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Intelligent Monitoring? …. Add Borehole Gravity Measurements!

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Abstract

Borehole Gravity Measurement (BHGM) tools have been available for several decades, but until now, widespread applications were not possible. The current BHGM tools are too bulky to be run in almost any well without pulling the tubing. In addition, BHGM tools are limited to vertical wells and the existing sensors fall short on stability for permanent installation.

BHGM tools could be very useful for reservoir and production monitoring. First, the depth of investigation is enormous when compared to many other measurements. Advancing flood fronts, not only gas-water but even oil-water, could be detected from a distance of tens, hundreds or even beyond thousand feet from a well, if suitable BHGM sensors were available. Second, only very few parameters are needed to convert the raw gravity measurements, via a bulk density, to the main output: saturation. This avoids the challenges with several special parameters which are needed to arrive at saturation when using resistivity logs. Third, the interpretation models are simple: for gravity interpretation Newton's laws are perfectly adequate, while for resistivity and acoustic measurements, research on response functions is still ongoing.

We have modelled the response of BHGM tools in a number of typical Saudi Arabian conditions, including advancing oil/water fronts, coning and near well bore monitoring, proving the significant potential for BHGM technology. Hence, as there is a need for improved production and reservoir monitoring, further BHGM development becomes very attractive.

From an analysis of current day gravity sensors, several possible further development routes can be painted, each with its own advantages. It is clear that if our industry desires additional monitoring capabilities, it will be relatively simple to achieve intelligent monitoring by selecting the most appropriate route and developing those BHGM sensors, tools and related systems.

Introduction.

The concept of "Intelligent Energy" when considered for the upstream part of the oil and gas industry, implies a sound understanding of the reservoirs to be and being produced, combined with a smart application of technology, leading to maximum hydrocarbon recovery and business value. For any maturing field, key to a sound understanding of the reservoirs is reservoir monitoring: no proper reservoir management without adequate knowledge of the current fluid distribution. Hence no "Intelligent Energy" without "Intelligent Reservoir Monitoring."

Across the industry there is a dire need to improve especially on the currently available reservoir monitoring capabilities. Apparently the existing tools and methods are inadequate. On the one hand, those methods which provide complete coverage of the reservoirs, such as seismic, cannot provide the desired and necessary resolution and actual quantitative saturation. On the other hand, those methods which do have a (very) high resolution and may provide the desired precision in saturation (i.e., Pulsed Neutron Logging and through casing resistivity methods) lack the needed full reservoir coverage, i.e., depth of investigation (DOI). Hence one of the main challenges for the logging industry is the capability to measure deeper into the formation. This has been expressed for many years already in various terminologies and more recently has been coined as a need for "telescopes" next to the apparently existing "microscopes".

We will consider the potential of Borehole Gravity Measurements (BHGM), as a complement to other currently existing methods. Some possible development routes will be painted and it will appear that to move forward in these areas, the industry should actively pursue these new developments.

Alternatives for improved monitoring capabilities.

It should be needless to say that chances for a single magical method which meets all requirements on fluid distribution monitoring are very slim even in the simplest of reservoirs. The best what one may expect is that by a combination of information from several sources a sufficiently accurate fluid distribution model may be derived. In fact analyses of some of the most successful reservoir fluid distribution measurements (including cases of generally accepted excellent seismic and cross well resistivity examples) led to the conclusion that even in some of these very successful cases, there was still too much ambiguity left. Hence more measurements, preferably of a different physical property, are needed to resolve such ambiguities.

In terms of hardware developments, these are most likely to happen in a “one step at the time” manner, even though “revolutions” sometimes do take place, Hence, if at present there is a large gap between the possibilities of the “microscopes” and “telescopes” as referred to above, one should not only be prepared for a long journey to get from one to the other but also actually take the first steps.

When considering various possible monitoring technologies, a whole range of criteria are to be included. See figure 1 for a comparison of technologies, with some focus on typical Saudi Aramco conditions.

Note the following in relation to the criteria given in this table.

- This table is meant to be neither exhaustive nor perfect for all reservoirs and operating conditions. As a first qualitative screening for methods however this sort of approach is very handy.
- “Snap shot possibility” refers to the possibility of making a single, quick snapshot and thus obtain the whole data set. For most technologies this is possible. For passive seismic though it is not, since continuous recording is required to pick up the signals when they are produced.
- “Complex physics” refers to both the simplicity and the maturity of the necessary underlying interpretation methodology. From a business point of view there are some obvious advantages for a method for which the underlying models and equations are very well established. For example, BHGM does not require anything more than Newton’s laws, while research into the exact response equations for some other technologies is still ongoing today.
  Note that for passive seismic, the determination of the location of the micro seismic events in itself should not be classified as “complex physics.” However, the actual interpretation in terms of actually unequivocally linking these acoustic events to an actual oil-water front and quantitative saturations is much more challenging.
- “Complex parameters,” or parameters with a relatively large uncertainty, will have a direct impact on the precision with which the final desired saturation values can be determined. Compare the situation for electro magnetic (em) / resistivity logging, where among several other parameters, the saturation exponent during both the imbibition and drainage cycles must be accurately known, with the case for gravity logging, where next to the porosity only the hydrocarbon and water densities are required.

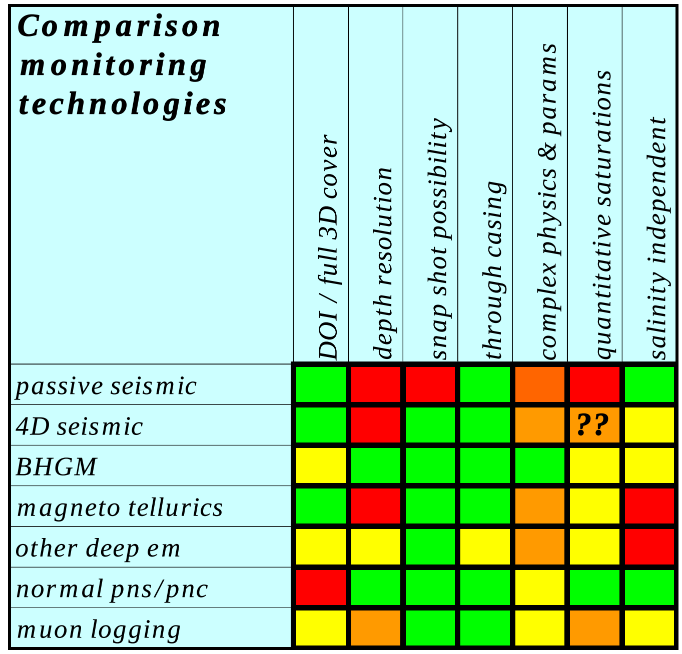

***Figure 1**. Qualitative comparison of some monitoring technologies.*
Colour coding used: red = no-go/very poor; orange= low chance/effect; yellow = medium chance/effect; green = OK.
“other deep em”: through casing constraints for those methods which require the measurements to be done in a well

- For at least many of the reservoirs in Saudi Aramco, the basic dry rock and fluid parameters are such that 4D seismic monitoring, which has been so successful in many other places in the world, is at least far more challenging. A simple fluid substitution exercise shows that the total acoustic impedance change when going from virgin oil bearing to residual saturation is only around 1/3 to 1/4 of the corresponding value for some North Sea Brent reservoirs. Note that, as part of this small impedance change is caused by a small difference in oil and water densities because of the typically low gas-oil ratios, when considering density (gravity) logging, we might also face some serious challenges.

From the above comparison it appears that BHGM might be a rather attractive technology for our purposes, complementing other technologies where those fall short. To quantify in a little more detail the BHGM potential for our reservoirs, we will show some results of a few simple modeling exercises. A brief description and the current state of technology of BHGM logging will first be given.

BHGM logging principles.

Giving a full description of BHGM principles and interpretation is beyond the scope of this paper, so we will limit ourselves just to the basic measuring principle.

A gravity sensor essentially measures the acceleration of the earth’s gravity field, g, and may thus be called a g-sensor. If this is done with sufficient precision, then the tiny variations in the earth's gravity field, caused by variations in density, can be measured and thus, using simply Newton's laws, something about the distribution of the mass (or density) of the surrounding media can be determined.

In borehole gravimetry, taking the measurements at two different (vertically separated) points will provide the bulk density of the horizontal layer between the two points (see figure 2 below). While in principle every point in this layer, has an impact on the readings, due to the inverse square rule effect of Newton's laws, there are some practical limits here.

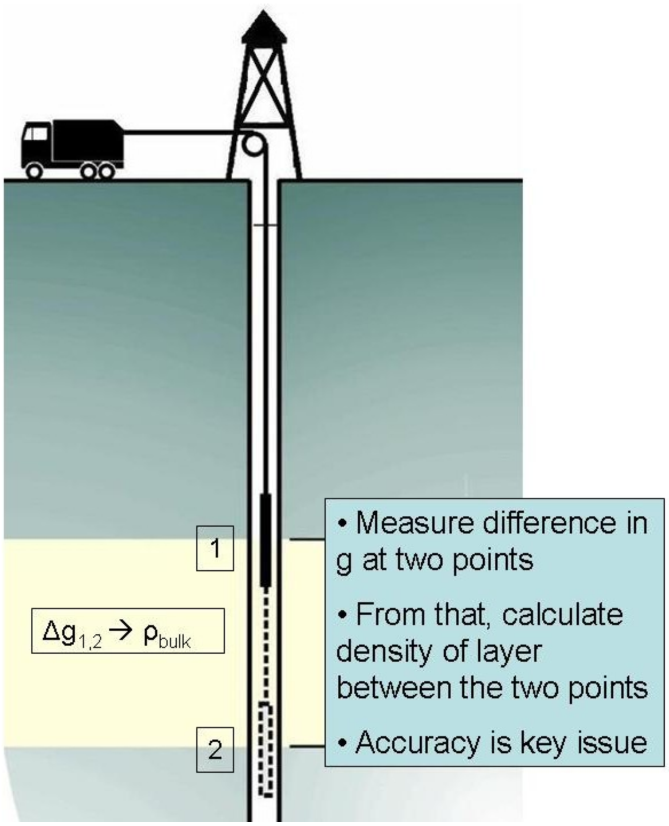

***Figure 2**. Principle of BHGM logging.*

As the difference in the local g-value at the two points is extremely small (determined by the ratio of the mass of the layer over the total mass of the earth) accuracies in the order of one in a billion are required for useful BHGM logging.
Furthermore a very precise depth determination is essential. The latter means that unless some very special depth control methods are used, the shortest possible distance between two measuring points, i.e. the best resolution, is in the order of 10 ft. Note also that the apparent variations in g due to density differences we are interested in, may be swamped by effects from tide and some other factors. Hence corrections for all these are to be made as part of the routine processing of the measurements.

Existing BHGM technology.

There are many simple means with which one may measure g. From basic physical principles, g could be determined from a swinging pendulum, a dropping ball, vibrating strings etc. The only successful BHGM sensor ever built however uses a mass-spring system. For a known mass and a known spring (i.e. spring constant), from a measured extension of the spring by the mass under the influence of gravity, one may calculate the change in g between two measurement points.

Going from this seemingly simple mass-spring system to an actually useful BHGM tool requires a masterpiece of design and instrument building work. LaCoste and Romberg (L&R) has developed these sensors several decades ago and the tools further built with these have been successfully run in many cases. In Saudi Aramco too, BHGM surveys have been successfully run, yielding among others an accurate Residual Oil Saturation (ROS).

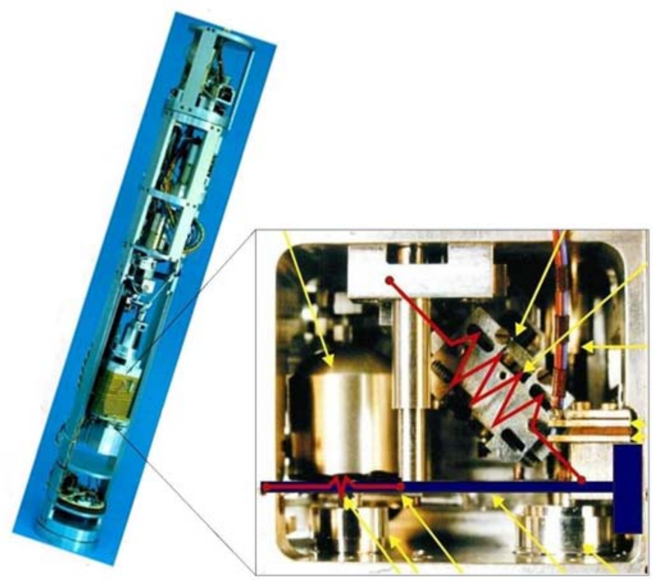

Figure 3. *Current day BHGM tool; courtesy Scintrex/L&R*

Selected BHGM modelling cases.

In this section, we present a few results of some modelling to investigate the ability of present and future borehole gravity sensors to resolve near borehole fluid saturations as well as other near well bore effects. We will among others limit ourselves here to cases relevant to reservoir monitoring and production optimisation, but it should be noted that deep-density logging will have a wealth of potential also for other applications, including exploration and appraisal settings.

In terms of actual specifications for potential future sensors, at this point we will assume the following, in terms of:

- Accuracy and precision: sufficient improvement over existing tools, such that oil/water contrasts, currently just beyond reach, can be picked up
- Tool size and deviated well capabilities: "no constraints"

- Stability, i.e., drift characterisation: sufficient for permanent monitoring
- Multiple sensors: "no constraints"

To study the potential to detect approaching oil-water fronts, a very simple two-dimensional model was used containing five horizontal layers each with uniform density properties. In this model, the middle layer was used to see the effects of the moving fluid front when approaching the wellbore. Figure 4 shows modeling results for a case with a very small contrast between the virgin oil bearing and residual oil saturated formation of 0.03 g/cc. This density contrast is based on a change in water saturation, and porosity and oil and water densities as typical for some of our largest fields.

The different curves in figure 4 each represent a different thickness of the layer being flooded. The results indicate that for a gravity sensor with a precision of 1 µgal we will get a detectable signal of a moving front in a 200 ft layer when the front is still more than 1500 ft away from the well and for a precision of 0.1 µgal the first signs of an approaching front would be picked up at 2500 ft. The effect of thinner layers is also indicated.

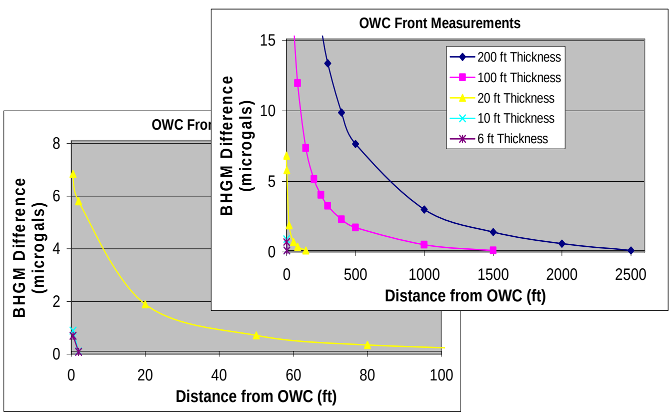

Figure 4. *Detection of approaching (oil-water) front for a density contrast of 0.03 g/cc*

While the distance from which a moving front can be detected as per the above graphs might be disappointing to some, it should be noted that the oil-water density differences used in these examples are very small and that when it comes to monitoring and "advance warning," when a typical flood front is moving at say 1 ft/day, 100 ft deep detection provides three months notice.

In the area of production management, the modelling work done confirmed that BHGM measurements provide both a very elegant and handy method to detect and quantify and thus provide the necessary information to manage coning and do well production optimisation. To illustrate this, the BHGM response of a cone (oil/water, same conditions as for flood front example above) is presented in figure 5 below.

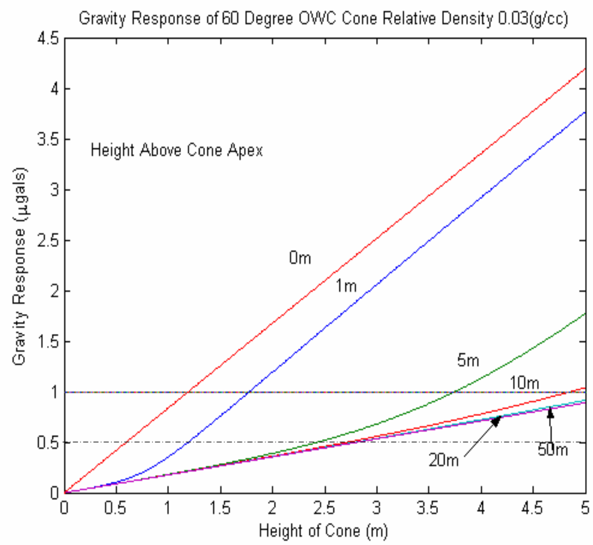

Figure 5*. BHGM response for a cone in a vertical well.*

It is interesting to note that also for near-wellbore monitoring, BHGM has the potential to become very interesting. Providing quantitative saturations at a resolution of a few feet or less in cases where current day alternatives so not work very well.

Ideal BHGM tool requirements.

As mentioned, the existing L&R sensor and BHGM tools, are a masterpiece of instrument building. Meeting the specifications to which they were built, they have provided technical answers and generated business value for those applications in which they could be run. However, there is an enormous gap between the capabilities of the current day tools and the specifications for the ideal g-sensor, tools and systems.

The most important issue to be tackled is sensor size. For both wireline tools and permanent monitoring systems, the sensor has to be reduced in size considerably for any serious future application. Currently, depending on pressure and temperature ratings, the tool diameter is typically above 4". Ideally a sensor which could be built into a 1 11/16" wireline tool is needed.

Next, for permanent reservoir monitoring systems, comes sensor drift. The drift of the current sensors is too large, or is not characterised precise enough, to allow permanent installation. Beyond size and drift, the ideal, "dream" g-sensor, should allow not just permanent installation and slim wireline tools suitable only for ideal hole conditions, but also tough open hole logging conditions and even FEWD logging.

Note also that for a wireline tool to be suitable as a "real-open-hole" tool, certain requirements in terms of logging speed (i.e. short station time) and tool ruggedness are to be met. These requirements are less stringent that those for LWD/FEWD purposes, but since there will be a specific application area for such tools, and because the existing tools certainly are lacking in this respect, it is worthwhile to provide a separate category for them. In the table below the requirements for our dream g-sensor are listed.

BHGM tool specifications	*Current technology*	*DREAM*
4 1/2" wireline tool		
3 3/8" wireline tool		
2 1/2" wireline tool		
1 11/16" wireline tool		
real OH wireline tool		
Permanent monitoring		
MWD/LWD		
Depth resolution		
Directional grav. meas.		
Absolute measurement		
Accuracy & precision		
High temperature		
Risk		
Sensor costs	***k$ 50***	

Figure 6. *Specifications for BHGM sensors. "Current Technology" reflects the present state of BHGM technology. "DREAM" reflects the ultimate, ideal situation.*

The reason that accuracy and precision of BHGM sensors also have to be improved is that with the current day sensors, while differentiating gas/water often is possible, oil/water differentiation normally is just beyond the existing capabilities.

From single g-sensors to strings.

The gravity field, once the large scale gradients which swamp and hide the subtle features are stripped off, provides a very interesting 3D curvature view of nature. Bouguer corrected and the free air gradient maps of large oil fields or even the whole world often show intriguing variations. At a smaller scale, km and tens or hundreds of meter, there are still noticeable variations which could therefore be exploited for our purposes. See figure 7 for the variations an inclined layer and an oil-water cone. One of the challenges in borehole gravimetry thus becomes the issue of "looking better" and be able to observe and measure these variations.

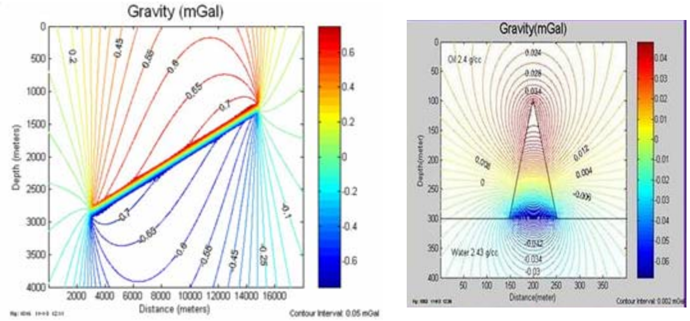

Figure 7*. Gravity field around an inclined subsurface layer(leftt) and around a cone in a producing vertical well.*

As the existing sensors as well as most likely several of the ones going to be developed in the near future, are non-directional sensors, the only possibility to get even close to being able to picture such 3D curvatures, is to have many g-sensors in a string. (The original idea for this concept is not from the authors of this paper.)

This requirement to have many g-sensors in a string becomes even more important for near well bore applications. As mentioned before: very precise depth control is crucial for any BHGM survey, but as the spacing between measurement stations gets smaller, the only practical way to obtain the required depth precision is have many g-sensors at fixed positions in a string. So called shuttle sondes, where a single sensor is moved inside the BHGM tool on an elevator or shuttle, to get a depth control much better than possible from wireline, will only be necessary and useful as long as sensor costs are high and/or complications due to drift characterisation would make these shuttle sondes necessary.

Anticipated future developments.

The design of the current BHGM tools dates from several decennia back. While in the mean time some attempts have been made to improve on this, there has not been a commercially successful product. From that we may deduce two important points.

First of all we have to realise that advancing BHGM technology is not trivial. Making any sensor with even only a fraction of our "dream" specifications will take R&D resources and commitment. Given the intrinsic risks in new technology development and the current general R&D climate in the industry, technology developers, service companies and operators are to work together, each providing their share towards the technology developments. Note also that the consequences of a slow technology development might affect not only the oil industry itself, but society at large.

Second, as outside of the rather small BHGM technology area itself, the industry at large has made major strides forward in almost any instrument and sensor technology, that it will be possible to at least make some significant improvements in BHGM hardware and thus start at least moving towards our dream specifications.

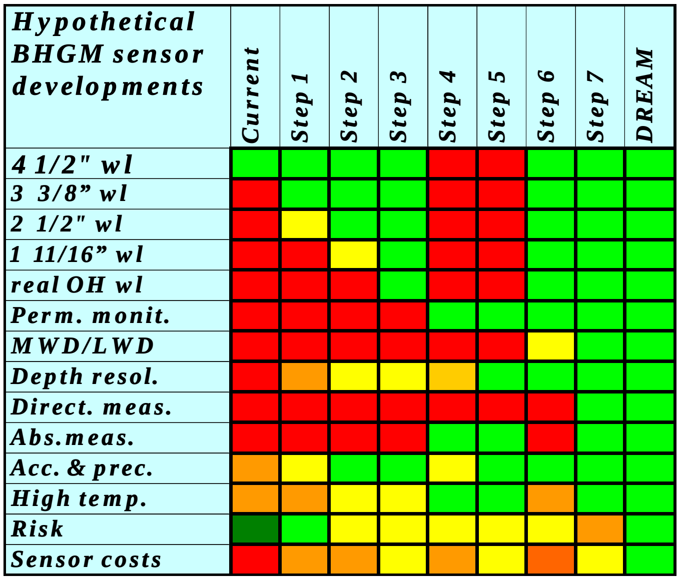

Figure 8. *Possible (hypothetical) development of BHGM technology through a number of (r)evolutionary concepts.*

In the table in figure 8, three groups of developments are represented. First, steps 1, 2, 3 represent what one might expect as evolutionary developments coming out of the existing commercial concepts: a step by step moving towards our dream specifications, but unlikely to be able to meet all of them.

Second, steps 4 and 5, represent some development which focuses on the key issue of permanent monitoring. The demands for improvements form the current sensor to be able to come to permanent monitoring capabilities are very large. Hence one might perceive the possibility of a completely different development which does have this capability. But since those demands are so large, such development might not be immediately suitable for wireline applications. This is because for permanent monitoring the time required to make a measurement is not an issue, while for wireline applications of course it is.

Third, represented by the (also still hypothetical) steps 6 and 7, comes a group of what might truely be called revolutionary developments. Some design which provides a major breakthrough in hardware capabilities. Inevitably the development risks for these will be a little higher than for the evolutionary concepts, but the rewards in terms of actually meeting the business needs for BHGM developments, will be correspondingly large.

As mentioned before, the above is only a notional painting of developments as might happen and is not meant to represent more than a general description of how BHGM technology could develop.

Conclusions.

- From the foregoing it will be clear that borehole gravimetry clearly has the potential to provide additional key monitoring capabilities which are a indispensable for the concept of Intelligent Energy and it's role in managing mature fields.

- Furthermore we have made it plausible that, given some dedicated efforts, significant steps forward can be made in BHGM hardware developments.

- Finally it should be clear that without serious commitment from some oil companies, especially the more risky, but high reward, developments are very unlikely to take place for some time to come, but that for those prepared to make such commitments, the rewards are likely to be very significant indeed.

Acknowledgements.

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