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IAPG Congress, Instituto Argentina del Petroleo y del Gas
Buenos Aires, Argentina, 7-10 August, 2012

Environmentally Friendly Drilling Fluids for Unconventional Shale

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Abstract

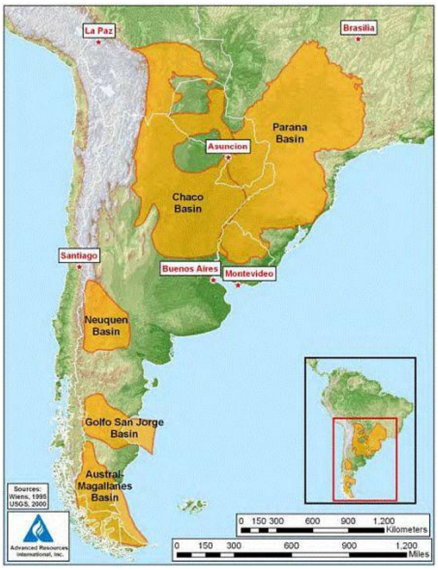
Although gas/oil shale vary considerably in terms of reservoir pressure, temperature, mineralogy and local stresses, the principal drilling-related issues are wellbore stability, hole cleaning and rate of penetration. Because most of the shale reservoirs are in environmentally sensitive and/or densely populated areas, the traditional shale inhibition method through either chemical inhibition or invert emulsions may not be enough to satisfy future environmental requirement, which will require new types of environment-friendly water-based drilling fluids.

This paper presents a new water-based drilling fluid and the associated test results for shale play drilling. It shows the design of an environmentally and economically acceptable fluid that meets stringent fluid performance, wellbore stability and drilling performance goals. The newly developed water-based mud is based on fresh water. Viscosity and fluid-loss are controlled with chloride free and environmentally-friendly products. Shale inhibition is provided using appropriately-sized nanoparticles by plugging the pores and micro-cracks in shale and preventing water invasion into the shale. Permeability reduction was used as a proxy of water invasion reduction into shale and thus the effectiveness of plugging of pores and micro-fractures in shale by nanoparticles. Many orders of permeability reduction were consistently observed for muds with nanoparticles for several oil/gas shale. Test results showed that although nanoparticles alone may be effective in preventing water invasion into shale samples with no micro-cracks, the combination of properly formulated mud and nanoparticles of appropriate material, size and concentration is the key to preventing water flow into shale samples with a wide range of initial permeability. This new water-based drilling fluid with nanoparticles provides an entirely different type of shale inhibition by physically plugging the shale micro-cracks and pores while meeting the strictest environmental regulations and the necessary lubricity for shale play drilling. This newly developed environmentally friendly water-based mud for unconventional shale drilling is under field trial and verification.

Introduction

Natural gas plays an important role in the global energy landscape both in North and South America as well as European and Asian markets. Shale gas is one of the most recent focuses for the source of natural gas in numerous countries including Argentina. According to the Annual Energy Outlook 2011, released in April of last year by the United States Energy Information Administration, Argentina is the country with the third highest geological potential for these types of hydrocarbons, after China and the United States. The study assessed the viability of 48 shale gas basins in 32 countries and estimated Argentina's shale gas reserves at 774 trillion cubic feet (TCF), 60 times greater than the country's current conventional reserves (**Figure 1**).

FIGURE 1 - Overview of Argentina Shale Gas Fields – (from Investment U article The Next Big Shale Gas Boom by Justin Dove, *Investment U* Research; Friday, October 7, 2011)



Shale gas is a natural gas produced from shale formations that typically acts as both a reservoir and source rock for the natural gas. Geologically, it is a sedimentary rock that is composed mostly of clay-sized particles. The very fine, sheet-like formation causes several wellbore stability issues during the drilling operation. When drilling in overbalanced conditions, mud pressure will penetrate progressively into the formation; due to a combination of saturation and low permeability, only a small volume of filtrate penetrates into the wellbore. This leads to an increase in pore fluid pressure near the wellbore and consequently a less stable wellbore condition is created. This is especially important in horizontal drilling which is largely used because of the ability to drain shale gas resources from a geographical area that is much larger than a vertical well due to the exposure of the targeted formation and reduces the traffic within the field. Generally, Oil Based Mud (OBM) is the preferred system used in these type wells due primarily to the wellbore stability of the long high angle/horizontal sections as well as the lubricity of the fluid and filtercake during horizontal drilling and running casing operations.

Wellbore stability in this type shale can be achieved using a Water Base Mud (WBM) by minimizing the fluid pressure penetration into the wellbore by physically plugging the pores of the shale. Commercially available fluid loss agents are not able to do this due to low level of fluid movement into the shale and thus cannot stop the invasion of fluid or water. Utilizing a technology comprised of nano-sized inert materials achieves the goal of wellbore stability quite successfully, thus providing a platform to formulation an environmentally friendly WBM which can address the requirements for drilling shale gas plays as well as any environmental concerns.

Background

The major drawback to OBM is the environmental issues that could be associated with the continuous phase (base oil; e.g. diesel) and the internal phase (brine) and thus problems associated with its disposal. Therefore the desire of many operators is to explore possibilities of using a WBM that may have similar performance advantages of an OBM, but a better environmental profile. The system described in this paper was developed with goals to meet the needs of various regions from an environmental and performance perspective: formulation based on fresh water which would avoid the use of chlorides (issues with disposal on land) and a straight-forward design for easy application with a low number of benign components.

When we think about wellbore stability with WBM in shale gas plays, we are dealing with a different type of "shale inhibition" then normally found. Shale in general has a high chemical reactivity with respect to hydration and swelling, therefore, a typical shale inhibitor such as amines or salts would be considered prime choices. With regard to numerous shale gas or shale oil plays, the reactivity of the shale is fairly low, and the issue that is dealt with typically is that this shale is considered a fissile shale. By this terminology, we mean that it is readily broken apart or deteriorated and not as chemically reactive as most gumbo or other shale types. In fact, the definition of shale is based not on reactivity but more on structure and particle size of the component rock. As an example, **Table 1** represents the typical geological composition and properties of Marcellus shale at a certain depth. The CEC value is relatively low, which is related to reactivity, as stated by the low smectite percentage.

Marcellus Shale Core	6711.05 – 6711.6 ft
Smectite	4%
Illite	25%
Quartz	47%
Feldspar	10%
Pyrite	5%
Chlorite	6%
Ankerite	3%
CEC, (meq/100gr)	3
Permeability (nd)	19 @ 3000 psi
Permeability (nd)	6 @ 6000 psi
Porosity	10%
Total organic content	9%

TABLE 1 Marcellus Shale Mineralogy

However, because of this fissile nature even with low permeability of shale, still a small volume of filtrate can penetrates into the wellbore, leads to an increase in pore fluid pressure near the wellbore. Consequently, this creates a less stable wellbore condition that, over time, can lead to significant wellbore stability problems. In **Figure 2**, a well-preserved Marcellus core was exposed to freshwater at 150°F. After several days, fractures with widths between 5 and 45 µm were observed, primarily parallel to the bedding plane. These results illustrate how the Marcellus shale, although, not very reactive to water in a chemical sense (e.g. swelling) still is prone to fracture destabilization, which can lead to wellbore instability, especially in long horizontal wells.

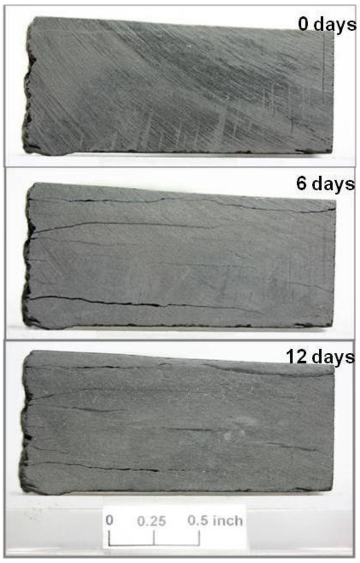


FIGURE 2 Marcellus Shale Micro-Fracturing in Freshwater at 150°F

Approach

One novel approach to stabilizing this type of fissile shale is to actually "plug" the nano-sized pores in the shale using specific nanoparticles. Chenevert and Sharma[1] have pioneered this with using nanosilica to seal pores and thus eliminated the ingress of water into these fissile shale types and subsequently render them inert.

Nanoparticles are defined as materials with a diameter less than 100 nm. Silica is the common name for silica dioxide (SiO_2), which is found in different forms: amorphous or crystalline, porous and non-porous, anhydrous and hydroxylated. From a structural point of view, the Si atom is in tetrahedral coordination with 4 atoms of oxygen and there is a variety of structures that can result from this combination of atoms and type of coordination. Silica is mainly synthesized from an aqueous solution, by dissociating monomeric silic acid or from the vapor of a silicon compound; many other synthesis routes are also available

Nanosilica can be found commercially in two forms, either in a solid form or in a dispersion. If the dispersion is not stabilized with either a dispersant chemistry or coating agent on the nanosilica, then the particles will agglomerate and precipitate. Typical examples of surface modifying groups are silanes, organic acids, or even alcohols. An alternative method to avoid agglomeration is to increase the viscosity of the continuous phase, thus preventing the separation of dispersions.

Therefore to further the practical and effective use of nanosilica particles as plugging tools to decrease the penetration of water into the nanometer sized pores shale, the design of such additives had several factors that needed to be considered such as the compatibility with the other mud additives, thermal stability, and ability to withstand contamination as well as general impact on fluid properties. Nanosilica solutions come in a large variety of sizes, from 5 to 100 nm, and use different suspension packages. Often the sizes that the manufacturer claims are not always the "effective" size of the particle (potentially due to agglomerate as described above). Thus their performance in a drilling fluid depend greatly on the effective size of the nanoparticles, the surfactant (if any) in the susapension and the specific coating agent on the nanoparticles. **Figure 3** shows a cryo Transmission Electron Microscope (TEM) of two different nanosilica particles with the same particle size but different stabilization/suspension packages to illustrate the potential differences in two "similar" nanosilica products.

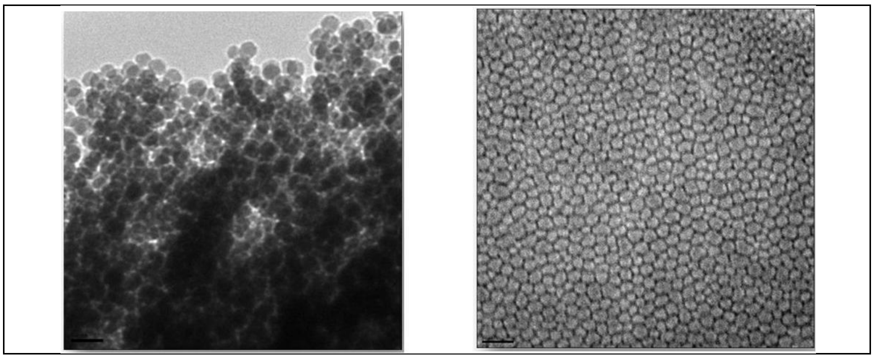


FIGURE 3 TEM image of two 20 nm nanosilica samples

Additionally, surfactant based suspensions could impact fluid properties and lead to excessive viscosity, syneresis or gelling. These aspects were all taken in consideration for the final choice of the best candidate.

Fluid Properties and Test Equipment

While OBMs can be applied in nearly every shale type, a typical WBM cannot. Typically WBMs are much more chemically active and vary in degree of reactivity from shale to shale as well as being sensitive to changes in conditions such as temperature, salinity, pH, and contaminants. Consequently, WBMs must be customized to fit a particular formulation that has been targeted. Several factors need to be taken into consideration when designing a formulation, not only from a performance point of view but also from an environmental and logistic standpoint. As an example, fluids containing chlorides are viewed as dangerous for the environment in many areas of land drilling.

This Shale Gas WBM (SGWBM) that was developed to achieve both environmental and performance goals, utilizes fresh water as a base fluid and additives which are targeted to achieve specific properties and make implementation of the fluid very easy for the operator. The viscosity package is a derivative of a natural polymer and provides the desired rheological profile with a low-end rheology able to suspend drilling cutting. The fluid loss package consists of a blend of water dispersible polymers, which together with the nanoparticles, is used to physically plug the shale formation pores. Finally, the system contains a lubricant package that provides good lubricity. The design of the fluid was such that each one of these components could be adjusted easily on the rig according to the demands of the drilling operation. The nanosilica was added to a level of 10.5 ppb as the optimal dosage, to be discussed later.

A typical rheological profile is showed in **Table 2**:

Property	Value
Period Aged	16
Temperature	150
Fann 35 viscometer data	
600 rpm	120
300 rpm	46
200 rpm	36
100 rpm	24
6 rpm	8
3 rpm	6
10 s	6
10 min	8
PV	28
YP	18

TABLE 2 Typical Rheology Profile for WBM Designed for Shale Gas Drilling.

Several contamination studies were conducted using Rev Dust (35 ppb), OCMA clay (10 and 35 ppb) and cement (15 ppb). **Table 3** shows there was little to no effect in the rheological profile as a result of contamination.

Rheology	10 ppb OCMA	35 ppb OCMA	15 ppb Cement	35 ppb Rev Dust
600 rpm	67	72	70	79
300 rpm	45	48	46	54
200 rpm	40	39	38	41
100 rpm	26	28	27	28
6 rpm	8	11	9	9
3 rpm	6	9	7	7
10 s	9	10	9	7
10 min	10	12	11	10
PV	22	24	24	25
YP	23	24	22	29

TABLE 3 Contamination Effect on Rheological Properties after Aging at 150°F for 16 hours

Lubricity was a very important parameter due to the long extended reach characteristic of such wells. The system developed used a low cost, general-purpose lubricant as shown in **Figure 4** that seemed to help substantially with the lubricity, especially at higher loadings. The choice of the lubricant can be changed depending on the availability and location of the well.

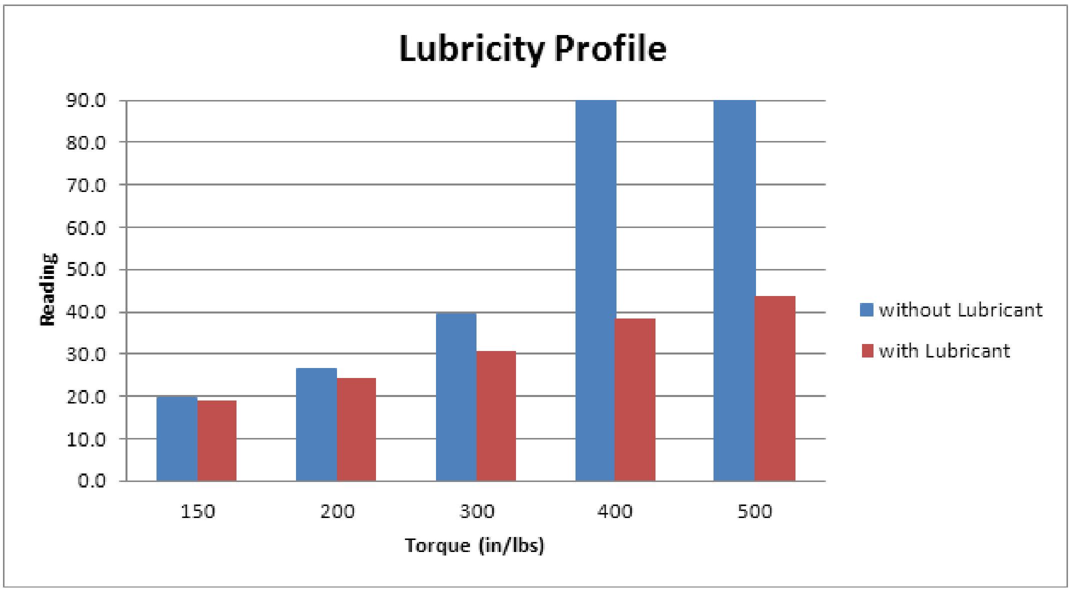


FIGURE 4 Lubricity on SGWBM using an OFI Tester

A Shale Membrane Test (SMT)[1] (aka pressure penetration test Al-Bazali, 2006) has been developed to study the effect of physical plugging on shale with the nanosilica particles. The SMT Cell is illustrated in **Figure 5**. Essentially, a shale sample is prepared (1/4" wafer) and inserted into the cell between the Top Cap and Base (**Figure 5**). A test fluid is pumped to flow across the top surface of a shale sample at a constant pressure (P1, P2), while measuring the pressure buildup (P3) in the bottom reservoir with a tiny constant volume. Shale sample permeability for the test fluid can be interpreted from the bottom pressure buildup (P3). Permeability changes of the same shale sample, with respect to various test fluids (brine and the WBM), are treated as an indicator of physical plugging (also shale stability) by solids and nanosilica particles in the WBM. The more significant the permeability reduction between the WBM and initial brine, the better the physical plugging by the solids and nanoparticles.

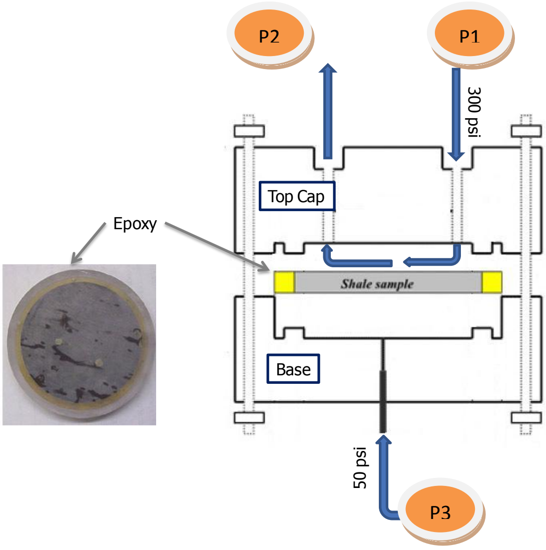


FIGURE 5 Schematic of SMT Cell

Typically, brine and a WBM are tested in a SMT test. Brine is tested first to determine the initial permeability of the shale sample. The mud is then tested in order to evaluate the performance of the physical plugging (shale stability) for mud. The test procedure is a follows:

- Fill the reservoir with a brine solution to match the shale a_W (water activity)
- Apply a back pressure of 50 psi (P3) and top pressure of 300 psi (P1 & P2)
- Measure the bottom pressure for pore fluid (brine) pressure transmission for initial shale permeability
- Displacement of upstream fluid with test solution (mud)
- Measure the bottom pressure for fluid pressure transmission for shale post-plugging permeability

Figure 6 shows the effect of several concentration of nanosilica using Atoka shales[3].

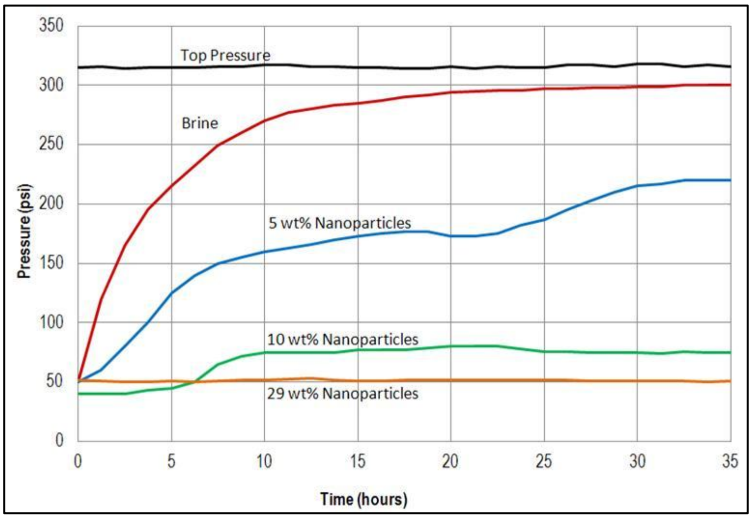


FIGURE 6 Plugging effect with different nanosilica concentrations

As the concentration of nanosilica was increased from 5% to 29% wt, an increase in plugging efficiency was observed thus reducing permeability. However, this high dosage would not be practical in oil and gas fields. By virtue of the system design described in this paper, the SGWBM is able to reduce this dosage that initially proved effective and uses only 3% w/v and the main results are shown in **Figure 7**.

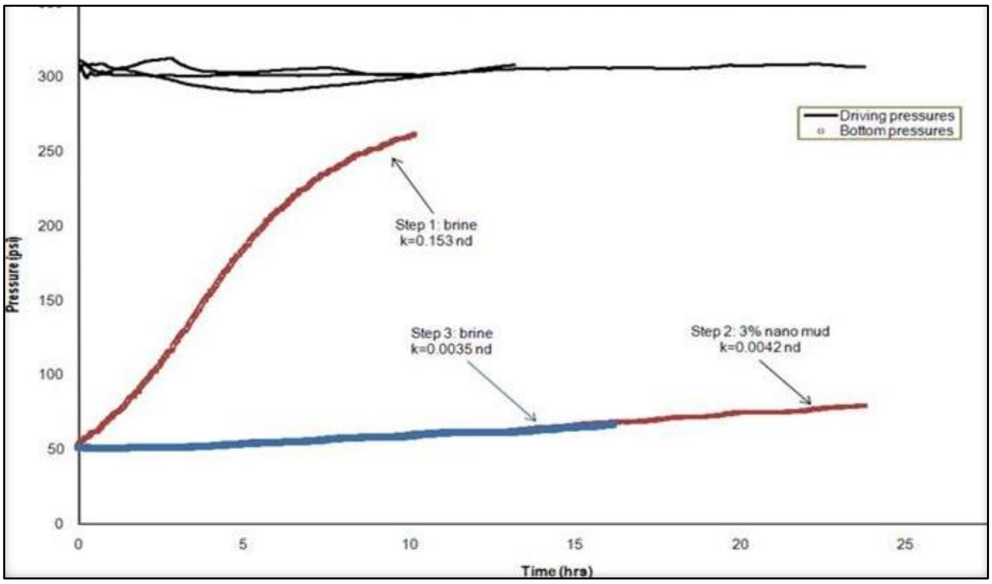


FIGURE 7 Experimental results using formulate SGWBM

- In step 1, the shale was tested with a 4% NaCl solution, which has the same a_w as the sample itself. After 10 hours with a 250 psi pressure differential, the bottom fluid pressure increased due to fluid transmission across the shale sample and gradually equilibrated with the top driving pressure.

- In step 2, the brine was displaced with the formulated drilling fluid (SGWBM) containing nanosilica and after 25 hours at 250 psi pressure differential there no pressure transmission. This shows that the shale has been properly sealed.

- In step 3, the drilling fluid was once more displaced with a 4% solution of NaCl and the test repeated. There was no bottom pressure transmission that registered. This meant that the shale had been physically plugged and that the plugging was sustainable.

Step	Test Fluid	Permeability, nD	Permeability Reduction, %
1	4% NaCl Brine	0.153	-
2	WBM without nanosilica	0.035	77.1%
3	WBM with 3% w/v of nanosilica	0.0042	97.2%
4	4% NaCl Brine	0.0035	97.6%

TABLE 4 Calculated Permeability Reduction using Nanosilica

From the flow information, the permeability was calculated and a 98.9% decrease in permeability was achieved using the formulation under study, as showed in **Table 4**. This significant permeability reduction proves that there is excellent physical plugging with the SGWBM. With the SGWBM, very little water invades into the shale, preventing wellbore instability problems in the field. Therefore, shale stability can be effectively maintained in a freshwater formulation.

Toxicity work was performed on both the nanosilica additive and the SGWBM as formulated. **Table 5** gives toxicity values using the Gulf of Mexico Mysid Shrimp protocol. These results show that both the nanosilica and the SGWBM as a system show little impact on toxicity and without the presence of chlorides, the overall mud system should be able to be readily disposable.

Sample	Medium	Dosage	Results (ppm)
NanoSilica	Gen #7	20.0 ppb	>500,000
NanoSilica	Gen #7	10.0 ppb	> 500,000
0	SGWBS	NA	114,520
NanoSilica	SGWBS	10 ppb	113,850

TABLE 5 Mysid Shrimp Toxicity for Nanosilica and SGWBM

Conclusion

The use of an improved water based drilling fluid (SGWBM) that is simple in formulation and maintenance shows excellent rheological properties, maintain wellbore stability, together with a good environmental profile has been studied. A combination of well-known and economically affordable material is combined with new nanomaterials to achieve desired rheological properties and wellbore stability in shale gas plays.

Reference

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2. Sensoy, T, Chenevert, M. E. and Sharma, M. "Minimizing Water Invasion in Shales Using Nanoparticles." paper SPE 124429 presented at the 2009 SPE Annual Technical Conference and Exhibition, 4-7 October 2009, New Orleans, Louisiana.