td>
<td>0.02380%</td>
</tr>
<tr>
<td>Diatomaceous earth, calcined</td>
<td>0.02050%</td>
<td>0.00213%</td>
<td>0.02263%</td>
</tr>
<tr>
<td>Fatty acid amidoalkyl betaine</td>
<td>0.01785%</td>
<td>0.00184%</td>
<td>0.01969%</td>
</tr>
<tr>
<td>Propan-2-ol</td>
<td>0.00897%</td>
<td>0.00093%</td>
<td>0.00990%</td>
</tr>
<tr>
<td>Aliphatic acids</td>
<td>0.00617%</td>
<td>0.00064%</td>
<td>0.00681%</td>
</tr>
<tr>
<td>Aliphatic alcohols, ethoxylated #1</td>
<td>0.00617%</td>
<td>0.00064%</td>
<td>0.00681%</td>
</tr>
<tr>
<td>Calcium chloride</td>
<td>0.00474%</td>
<td>0.00049%</td>
<td>0.00523%</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>0.00474%</td>
<td>0.00049%</td>
<td>0.00523%</td>
</tr>
<tr>
<td>5-chloro-2-methyl-4-isothiazolin-3-one</td>
<td>0.00342%</td>
<td>0.00035%</td>
<td>0.00377%</td>
</tr>
<tr>
<td>Magnesium nitrate</td>
<td>0.00342%</td>
<td>0.00035%</td>
<td>0.00377%</td>
</tr>
<tr>
<td>Prop-2-yn-1-ol</td>
<td>0.00206%</td>
<td>0.00021%</td>
<td>0.00227%</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0.00205%</td>
<td>0.00021%</td>
<td>0.00226%</td>
</tr>
<tr>
<td>Ethoxylated alcohols</td>
<td>0.00199%</td>
<td>0.00021%</td>
<td>0.00220%</td>
</tr>
<tr>
<td>Ethoxylated alcohols #2</td>
<td>0.00199%</td>
<td>0.00021%</td>
<td>0.00220%</td>
</tr>
<tr>
<td>Synthetic organic polymer</td>
<td>0.00193%</td>
<td>0.00020%</td>
<td>0.00213%</td>
</tr>
<tr>
<td>Sodium hydroxide (impurity)</td>
<td>0.00180%</td>
<td>0.00019%</td>
<td>0.00199%</td>
</tr>
<tr>
<td>2-Methyl-4-isothiazolin-3-one</td>
<td>0.00171%</td>
<td>0.00018%</td>
<td>0.00189%</td>
</tr>
<tr>
<td>Magnesium chloride</td>
<td>0.00171%</td>
<td>0.00018%</td>
<td>0.00189%</td>
</tr>
<tr>
<td>Sulfonated polystyrene</td>
<td>0.00051%</td>
<td>0.00005%</td>
<td>0.00056%</td>
</tr>
<tr>
<td>Tnsodium nitritonacetate (impurity)</td>
<td>0.00036%</td>
<td>0.00004%</td>
<td>0.00040%</td>
</tr>
<tr>
<td>Crystalline silica, cristobalite</td>
<td>0.00034%</td>
<td>0.00004%</td>
<td>0.00038%</td>
</tr>
</tbody>
</table>

Talisman Energy
Drill hole Altares, BC

**Total water vol.**
89% (37,201 m³ 37.2 m litres 9.82 m gallons)

**Sand**
9.8%

Source: Talisman Energy
Fracturing process
Global market & activity: treatments

Source: Dr Michael Economides 2011
Fracturing process
Global market & activity: US$ value

Source: Dr Michael Economides 2011
Fracturing process

Global market & activity: pumping capacity HHP

Source: PacWest; Manaar Energy
Proppant Prospects for Bauxite  Mike O’Driscoll

Proppant types
A variety of types have been used

“The ideal proppant is one that has:

• the specific gravity of water,
• the strength of iron,
• and is cheaper than dirt!”

- walnut shells
- silica sand
- ceramic proppants
- resin coated proppants
- fused zirconia
- plastic pellets
- steel shot
- glass beads
- aluminium pellets
- fly ash
Proppant types
The main large volume use types

- Silica sand (“frac sand”)
- Ceramic proppants
- Resin coated proppants
Proppant types
The main large volume use types

Silica sand ("frac sand")
Derived from silica sand deposits, high % SiO₂

Ceramic proppants
Derived mainly from calcined bauxite, kaolin, blends of bauxite & kaolin, also magnesium silicate
Proppant types

Proppant market share by volume (60bn lbs 2011)

- Silica sand ("frac sand") 80%
- Resin coated proppant 10%
- Ceramic proppant 10%

Source: Cadre Proppants
Proppant types
Proppant market share by value ($3.7bn 2011)

- Ceramic proppants: 49%
- Silica sand: 45%
- Other: 6%

Source: Freedonia 2011
Proppant types
Required functionality: enhance conductivity

- Conductivity of “proppant pack” has direct effect on deliverability of oil/gas to wellbore

- Good conductivity is the primary goal

- Conductivity = permeability of proppant pack x propped width

- Since conductivity is heavily influenced by propped width, which can be only estimated after treatment, most engineers use actual proppant permeability to choose between proppants.

Fracture width:
Proppant density, proppant loading, embedment, gel filter cake

Permeability:
Proppant size, strength, sphericity, fines, gel damage
Proppant types

Required functionality: enhance conductivity

Ceramic
- Uniform size/shape enhances conductivity of proppant pack

Silica sand
- Broadly sized, irregular shaped, tightly packed grains reduce conductivity

Increasing conductivity
**Proppant types**

**Proppant selection: general comments**

- Natural FS appropriate for reservoirs with 6,000 psi closure stress, i.e., depth of about 6,500 ft in shale gas reservoir.

- Ceramic proppants used in higher closure stress environments, invariably deeper reservoirs, can increase well stimulation by up to 30%;
  - stronger,
  - more uniformly dense
  - more spherical = better conductivity
  - more expensive
  - high strength, intermediate density, lightweight

- Resin coated proppants can enhance conductivity of FS & ceramic proppants; strengthens grain by spreading pressure load more uniformly; also traps pieces of broken grain preventing flowback to wellbore (grains also bond together under pressure to prevent flow back)
Proppant types
Proppant selection: performance comparison

<table>
<thead>
<tr>
<th>Proppant Type</th>
<th>Conductivity (md-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW ceramic proppant</td>
<td>~8,500</td>
</tr>
<tr>
<td>RC sand</td>
<td>~6,000</td>
</tr>
<tr>
<td>Northern White sand</td>
<td>~5,500</td>
</tr>
<tr>
<td>Texas Brown sand</td>
<td>~4,000</td>
</tr>
<tr>
<td>River sand</td>
<td>~500</td>
</tr>
</tbody>
</table>

Stress, psi (higher pressure from deeper wells)

Source: Carbo Ceramics
**Proppant types**

**Proppant selection: comparison of types**

<table>
<thead>
<tr>
<th></th>
<th>Frac Sand</th>
<th>Resin Coated Sand</th>
<th>Ceramic Proppant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductivity</strong></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Strength</strong></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Shape</strong></td>
<td>Irregular</td>
<td>Irregular</td>
<td>Uniform</td>
</tr>
<tr>
<td><strong>Well Type</strong></td>
<td>Low Pressure</td>
<td>Medium-High Pressure</td>
<td>High Pressure</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$</td>
<td>$$$</td>
<td>$$$$$</td>
</tr>
</tbody>
</table>

Source: AJ DeCenso, M-I Swaco 2013
Proppant types
Proppant selection: comparison of types

Increasing Cost $/lb

Source: Carbo Ceramics
Proppant types
Proppant selection: conductivity performance

Eagle Ford Shale Play (liquid)  Haynesville Shale Play (gas)

Example: February 2013

Bakken shale basin
Mackenzie county, North Dakota

20-30% wells fractured with ceramic proppants

Ceramic proppants 6x more expensive

$0.89/lb v $0.16/lb frac sand

Operators using blends of sand and ceramic proppants

Source: AJ DeCenso, M-I Swaco 2013
**Proppant types**

Proppant selection: comparison of plant economics

<table>
<thead>
<tr>
<th></th>
<th>Frac Sand</th>
<th>Ceramic Proppant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Rate</td>
<td>150 t/h</td>
<td>25 t/h</td>
</tr>
<tr>
<td>Plant Output</td>
<td>1,000,000 t/a</td>
<td>175,000 t/a</td>
</tr>
<tr>
<td>Unit Price</td>
<td>$70/t</td>
<td>$1,200/t</td>
</tr>
<tr>
<td>Annual Turnover</td>
<td>$70m</td>
<td>$200m</td>
</tr>
<tr>
<td>Investment</td>
<td>$35m</td>
<td>$100m</td>
</tr>
</tbody>
</table>

Source: AJ DeCenso, M-I Swaco 2013
Proppant Prospects for Bauxite  Mike O’Driscoll

Proppant types
Specifications

American Petroleum Institute
API RP 56
API RP 60

- Chemical composition
- Size fraction
- Roundness & sphericity
- Crush resistance
- Acid solubility
- Turbidity
Proppant types
Specifications: chemical composition

Frac sand
Quartz composition
99+% SiO₂

Ceramic proppants
Alumina composition
>50% Al₂O₃
Proppant types
Specifications: size fraction

<table>
<thead>
<tr>
<th>Sieve Opening Sizes (micrometers)</th>
<th>Frac Sand Size Designations</th>
</tr>
</thead>
<tbody>
<tr>
<td>3350/1700</td>
<td>b</td>
</tr>
<tr>
<td>2360/1180</td>
<td>b</td>
</tr>
<tr>
<td>1700/850</td>
<td>a</td>
</tr>
<tr>
<td>1180/600</td>
<td>b</td>
</tr>
<tr>
<td>850/425</td>
<td>a</td>
</tr>
<tr>
<td>600/300</td>
<td>b</td>
</tr>
<tr>
<td>425/212</td>
<td>a</td>
</tr>
</tbody>
</table>

90% to fall within range
Proppant types
Specifications: roundness & sphericity

Source: redrawn from Krumbein & Sloss 1955

API \geq 0.6
Proppant types

Specifications: crush resistance, acid solubility, turbidity

- **Crush resistance - high:**
  withstand compressive stresses of 4,000-6,000 psi
  max. fines wt.%:
  14% for 20-40, 16-30 mesh
  10% 30-50 mesh
  6% 70-40 mesh
  20% 6-12 mesh

- **Acid solubility - low:**
  – solubles (CO$_3$, fsp) usually washed out in processing
  in wt. %
  <2% 6-12 to 30-50 mesh
  <3% 40-70 to 70-140 mesh

- **Turbidity:**
  amount of silt-clay size minerals in sand
  – usually washed out in processing
Proppant types
Summary route components to ultimate goal

Select right quality of proppant

Specific to target formation & drilling environment

At economic delivered cost

To deliver desired level of economic conductivity

Proppant Cost + Logistics Cost
Ceramic proppants
Main properties & benefits

• **High strength**
  - minimises crush

• **Uniform size and shape**
  - maximises frac porosity and permeability

• **Thermally resistant**
  - durable, minimises degradation

• **Superior shape**
  - spherical, smooth proppants maximise porosity and streamline fluid flow.

• **Uniform particle size**
  - well-sorted, uniform grains provide large pore bodies and better flow capacity

• **Strong particles**
  - resist crush and compaction
Ceramic proppants
Main considerations

- Raw material quality
- Consistency of raw material quality & availability
- Manufacturing process
- Meeting chem/phys specifications
- Logistics
- Targeting proppant grade markets

Ceramic proppant grades
- LWC Lightweight
- IDC Intermediate density
- HDC High density
Ceramic proppants

Raw material feedstock

Primary raw materials
- bauxite
- kaolin
- bauxitic kaolin
- bauxite/kaolin blends

Alternative raw materials
- magnesium silicate: eg. serpentine, CCM, talc, brucite; proppant 64-72% SiO₂, 11-18% MgO; made from 30-40% serpentine aggregate, 60-70% quartz-feldspar sand, sintered at 1,140-1,190°C
- metabasalt
- “proppant grade clay” (not kaolin)
- nanostructured ceramic/glass proppants
- fly ash
- bauxite tailings

Additives:
- Diatomite
- Titanium dioxide
- Chromite
- Boron
- Magnetite
- Magnesia
- Manganese oxide
- Rare earth oxides
Ceramic proppants
Raw material feedstock

Selection depends on:

• required chem/phys properties of desired proppant grade
• manufacturing process – wet/dry, slurry, pelletising, sintering
• availability of raw materials
• many variations on blending bauxite/kaolin, and with additives
Ceramic proppants
Raw material feedstock: abrasive grade bauxite

<table>
<thead>
<tr>
<th>%</th>
<th>Abrasive</th>
<th>Refractory</th>
<th>Chemical</th>
<th>Metallurgical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>min. 55.0</td>
<td>min. 59-61.00</td>
<td>min. 55-58.00</td>
<td>50-55.00</td>
</tr>
<tr>
<td>$\text{SiO}_2$</td>
<td>max. 5.00</td>
<td>max. 1.50-5.50</td>
<td>max. 5-12.00</td>
<td>0-15.00</td>
</tr>
<tr>
<td>$\text{Fe}_2\text{O}_3$</td>
<td>max. 6.00</td>
<td>max. 2.00</td>
<td>max. 2.00</td>
<td>5-30.00</td>
</tr>
<tr>
<td>$\text{TiO}_2$</td>
<td>min.2.50</td>
<td>max. 2.50</td>
<td>0-6.00</td>
<td>0-6.00</td>
</tr>
</tbody>
</table>

Source: Errol Sehnke, USGS, 1995

- not as strict as refractory grade
- flexibility with iron, not critical
- low silica and alkalies ($\text{CaO} <0.1$ to minimise glass phase)
- supply sources: Australia, Brazil, China, Greece, Guinea, Guyana, Italy
**Ceramic proppants**

**Raw material feedstock:** known specification examples

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bauxite</strong></td>
<td>70% $\text{Al}_2\text{O}_3$ for IDC grade</td>
</tr>
<tr>
<td></td>
<td>$70% \text{Al}_2\text{O}_3$, $25.5% \text{SiO}_2$, $0.61% \text{Fe}_2\text{O}_3$, $3.82% \text{TiO}_2$</td>
</tr>
<tr>
<td></td>
<td>$55-71% \text{Al}_2\text{O}_3$, $7-16% \text{SiO}_2$, $1.5-19% \text{Fe}_2\text{O}_3$, $2.5-3.8% \text{TiO}_2$</td>
</tr>
<tr>
<td><strong>Bauxite (calcined)</strong></td>
<td>82% $\text{Al}_2\text{O}_3$, $7% \text{SiO}_2$ (Australia)</td>
</tr>
<tr>
<td>+Kaolin</td>
<td>$52% \text{Al}_2\text{O}_3$, $45% \text{SiO}_2$</td>
</tr>
<tr>
<td>+Bayer alumina fines (dust</td>
<td>$99% \text{Al}_2\text{O}_3$</td>
</tr>
<tr>
<td>collector by-product)</td>
<td></td>
</tr>
<tr>
<td><strong>Calcined kaolin (75-90%)</strong></td>
<td>45.60% $\text{Al}_2\text{O}_3$, $51.21% \text{SiO}_2$, $0.96% \text{Fe}_2\text{O}_3$</td>
</tr>
<tr>
<td>+Calcined diatomaceous earth</td>
<td>4.37% $\text{Al}_2\text{O}_3$, $87.51% \text{SiO}_2$, $1.91% \text{Fe}_2\text{O}_3$</td>
</tr>
<tr>
<td>(5-10%)</td>
<td></td>
</tr>
<tr>
<td><strong>Bauxite (55%)</strong></td>
<td>85% $\text{Al}_2\text{O}_3$, $7% \text{Fe}_2\text{O}_3$</td>
</tr>
<tr>
<td>+Kaolin (45%; + iron oxide, 7%)</td>
<td>45% $\text{Al}_2\text{O}_3$, $1% \text{Fe}_2\text{O}_3$</td>
</tr>
<tr>
<td><strong>Bauxite/kaolin blend</strong></td>
<td>72% $\text{Al}_2\text{O}_3$ total for IDC grade</td>
</tr>
<tr>
<td><strong>Kaolin</strong></td>
<td>48% $\text{Al}_2\text{O}_3$ for LWC grade</td>
</tr>
<tr>
<td></td>
<td>$45-50% \text{Al}_2\text{O}_3$, $&lt;0.13% \text{S}$, $&lt;1.0% \text{Fe}_2\text{O}_3$, $&lt;1.0% \text{K}_2\text{O}$</td>
</tr>
<tr>
<td><strong>“Alumina clays”</strong></td>
<td>41.5-49.0% $\text{Al}_2\text{O}_3$ by wt. calcined basis</td>
</tr>
</tbody>
</table>
# Ceramic proppants

Raw material feedstock: main producers

<table>
<thead>
<tr>
<th>Producer</th>
<th>Plant locations</th>
<th>Capacity (m lbs)</th>
<th>Raw material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbo Ceramics</td>
<td>Eufaula, AL</td>
<td>275</td>
<td>kaolin</td>
</tr>
<tr>
<td></td>
<td>McIntyre, GA</td>
<td>275</td>
<td>kaolin &amp; bauxite</td>
</tr>
<tr>
<td></td>
<td>Toomsboro, GA</td>
<td>1,000</td>
<td>kaolin</td>
</tr>
<tr>
<td></td>
<td>Millen, GA (Q1 2014)</td>
<td>(500)</td>
<td>kaolin &amp; bauxite</td>
</tr>
<tr>
<td></td>
<td>Luoyang, Henan, China</td>
<td>100</td>
<td>kaolin &amp; bauxite</td>
</tr>
<tr>
<td></td>
<td>Kopeysk, Chelyabinsk, Russia</td>
<td>100</td>
<td>bauxite</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>1,750</td>
<td></td>
</tr>
</tbody>
</table>
# Ceramic proppants

## Raw material feedstock: main producers

<table>
<thead>
<tr>
<th>Producer</th>
<th>Plant locations</th>
<th>Capacity (m lbs)</th>
<th>Raw material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saint-Gobain Proppants</td>
<td>Fort Smith, AR</td>
<td>265e</td>
<td>bauxite/kaolin</td>
</tr>
<tr>
<td></td>
<td>Saline, AR (Q4 2012)</td>
<td>300e</td>
<td>bauxite</td>
</tr>
<tr>
<td></td>
<td>Puerto Ordaz, Venezuela</td>
<td>110e</td>
<td>bauxite</td>
</tr>
<tr>
<td></td>
<td>Guanghan, Henan, China</td>
<td>176e</td>
<td>bauxite</td>
</tr>
<tr>
<td>Mineração Curimbaba Ltda</td>
<td>Pocas de Caldas, Minas Gerais</td>
<td>440-660e</td>
<td>bauxite</td>
</tr>
<tr>
<td>Fores LLC</td>
<td>Sukhoy Log, Chelyabinsk, Russia</td>
<td>580</td>
<td>bauxite mag-silicate</td>
</tr>
<tr>
<td>JSC Borovichi Refractories Plant</td>
<td>Borovichi, Novgorod, Russia</td>
<td>440</td>
<td>kaolin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bauxite</td>
</tr>
<tr>
<td>Imerys</td>
<td>Andersonville, GA</td>
<td>220</td>
<td>bauxitic kaolin</td>
</tr>
<tr>
<td>Shamrock Proppants LLC</td>
<td>Wellsville, MO</td>
<td>--</td>
<td>kaolin</td>
</tr>
</tbody>
</table>
Ceramic proppants
Raw material feedstock: Chinese producers

All use bauxite except for Carbo Ceramics (China) which also uses kaolin.

>100 plants, 20-30 “main” producers 20,000-210,000 tpa ceramic proppant plant capacities
Ceramic proppants
Raw material feedstock: Chinese producers

• est. 400-500,000 tpm output ceramic proppants

• 2012: 25% exported to N. America – 30 “shippers” supplied by 10-12 plants

Carbo Ceramics (China) Co. Ltd
China Ceramic Proppant (Guizhou) Ltd
China Gengsheng Minerals Inc.
CMEC Proppant
CMP Xiuwen Mining Development Co. Ltd
Dayang Ceramic Proppants Co.
Fujian Raystone New Material Co. Ltd
GDG Ceramic (Gongda Group Ltd)
Guizhou ChengQian Metallurgical Material Co. Ltd
Handan Shenghuo Ceramic Proppant Co. Ltd
Hebei Ceramic Proppant Co. Ltd
Inner Mongolia Yidong Petroleum Fracturing Proppant Co. Ltd
Jiaozuo FangHua Ceramics Co. Ltd
Junoda
Luoyang Maide Ceramics Co. Ltd

Pingxiang Chemshun Ceramics Co., Ltd
Proppant Plus LLC/Kailiton International
Saint-Gobain Proppants (Guanghan) Co. Ltd
Santrol (Yixing) Proppant Co., Ltd
Shanxi Fengshuo Ceramic Proppant Co. Ltd
Shanxi Tianyi Ceramic Proppant Co. Ltd
Shanxi Yangquan Tianhong Oil Fracturing Support Agent Co. Ltd
Tao Ceramics
Xinan Tengfei Oil Fracturing Proppant Ltd
Xinmi Wanli Industry Development Co. Ltd
Xinyineng Fracture Proppant Co. Ltd
Yangquan Changqing Proppant Corp.
Yixing Orient Petroleum Proppant Co. Ltd
Yixing Tengfei Oil Fracturing Proppant Co., Ltd
Yu Feng Ceramic Proppant
Zhengzhou Yuxiang Ceramic Sand Co., Ltd
Ceramic proppants
Raw material feedstock: proppant plant proximity

- Bauxitic kaolin, AL
- Bauxite, AR
- Kaolin, GA
- Carbo Ceramics, AR, AL
- Imerys, GA
- Saint-Gobain, AR
- Pyramax, GA

- Kaolin, Borovichi-Lyubytsinsk, Novgorod
- Borovichi

- Bauxite, Urals, Magnesite, Chelyabinsk
- Fores, Chelyabinsk

- Bauxite, Henan, Guizhou, Shanxi
- 30+ producers

- Bauxite, MG
- Mineracao Curimbaba, MG

- Bauxite, kaolin, north India
- Hallmark, Pune

Source: adapted from Hill & Sehnke 2007
Ceramic proppants
Raw material feedstock: bauxite geology

Classification by deposit shape: blanket & interlayered

Source: Hill & Sehnke 2007
Ceramic proppants
Manufacturing process

Feedstock mineral(s) → Extrusion → Calcining Kiln → Cooling Drum → Milling → Classification → Binder Mixing → Pelletization → Green Pellet Screen → Sintering Kiln → Cooling Drum → Grading Screen → Proppant

Variations:
wet process, slurrying prior to binder mixing; fluidizer sprays slurry onto seed particles prior to sintering

Source: AJ DeCenso, M-I Swaco 2013

Proppant Prospects for Bauxite  Mike O'Driscoll
Ceramic proppants
Manufacturing process: mixing & pelletising

Eirich Intensive Mixer: R-series
Ceramic proppants
Manufacturing process: mixing & pelletising

Process technology: Build-up agglomeration

Dry mixing  Liquid addition  Agglomeration  Finished

Primary grain size distribution  "Blackberry" structure

Source: AJ DeCenso, M-I Swaco 2013
Ceramic proppants
Manufacturing process: mixing & pelletising

Chinese proppant feedstock mixers
## Ceramic proppants
### Types & properties

<table>
<thead>
<tr>
<th>Ceramic proppant grade examples (Carbo Ceramics)</th>
<th>LWC Lightweight ceramic proppant</th>
<th>IDC Intermediate density ceramic proppant</th>
<th>HDC High density ceramic proppant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>kaolin</td>
<td>bauxite</td>
<td>bauxite</td>
</tr>
<tr>
<td>Apparent SG</td>
<td>2.71</td>
<td>3.27</td>
<td>3.56</td>
</tr>
<tr>
<td>Bulk Density (g/cm³)</td>
<td>1.57</td>
<td>1.88</td>
<td>2.00</td>
</tr>
<tr>
<td>Alumina %</td>
<td>51.0</td>
<td>72.0</td>
<td>83.0</td>
</tr>
<tr>
<td>Silica %</td>
<td>45.0</td>
<td>13.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Iron %</td>
<td>1.0</td>
<td>10.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Titania%</td>
<td>2.0</td>
<td>4.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Ceramic proppants
Raw material feedstock: Chinese proppants

### Comparison of Bauxite Proppant Chemistry

<table>
<thead>
<tr>
<th>Chemistry (%)</th>
<th>CarboHSP</th>
<th>CarboProp</th>
<th>SinterBall</th>
<th>SinterLite</th>
<th>China MD</th>
<th>China LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>83 %</td>
<td>72 %</td>
<td>76.5 %</td>
<td>71.7 %</td>
<td>70~75 %</td>
<td>60~70 %</td>
</tr>
<tr>
<td>$\text{SiO}_2$</td>
<td>5 %</td>
<td>13 %</td>
<td>5.3 %</td>
<td>12.8 %</td>
<td>10~15 %</td>
<td>15~25 %</td>
</tr>
<tr>
<td>$\text{TiO}_2$</td>
<td>3.5 %</td>
<td>4 %</td>
<td>1.8 %</td>
<td>1.8 %</td>
<td>2~3 %</td>
<td>2~3 %</td>
</tr>
<tr>
<td>$\text{Fe}_2\text{O}_3$</td>
<td>7.0 %</td>
<td>10 %</td>
<td>15.5 %</td>
<td>13.0 %</td>
<td>4~6 %</td>
<td>4~6 %</td>
</tr>
<tr>
<td>Other</td>
<td>1.5 %</td>
<td>1 %</td>
<td>0.9 %</td>
<td>0.7 %</td>
<td>3~5 %</td>
<td>1~3 %</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.56</td>
<td>3.27</td>
<td>3.62</td>
<td>3.25</td>
<td>3.15</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Source: Gene Kim, AM2F energy 2013
Ceramic proppants
Raw material feedstock: Chinese proppants
lower quality but developing

Source: Carbo Ceramics
Ceramic proppants
Specification variation: alumina content of ND IDC

68-85% Al₂O₃

Source: Terry Palisch, Carbo Ceramics 2012
Ceramic proppants

Specification variation: apparent SG of ND IDC

Source: Terry Palisch, Carbo Ceramics 2012
Ceramic proppants
Density significance

**Bulk Density**
- How many lbs of proppant will fill a given volume?
- Proppants purchased by mass, not volume
- Important for final fracture geometry

*If a fracture can be filled with 100,000 lbs of sand, RCS, or LWC:*

*It will require purchase of 120,000 lbs of IDC, or 130,000 lbs HDC*
Market demand trends
Drivers: unconventional oil & gas development, the “Dash for Gas” – an LNG future
Market demand trends
Drivers: unconventional oil & gas development

Population, industrialisation drives energy demand and growth
Market demand trends
Drivers: unconventional oil & gas development

We still expect global energy demand to grow – by 36% between 2011 and 2030 - driven by the emerging economies.

Supply patterns are shifting…unconventional oil and gas are playing a major role in meeting global demand.

From 2011 to 2030 shale gas more than trebles and tight oil grows more than six-fold. Together they will account for almost a fifth of the increase in global energy supply to 2030.
Market demand trends
Drivers: unconventional oil & gas development

Primary energy share – fossil fuel dominance expected to continue

*Includes biofuels

BP Energy Outlook 2030
Market demand trends
Drivers: unconventional oil & gas development

Demand & quest for low cost fossil fuel energy sources
May 2012: IEA
World Energy Outlook – Golden Rules for a Golden Age of Gas

World primary energy demand by fuel in “Golden Rules” case
Market demand trends
Drivers: unconventional oil & gas development

May 2012: IEA
*World Energy Outlook – Golden Rules for a Golden Age of Gas*

- World production of unconventional gas, primarily shale gas, more than triples between 2010 and 2035 to 1.6 trillion cu metres
- USA becomes a significant player in international gas markets
- China emerges as a major gas producer
- Faster growth in global gas demand, rising >50% between 2010 and 2035.
Market demand trends
Drivers: unconventional oil & gas development

Shale gas production by region and LNG exports to 2030
Market demand trends
Drivers: unconventional oil & gas development

Energy production by region to 2030
Market demand trends
Drivers: unconventional oil & gas development

Shale gas and tight oil resources & production to 2030

Graph showing current resources and production in 2030 for different regions.
Market demand trends
Drivers: unconventional oil & gas development

EIA US energy consumption outlook to 2035
Market demand trends
Drivers: unconventional oil & gas development

Shale gas “revolution” & boom for fracturing in N. America late 2000s
Market demand trends
Drivers: unconventional oil & gas development

Increased exploration and horizontal drilling = rise in proppant demand

Source: Baker Hughes
Market demand trends
Drivers: unconventional oil & gas development

Increased exploration and horizontal drilling = rise in proppant demand

Barnett, Texas shale gas boom 1997 compared to 2009
Market demand trends
Drivers: unconventional oil & gas development
Going global: China, Australia, Middle East, Latin America, Europe
Market demand trends
Drivers: unconventional oil & gas development
China: huge potential

<table>
<thead>
<tr>
<th>Institution</th>
<th>Shale Resource Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Energy Information Administration</td>
<td>1,274.85 tcf</td>
</tr>
<tr>
<td>International Energy Agency</td>
<td>918.18 tcf</td>
</tr>
<tr>
<td>China Ministry of Land and Resources</td>
<td>886 tcf</td>
</tr>
<tr>
<td>China National Petroleum Corporation</td>
<td>1,084 tcf</td>
</tr>
</tbody>
</table>

12th Five-Year Plan [2011-2015]:
- 6.5 bcm shale gas production by 2015
- 2-3% of projected 2015 Chinese gas production
- >60 bcm shale gas production by 2020
- Widespread domestic ceramic proppant sources established and developing

Source: CSIS
Market demand trends
Drivers: unconventional oil & gas development

Australia: aiming to become LNG leader – needs gas development

- Ambitious LNG projects ahead of feedstock gas
- Coal seam gas, shale gas
- Limited frac sand sources, no ceramic proppant sources
Market demand trends

Drivers: unconventional oil & gas development

Middle East: new era, unconventional development imminent

- gas projects in Kuwait, Iraq
- Aramco training staff in US on fracturing unconventional; pledged huge unconventional expl/dev strategy
- no ceramic proppant sources

- Large potential for new conventional and unconventional gas resources

Source: Robin Mills, Manaar Energy, Oilfield Minerals Outlook: Middle East 2013
Market demand trends

Drivers: unconventional oil & gas development

South America: Argentina, Brazil show promise

- Argentina 3rd in world after US, China for potentially recoverable shale gas reserves, 774 tcf
- investment required
- geology & infrastructure “there”
- Chevron j-v expl. deal
- Ceramic proppant source: Brazil
Market demand trends
Drivers: unconventional oil & gas development
Europe: the debate rages on – geopolitical/technical factors

Pushing ahead:
- Estonia
- Hungary
- Lithuania
- Poland
- Romania
- UK
- Ukraine

Potential:
- Austria
- Bulgaria
- France
- Norway

Cer. prop. sources:
- Russia
- Imports
Market demand trends
Drivers: unconventional oil & gas development
Europe: the debate rages on – geopolitical/technical factors, all will be discussed at IM Roundtable:

Stationers’ Hall, London, 30 April 2013

Oilfield Minerals Outlook
Proppant Prospects for Europe
Market demand trends
Drivers: drilling technology developments

Ceramic proppant demand from:
- More horizontal drilling
- Longer well bores
- Bigger fracture treatments = more proppant demand
- More fracturing stages, eg. 40+
- Deeper wells: high pressure, high temperature (HTHP) environments
Market demand trends
Drivers: drilling/proppant developments

Schlumberger HiWAY
- “slugs” of proppant pumped down well
- synthetic fibres bond proppants together
- enhances conductivity
- uses 40% less proppant!
- Carbo ultra-high stress proppant new in 2013
- Imerys rod shaped proppants

Source: Schlumberger; Imerys
Proppant Prospects for Bauxite  Mike O’Driscoll

Market demand trends
Proppant supply developments: expansions

Frac sand frenzy!

Map of frac sand facilities in Wisconsin, October 2012

State of Wisconsin, USA

Frac sand operations:

115 permitted or proposed
95 permitted
20 at proposal stage

160% up on 2011

Source: Wisconsin Center for Investigative Journalism
Market demand trends
Proppant supply developments: expansions
Frac sand frenzy!

Rise of US silica sand used for fracking, well cements 2000-2011

Source: USGS data
Market demand trends
Proppant supply development: market growth

Total proppant market nearing 60bn lbs 2011

Source: Proptester Report 2011
Market demand trends
Proppant supply development: market growth

US proppant demand m. tons

- 2007: 10.0
- 2008: 15.0
- 2009: 20.0
- 2010: 25.0
- 2011: 30.0
- 2012: 35.0
- 2013: 40.0
- 2014: 45.0
- 2015: 50.0
- 2016: 55.0
- 2017: 60.0

Source: Warlick Energy 2012
Market demand trends

Proppant supply development: market growth

| International Frac Capacity (MM HHP) |
|---|---|---|---|---|---|---|---|
| 3.1  | 4.4  | 6.0  | 8.0  | 10.0 | 12.3 | 15.1 |

5-yr Growth 243%

Source: PacWest Consulting Partners; Manaar research

China

Other  MENA  Mexico  Argentina  Poland  China  Offshore  Australia  Russia
Market demand trends
Proppant supply development: expansions

Ceramic proppant developments:

**US new plants**
- Carbo Ceramics, Millen, GA, Q1 2014
- Imerys, Andersonville, GA, end-2012
- Saint-Gobain, Saline, AK, end-2012
- Pyramax, Wrens, GA, April 2013; 500m lbs year; +2 prod. Lines 2015

**China recent or ongoing expansions**
- China Ceramic Proppant (Guizhou) Ltd
- CMP Xiuwen Mining Development Co. Ltd
- Hebei Ceramic Proppant Co. Ltd
- Inner Mongolia Yidong Petroleum Fracturing Proppant Co. Ltd
- Luoyang Maide Ceramics Co. Ltd
- Xinyineng Fracture Proppant Co. Ltd
- Yangquan Changqing Proppant Corp.

**India planned expansion**
- Hallmark Minerals (I) Pvt Ltd
Market demand trends

Challenges: environmental, geopolitical, logistics, competitive raw materials

US logistics = 58% frac sand price

Source: Professional Logistics Group, July 2012
Market demand trends

Raw material feedstock: development opportunities

**Bauxite**
- First Bauxite, Bonasika deposit, Guyana
- Bosai Minerals, Linden, Guyana
- Imerys acquired former MSL Minerais bauxite reserves in Para, northern Brazil
- Many Chinese bauxite producers looking to diversify into proppants

**Other alumina sources**
- clays “not kaolin & bauxite” – Brownwood Clay Holdings, TX
- alunite - Potash Ridge, Blawn Mtn, UT
- waste products, fly ash
Summary & conclusions
Exciting era for the proppants market

• Future energy demand will require exploration & development of fossil fuel resources through to at least 2030

• Natural gas – through LNG – fast becoming favoured clean and efficient fossil fuel option, thus feedstock gas supply required

• Recent advances in drilling/fracturing/proppant technology has enabled exploration & development of unconventional oil/gas resources

• North America has witnessed boom in this industry, leads world, but other regions to follow, notably China, Australia, Middle East, S. America, Europe

• Both silica sand and ceramic proppants in high demand – each have grades specific to different drillhole requirements

• Ceramic proppants supply is, so far, limited to very few producers worldwide, this is likely to change as global demand increases
Summary & conclusions

Raw material feedstock opportunities for bauxite and alumina developments

- Bauxite and kaolin used as proppant feedstock raw material, few manufacturers hold captive supply, most buy feedstock
- Proppant grade range dictates selection of feedstock that must meet specs., but manufacturers are adaptable to use/change feedstock as/when required
- Most important to track fracturing trends, eg. liquids- v gas-rich target formations (affects grain size required), LWC favoured over IDC (less volume required for LWC) – driven by economics/strategy of E&P companies
- Situation is that there are few commercially developed sources of non-met. bauxite, thus demand for proppant grade bauxite competes with that for abrasive and refractory (and other) non-met. bauxite demands – compounded by perceived overall future bauxite supply tightness owing to China/Indonesia
- Clear opportunity for new/alternative bauxite/alumina sources to offer proppant feedstock options for future demand requirements from manufacturers
- Expect former non-met. bauxite sources to be re-evaluated, eg. Australia, Brazil, Guinea
- Note anticipated growth regions lacking in local proppant sources
Summary & conclusions

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Proppant prospects for bauxite/alumina are good!
Like to know more?
Mike O’Driscoll, IM Research, modriscoll@indmin.com

Thank you