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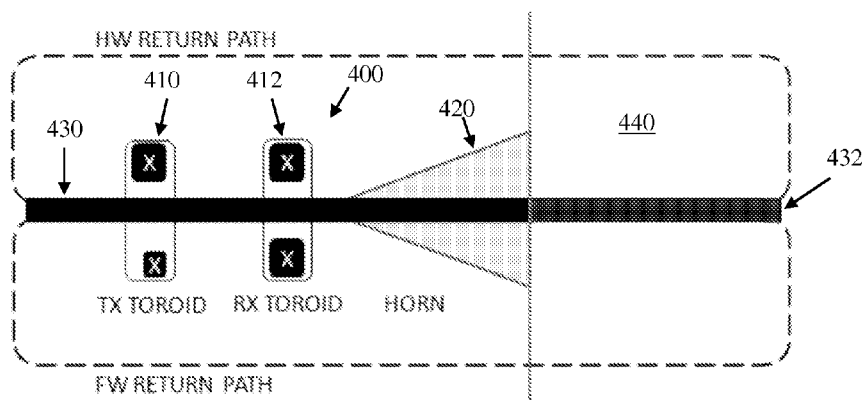


Figure 4

(57) Abstract: A system and method for imaging a formation from an underground borehole. A drill rod drives a drill bit from an underground stope. At least one paired electromagnetic transmitter and receiver are electromagnetically coupled to the drill rod at or proximal to an entrance to the borehole, and are configured to launch electrical or electromagnetic signals onto the drill rod within the borehole and to store a response so as to obtain an electromagnetic map of the borehole, thereby imaging features of the formation which are less than substantially 5 metres away from the borehole.

SHORT RANGE BOREHOLE RADAR

Cross-Reference To Related Applications

[0001] This application claims the benefit of Australian Provisional Patent
5 Application No. 2012901362 filed 5 April 2012, which is incorporated herein by
reference.

Technical Field

[0002] The present invention relates to electromagnetically mapping while drilling a
borehole and in particular relates to the imaging of faulted formations close to the
10 driller and/or the drill, for example within a few metres of a drill rod that is collared in
the wall of an underground tunnel or stope.

Background of the Invention

[0003] Rockbursts and rockfalls cause roughly two thirds of all deaths underground.
Roof defect maps are needed to deploy ground control assets more effectively. Miners
15 need as much warning as possible of impending fluid in-rushes which can overwhelm a
mine.

[0004] For example, the UG2 reef in South Africa's Bushveld Igneous Complex,
which supplies about half world platinum, is a shallow-dipping sub-meter thick
chromitite plate which, leaving local defects like potholes and faults aside, is
20 remarkably consistent over a 300km span. As shown in Figure 1A, just above the UG2
in its immediate hanging wall, there are weak parting planes known as the triplets,
through which UG2 rock-bolts must be driven to reach competent rock. Figure 1B
illustrates the operating environment of a narrow underground stope in a deep South
African gold mine. Gold and platinum miners are vulnerable to rock-falls which
25 typically develop from flat extension fractures, that are driven by cantilevering at the
stope face, and from bedding plane fractures that develop on weakness planes like the
triplets shown in Figure 1A. They are also vulnerable to rock-bursts, which may
develop if on the approach of a face to a fault, the near-vertical extension fractures that

form to relieve stresses become crowded, the vertical foliations thin, then buckle violently.

[0005] Similar problems arise when underground mines, pass beneath reservoirs or aquifers, or close on fluid pockets under ultra-high pressure. Mine activities must
5 avoid puncturing the reservoir to prevent either flooding or the explosive release of water or gas.

[0006] Miners can take steps to reduce rock-burst and rockfall risks, such as grouting, diving or climbing early through competent rock before entering brecciation or realigning the face to avoid extensive sudden slippage along a stope face by carrying
10 the fault at an angle, however this is so only if they know of a fault's existence, its position, orientation, throw, and can estimate brecciation of its margins, & its paleo-stressed state well before they meet it.

[0007] In order to obtain some warning of water-bearing fissures and potentially hazardous structures ahead of proposed workings, cover boreholes are often drilled
15 ahead of tunnel and or shaft development prior to mining. Such holes, which are drilled at a slight angle ($\sim 5^\circ$) to the proposed development line are typically between 50m and 150m long. Such cover boreholes are monitored at their collars often with methanometers to detect the release of gases. Their collars are also watched closely to detect the first signs of water flow. However, to detect fluid-bearing faults and other
20 reservoir housing structures, currently, cover holes must actually pierce them.

[0008] Much shorter coverholes are sometimes drilled ahead of stopes, raises, ore drifts as a routine part of their development. Fig 2 shows a low-profile "jumbo" percussion drill. Drills of this type can drill coverholes up to 50m long in 2-3 hours if they are equipped with drill rod carousels. However many "jumbos" are set up to drill
25 matrices of shallow (2-3m deep) blast holes in minutes with a single rod, typically 4.8m long. After drilling one of these blast-holes, if knowledge of rock ahead is limited, additional rods are sometimes added manually to probe a short distance, perhaps 7m ahead, say for any faults that might release fluids uncontrollably after the blast.

[0009] VHF-UHF bistatic borehole radars used to date have been over 5m long, while comparable monostatic borehole radars have been about 1.8m long. Such devices struggle to provide useful synthetic aperture radar sweeps of boreholes only 3 to 7 metres long. Moreover, existing bistatic borehole radars typically have a minimum radial range of about 2m due the offset between transmitter and receiver. Existing monostatics typically have a minimum range of 5m, due to the receiver being saturated by the transmitted pulse. Thus disabled, for a short time period reflections from any object closer than 5m away from the borehole are lost. However, as shown in Figure 1, many critical formation features of immediate relevance to miners can be less than 5m away from the borehole, and knowledge of such formation features is desirable, for example to ensure roof bolts are long enough provide the desired stability in the roof; or for example to warn miners of the crowding of vertical extension fractures that might herald a rock-burst.

[0010] The boreholes that these miners drill are too short to scan with conventional 4-5m span bistatic VHF borehole radars, and the targets of relevance to miners are too close to be picked up clearly by conventional VHF monostatic borehole radars. Site access restrictions present unique challenges to effective underground radar mapping in stopes, for example due to stope height restrictions, which force drill-string designers to compromise between on the one hand drill-plus-rod length and borehole take-off angles; on the other between rod length and borehole depth. For while many short drill rods can be screwed together to make a long drill string, energy losses at the joints limit the power reaching the bit of a percussive drill rig. These physical restrictions on borehole radar surveying aside, interrupting production to drill a borehole radar survey hole ahead of a miner in a stope is rarely an economically viable option, unless of course there is a very good reason to suspect the presence of a potentially life-threatening fault..

[0011] Conventional borehole radars work by accelerating electrons axially up and down the borehole on antennas with near-wavelength dimensions. They have toroidal polar patterns, i.e. they are all but blind to plane faults normal to the borehole axis, like

the extension fractures ahead of the airleg blast-hole face driller, and the flat extension fractures above the roof-bolt hole driller in Figure 1B.

[0012] Various modes of electromagnetic waves can be launched on drill rods while drilling boreholes. For example improvements to and extensions of single point
5 electrical resistivity measurement techniques, derived from Schlumberger (US1,819,923), Karcher (US 1,927,664) and Jakosky (US 2,150,169, US 2,153,802, US 2,181,602) have been described recently by Gorek (US2008/0297161), Alberty (US2010/0000791, US2010/0000792, US2010/0000729) and MacLeod (US 4,578,675); and applied to a wide variety of tasks, which include the geostopping of a
10 remote drill bit as it approaches a critical interface, say that capping an over-pressured reservoir.

[0013] Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is solely for the purpose of providing a context for the present invention. It is not to be taken as an admission that
15 any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present invention as it existed before the priority date of each claim of this application.

[0014] Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated
20 element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

Summary of the Invention

[0015] According to a first aspect the present invention provides a method of imaging a formation from an underground borehole, the method comprising:
25 during drilling of the borehole from the underground stope, obtaining an electromagnetic map of the borehole which images features of the formation which are less than substantially 5 metres away from the borehole.

[0016] According to a second aspect the present invention provides a system for imaging a formation from an underground borehole, the system comprising:

at least one drill rod for driving a drill bit from the underground stope;

at least one paired electromagnetic transmitter and receiver which are
5 electromagnetically coupled to the drill rod at or proximal to an entrance to the borehole, and configured to launch electrical or electromagnetic signals onto the drill rod within the borehole and to store a response so as to obtain an electromagnetic map of the borehole imaging features of the formation which are less than substantially 5 metres away from the borehole.

10

[0017] The formation may be any object of immediate or near-immediate relevance to miners from underground boreholes, such as faults, weak interfaces, or fluids under pressure. The boreholes may be short 2-10m blast holes, roof-bolt holes, or longer 7-150m coverholes.

15 [0018] The electromagnetic mapping method may comprise one or more of time domain reflectometry (TDR), frequency domain reflectometry (FDR), short range borehole radar (BHR), single point resistivity (SPR) involving ohmic and/or displacement currents, and a form of guided wave radar using electromagnetic surface waves which are guided tightly, weakly or leakily along the axis of a borehole that
20 contains a conductor, such as a wire, a drill rod, or even brine and known collectively, here at least, as Barlow-Goubau-Sommerfeld (BGS) modes.

[0019] In some embodiments, this invention may be employed to provide a near-real-time stope rock fall hazard reduction tactical mapping tool. Such a tool may be utilised to detect and/or aid tactical BHR surveying of close in targets, for example.

25 Additionally or alternatively, some embodiments may provide other applications such as the use of signal processing means to store and process echoes, in order to detect and advise miners while drilling or shortly thereafter of, for example, anomalous BGS TDR back scatter from foliations developing in front of a face, unexpected BHR interruptions to bedding reflections, anomalous phase rolls that might indicate changes
30 in the elevations of weakness planes, or the approach of a drill bit to a fluid reservoir.

BGS TDR can, for example be used to: secure and issue geostopping warnings to coverhole drillers who may be working in hazardous fissured ground; detect faults and other interfaces that lie near normal to the axes of 100+m rotary drill reconnaissance holes; map faults using either airleg or mechanized 7m – 60m percussion coverholes
5 and blastholes and/or; build BGS & BHR maps of critical interfaces such as the base of the 2nd triplet from data shot in arrays of typically 2m airleg blast holes .

[0020] In preferred embodiments, the measurement traces acquired are held along with related time stamped drill bit positional information within the electromagnetic device in local memory for subsequent translation into strip fault maps before the faults
10 are exposed by blasting. However, data may also be collected by local or distributed area networks. Preferred embodiments deploy both SPR and BGS techniques in order to detect faults lying near-normal to the borehole, and BHR imaging to better detect interfaces like the UG2's triplets that near-parallel borehole axes

[0021] A still further application of the present invention is in mapping roof-bolt
15 boreholes during drilling, using SPR, BHR and/or BGS modes either simultaneously or individually so as to map potential partings in the roof by roof-bolting machines as they operate.

[0022] Notably, in some embodiments of this invention it is possible to produce complementary maps simultaneously or near simultaneously based on one hand on
20 observed variations the transport of alternating currents down the drill string and either reflected from the bit back to the collar (BGS) or out into the formation: through the bit SPR & leaky BGS-mode-converted to BHR at the bit on the other; or on a third hand on the observation of variations in the spontaneous potentials (SP) that are produced by electrolytic and other eg electro-kinetic interactions between the drill bit and the
25 formation spontaneous potential and/or on a fourth hand on the observation and/or recording of seismic emissions from the drill bit. The utility of each or all of these depends on the electrical characteristics of the rocks, and the drill steel

- [0023] Some embodiments may further comprise, for example after drilling, manually pushing a tactical bistatic BHR survey with a good small minimum range ($R_{\min}$), into a short blast hole. Manual deployment on a dielectric rod may be speed-controlled by a mechanical or electro-mechanical clutch, motor or “governor” at the collar of the drill rig. $R_{\min}$ of the BHR is preferably less than 5m, more preferably less than 2m, most preferably less than 50cm, and for example may be between 20-30 cm. Swapping the dielectric rod for a metal pipe would encourage the borehole radar to explore the formation axially by launching BGS modes along the pipe, instead of BHR modes radially outwards into the rock surrounding the borehole
- 10 [0024] Embodiments utilising BGS modes may launch signals by any suitable means such as a horn antenna encircling the drill rod; a proximal coupling from a BHR in an adjacent hole onto the drill rod during drilling of the borehole being mapped; a Rogowski coil encircling the drill rod, or driving an in-line gap of the drillstring (provided such a gap is resistant to force from the drill). It is noted that the launching
- 15 means may excite not only the expected mode – e.g. the fundamental BGS mode of a drill rod, with a radial E field and a circumferential B field, but also say conventional bulk “radar” modes, and for that matter higher order leaky BGS modes, any or all of which may interact with the drill string, sometimes usefully, say at the drill bit in a leaky-BGS-to-bulk-radar mode conversion at the slowly moving drill bit, which
- 20 conversion may form the basis of mapping scheme, because the bit scans systematically through object space. It is also noted that proximal BGS launching, in which a wideband borehole radar is placed say near the collar of a short borehole say a meter away from and parallel to the hole currently being driven may present a useful opportunity for similarly wideband BGS mode excitation. Moreover, because proximal
- 25 launching allows the transceiver electronics to be positioned in an already drilled borehole proximal to the borehole being drilled and mapped, this substantially eases the need to mechanically protect the transceiver electronics from the large mechanical forces applied by the drillstring. It is noted further that ferrite rings and/or wire-meshes may be usefully deployed on the drillstring short of the borehole’s collar to encourage
- 30 electromagnetic propagation into the rock and to discourage the propagation of electromagnetic energy towards the drill rig and the driller, in the stope.

- [0025] In yet another embodiment the present invention may be employed to monitor and/or optimise the stroke of a percussion or rotation drill as it drills a borehole. In such embodiments, the method of the present invention further comprises obtaining SPR and/or BGS and/or SP measurements, and time-synchronizing those measurements to the stroke of the drill. A synchronizing signal following the stroke of the drill can be obtained by filters, clippers, amplifiers and/or accelerometer suitably mounted on or coupled to the drill rig. Should the drill undesirably be operating with too little thrust, this can be detected for example by observing spikes in resistivity occurring when the drill bit recoils and loses contact with the drilled rock face. If under-thrust is detected, the drill stroke can be adjusted and optimised in a feedback loop. Stroke optimisation is important in narrow underground stopes as the drill may need to be small enough to be handled manually, and may therefore have limited power budget, optimisation of which may effect valuable increases not only in drilling rate, but also potentially in drill rod and drill rig fatigue life.
- 15 [0026] Some embodiments of the present invention may thus provide support and improved safety for miners in narrow underground stopes, by enabling electromagnetic mapping of surrounding formations and/or drill operation, during the normal underground drilling process and thus without significantly impeding normal mining processes.
- 20 [0027] According to a further aspect the present invention provides a borehole radar for short range imaging, the borehole radar comprising:
- a power source comprising one or more compact high energy density batteries;
 - a receiver configured to remain on during transmitter operation, and having a front-end rectifier chain configured to ensure soft receiver saturation in the presence of
 - 25 large transmitter signals and to provide a high receiver dynamic range; and
 - one or more resistively (and/or capacitively and/or inductively) loaded antennas for radiating broadband BHR and BGS signals produced by the transmitter and for detecting similar electromagnetic reflections for the receiver, The antennas may be isolated electromagnetically if and when where appropriate either spatially or by ferrite
 - 30 loading

wherein the borehole radar is elongate to fit within boreholes and is less than substantially 2 metres in length.

[0028] The batteries may each comprise a lithium ion polymer battery, such as a
5 1000mAh battery having dimensions of 70 x 24 x 6 mm³. Some embodiments may utilise four such batteries to power the transmitter and three such batteries to power the receiver.

[0029] It is possible and it may be desirable in some circumstances to power the radar system either from a remote source, connected to it by an armoured ferrite loaded
10 cable, or by harvesting the electrical power required from mechanical vibrations, rotations, and/or fluid flow.

[0030] The borehole radar is preferably less than about 1.5 metres in length. Such a radar length permits short range operation of the order of $R_{\min} < 30$ cm, and allows EM probing and mapping of underground stope blast holes of 3 to four meters in length,
15 and cover-holes of about 7 metres length, rather than only mapping lengthy exploratory holes. It may be found desirable, for example when surveying in an array of blast-holes, to operate the transmitter and the receiver in different boreholes, both located in close proximity to the borehole being surveyed.

[0031] The link between the receiver's front end and the analog-to-digital converter
20 ADC may be furnished with some means of companding the signal as it is amplified; for example by feeding amplifier output into a potential divider made of two resistors in series, feeding the ADC from the mid-point of the divider, and placing a back-to-back diode pair in series with the resistor which bridges the ADC. The diode pair will fire, and the potential divider will operate as such only when the instantaneous voltage
25 exceeds a set threshold. Back-to-back diodes recover rapidly and cleanly after firing.

[0032] The borehole may be a blasthole drilled in a reef stope, with radar imaging being undertaken prior to explosive blasting. The formation to be imaged may

comprise the roof body above a stope in order to assess roof stability and required stabilisation measures.

[0033] The present invention thus recognises that the rock volumes which are investigated by blast-holes, pilot and cover boreholes can be expanded, economically
5 and without significantly altering existing mine infrastructure or processes, by employing borehole radars or the like within or proximal to the cover-holes or even within blast-holes prior to blasting. It recognises that maps can be derived at least semi-automatically by linking together geo-registered gathers of signals, recorded for example on a succession of days, weeks, months, as a stope, an ore drift, a tunnel is
10 progressively developed.

[0034] It also recognises that the signals that are recorded during the drilling of a single hole can be monitored automatically to warn drillers of their bit's approach to say a brine-filled fault, or the unexpected absence of say the second triplet from its expected position above the UG2 as a result of proximity of the stope to fault or a
15 pothole.

Brief Description of the Drawings

[0035] An example of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1A illustrates the UG2 reef strata, and Figure 1B generally illustrates the
20 operating environment of a narrow underground stope;

Fig 2 shows a low-profile twin boom development drill;

Figure 3 illustrates a sturdy compact bistatic borehole radar (BHR) in accordance with one embodiment of the invention;

Figure 4 illustrates a second imaging tool in accordance with another
25 embodiment;

Figures 5a to 5c illustrates another embodiment of the present invention in which time-domain reflectometry is used to effect measurement-while-drilling;

Figure 6 illustrates BGS mapping before blasting of a blast-hole near the top of the UG2 reef in another embodiment;

Figure 7 illustrates proximity coupled BGS mapping of a blast-hole before a burn-cut, in accordance with a further embodiment;

Figure 8 shows a BHR image of faults imaged by the device of Fig 3;

Figures 9a to 9b are BHR profiles shot with a BHR of the form of that in Figure 3, pushed on drill rods into a borehole that passes through a kimberlite dyke;

Figure 10 illustrates a radar trace obtained by use of BGS modes, in another embodiment;

Figure 11 illustrates yet another embodiment in which BGS electromagnetic wave waves are coupled to a drill string by fitting a Rogowski coil to an underground drill rig;

Figure 12 illustrates a further embodiment of the invention relating to the optimisation of drilling efficiency;

Figures 13 and 14 illustrate mapping of microfaulting during roof-bolting using leaf antennas and a horn antenna, respectively; and

Figure 15 illustrates another embodiment in which a triaxial cable antenna is provided for imaging narrow boreholes.

Description of the Preferred Embodiments

[0036] In one embodiment, illustrated in Fig 4 the present invention provides a low-cost universal retrofit kit for raising miner safety, by imaging with tactical borehole radars, time-domain reflectometers and single point resistivity tools while drilling underground in confined stopes in tabular reefs, seams or dykes, with percussion and rotary blast-hole and cover-hole drilling rigs.

[0037] Figure 3 illustrates a sturdy compact 10-125 MHz band bistatic borehole radar (BHR) (300) which is 1.25m long. In this embodiment, the BHR (300) uses for a power source lithium ion polymer batteries having capacity 1000 mAh and dimensions 70x24x6 mm³, which are ideally sized for mounting beneath a BHR receiver's PCB. Use of this particular small but high energy density battery permits the tool to be made smaller and stronger, with the reduced size in turn opening the antenna designer's options for improving short range performance and R_{min} . Four Li Ion batteries are provided in series for the transmitter, and three in series for the receiver. Presently

available batteries give about 4 to 5 hours operation of BHR (300), which is important for a tool which is to be used throughout a working shift. The transmitter and receiver antennas are made up with impedances, that are distributed axially and profiled to broaden system bandwidth by reducing dipole axial reverberation. It is possible to
5 insert ferrite rings to raise mutual isolation between transmitter and receiver.

[0038] The 1.25m long radar (300) has a <30 cm minimum range, which represents a significant improvement over the 5 m minimum range of previous borehole radars. To ensure that the receiver electronics are ready to capture reflections from 30 cm range in order to exploit the reduced range made possible by the reduced overall tool
10 size, in this embodiment the receiver circuitry is ON, though its gain may be temporarily reduced, throughout the transmit cycle. The receiver undergoes a soft saturation during the transmit cycle, and this is achieved by using a chain of fast back-to-back diodes, that compand overload signals in order to preserve dynamic range by avoiding clipping by overdriving the ADC. Together, the reduced device size and
15 improved receiver circuitry operates to allow observation of reflections from nearby objects and effects a <30 cm minimum range. The BHR 300 thus provides one imaging tool suitable for use in accordance with the present invention. Such uses include intra-borehole post-drilling radar surveys of blast-holes, coverholes or exploration holes, or extra-borehole surveys-while-drilling for example by placing the
20 BHR 300 in a stationary position in an adjacent borehole to the hole being drilled and utilising proximity coupling and taking sequential differential measurements as drilling progresses.

[0039] The bistatic radars of the type shown in Fig 3 are typically 1.5m but, rock properties permitting, potentially significantly shorter than this. They are small
25 compared to many borehole radar bistatics currently in service. They are short enough to be handled easily in confined stopes, and to build up synthetic apertures from stored signals shot in blast-holes and/or (given accurate trace geo-registration) blasthole arrays. Imaging well in much same wideband VHF spectrum as current reconnaissance borehole radars, at short- and mid- ranges, without necessarily or significantly losing
30 the long range capability of suits the length and inclination limits that apply to tactical

boreholes which are drilled from the sharp ends of narrow stopes. Thus, small radars enable probing of short blast holes instead of requiring exploratory holes, which presents some important benefits.

[0040] The present embodiment further recognises a unique application of short
5 range imaging from short boreholes, such as 3 to 6m long blastholes. In narrow stope underground hard rock mines eg UG2 platinum mines, a “jumbo” percussion drill such as shown in Figure 2 is often used to drill arrays of shallow blast holes to permit the stope face to be progressively blasted free in order for the mine to progress. Variants of the procedure are known as fire-driving or burn cutting, in the context of tunnelling and
10 drifting; and as breast-mining in the case of stoping. The present embodiment recognises that such blastholes can, prior to blasting, be used in a number of ways to examine and/or map variations in surrounding formations such as strata above. Indeed, in some embodiments such electromagnetic mapping can be performed while the blasthole is being drilled so that mapping does not delay the normal mining process in
15 any significant way.

[0041] Figure 4 schematically illustrates another imaging tool 400 in accordance with the present invention which may be used to complement, or as an alternative to, the BHR 300 of Figure 3. Tool 400 is a “snap-on” mapping-while-drilling transceiver, the horn at the front-end of which could be driven (in part) by some of the modules in
20 the borehole radar in Figure 3 to effect SPR & TDR BGS surveying at low cost and retrofitable to existing drilling systems. In this arrangement the drill rods pass through the centre of two toroids 410, 412, and a horn antenna 420. The transducers 410, 412, 420 are each configured to couple electromagnetically with the drill string 430 but are isolated from it mechanically to avoid subjecting the transducers to the high drilling
25 forces as the drillstring 430 drills into the face of an underground narrow stope 440. The transducers 410, 412, 420 may be excited or operated synchronously with the drill for example being strobed by the drill’s mechanical excitation, using the filtered, clipped, amplified output of an accelerometer on the drill frame. The horn may be filled, usefully, with a dielectric of permittivity/shape/thickness matched to that of rock.

[0042] The components of tool 400 allow VHF or UHF -band electronic radar pulses to be launched onto the drill string 430 through the horn 420, gated in time to reflect from and interrogate the drill bit 432, say, as it physically recoils from the end-of-hole (at approx. 67Hz for a typical percussion drill). Rock crushing may be

5 monitored by varying the relative phase between the drill stroke and the probe signals which are transformer-coupled onto the drill rod by the rear Tx toroid 410. The front Rx toroid 412 senses signals reflected from the drill-bit and thus allows monitoring of drill operation and can enable drill stroke optimisation, for example by increasing drill stroke or thrust if under-thrust is detected.

10 [0043] In another application of the tool 400, additional receiver toroids may be mounted elsewhere in the proximity, for example on the drill rig's roof supports and floor supports which are or may be in physical and electrical contact with the roof and floor, respectively. This arrangement allows comparison of currents circulating in the hanging roof and the footwalls and may for example allow guided drillers to estimate
15 the vertical position of the bit in a reef or a seam. A resistivity map showing geological variations in strata could be computed from potential changes sensed by electrode arrays in adjacent boreholes as drilling progressed.

[0044] In figure 4 the toroids 410, 412 and the horn antenna 420 can coexist and can for example be used sequentially so that both EM launching options are available for
20 the application concerned. The present embodiment is thus a snap-on tool which fits to existing drill rigs and requires little or no modification of drill rigs already in place. This embodiment thus proposes that two technologies, SPR surveying and BGS time domain reflectivity, can be built; into a module which snaps onto & turns existing blast & cover-hole rigs; to run tactical surveys, while drilling or soon thereafter, either
25 independently or in combination with other geophysical memory logging devices such as low minimum range, miniature borehole radars. On-board data storage would facilitate either post processing, or near-real time processing, to warn say of unusually high BGS TDR clutter rates, or abnormal phase changes in the BGS bit-reflection, which might respectively herald the convergence of the stope on a rock-burst-prone
30 shear fracture (as in Figure 1B) or the approach of the drill bit to a high-pressure fluid-

bearing fault. The data harvest may be combined with data flows from other machines using perhaps a data networking system such as WiFi, BlueTooth, Zigbee, to achieve the syndication of sensory information with positional information that is needed to create a cost-effective mapping while-drilling system, which without interrupting ore
5 production in any significant way is capable of generating maps cost-effectively and fast enough to enable before blasting the concentration of ground control assets such as rock-bolts and rapid yield props onto the arrest of impending rock-falls in narrow stopes, before they are induced by blasting.

[0045] With regard to figure 4, it is noted that horn antennas are directional, in the
10 sense that they drive energy preferentially in one direction along a drill rod, but toroids typically are not. However, in this embodiment the toroids 410, 412 could be made more directional by winding a ring of ferrite (or multiple rings) on one side i.e. above the toroid (to the left of the toroid in the view of Figure 4) so that more energy goes down (into the hole) than up (towards the drill motor etc). Equally and additionally, the
15 dielectric contrast between rock and air, aided if needs be by wire mesh screens can be used to isolate the drill rig from the drill string electromagnetically

[0046] Figure 5 illustrates another embodiment of the present invention, in which time-domain reflectometry is used to measure-while-drilling (MWD) a 7m cover-hole being pushed ahead of a face advancing into unknown territory. In Figure 5a, the low-
20 profile mechanized "jumbo-drill" of Figure 2 is shown in side elevation in an ore drift, drilling a 7m coverhole. The tool 400 of Figure 4 is against the face and is functioning as a TDR-MWD transceiver. Substantially continuous BGS pulses, one pulse being portrayed at 510 in flight from the TDR-retrofit cone 420 to the drill bit 532, survey vertical fractures in the rocks through which they fly in reflection; separably a
25 "scanned-while-drilling" image develops of the succession of rocks in front of the drill-bit, as they host in turn the transient Goos-Hanschen EM "bubble" that develops on the bit during BGS pulse reflection; and possibly separably, variations in pulse travel time, & shape map into changes in the effective dielectric through which the BGS pulse flies.

[0047] A common mining scenario in which this technique presents significant value is shown in Figure 5b. The TDR measurement-while-drilling system BGS MWD portrayed in Figure 5a reveals that in this case kimberlite dyke of interest 550 is lost when the cover-hole strikes granite at location 540. This gives the driller immediate
5 advice that a long tactical survey hole 542 is required in order to aid in identifying and overcoming the obstacle 550. The percussion drill can, if equipped with a carousel of drill rods, be inclined upwards to drill the “tactical survey hole” 542 in two hours.

[0048] Electromagnetic mapping techniques can be applied during and/or after drilling of tactical hole 542 in order to image the surrounding formation. For example,
10 the predominantly axial modes of a BGS survey, run while drilling, by placing a memory logging borehole radar close to the collar of a near-by short blasthole may be used to monitor structures ahead of the bit and to locate near-vertical fractures and other interfaces through which the bit has just passed, precisely. A subsequent BHR radar survey, run say immediately post-drilling by tripping the drill rods out and
15 screwing the same borehole radar on a spacer rod onto the leading drill rod in place of the bit, might return a profile of the general form illustrated in Figure 5C, interpretation of which annotated in the Figure, could be carried out on site. Note that many tabular ore bodies are VHF BHR translucent. This is why the lower kimberlite dyke, beneath the granite block can be “seen” through the upper. Thus, the present invention
20 importantly recognises and verifies that it is possible to image a target outside a tabular ore body, from a borehole radar or the like which operates close to or even inside that ore body.

[0049] Given that mining engineers need to know ahead of time whether a dyke splits, where it goes, whether to carry a split or retreat from it the tactical BHR & BGS
25 surveys underlying Figure 5b can, individually or together add considerably to ore yield, and the safety of its extraction. Moreover, without such knowledge miners would very likely encounter roof instabilities as they near the secondary inclined fault linking the two dykes in Fig 5c, whereas the foreknowledge provided by the present embodiment would allow for appropriate safety precautions to be taken, sometimes
30 even before the hazard is developed by blasting.

[0050] In the case illustrated in Figures 5, the driller can thus learn that, despite a short rise in the kimberlite dyke immediately ahead of the production drift face, the mine angle should counter intuitively be planned to head early downwards through the divided section of reef 550, as trackless mining machinery can typically only negotiate slopes of less than 1 in 9. Thus, with the methods of the present invention, the long tactical hole(s) 542 need only be drilled when short coverhole mapping so indicates, improving operational productivity. It is also notable that drilling and mapping the extra tactical 28m borehole 542 can be completed in the space of a few hours (approx. 3 hours), which is a fraction of the time that would be wasted if the mine plan maintained elevation or started to rise so as to follow the initial reef rise. It is also notable that interpretation of tactical BHR and/or BGS maps can be rapid and it may not be difficult, given that miners have immediate experience with conditions near the collar, and the task of the mapping system may be simply one of illuminating and/or challenging an experienced miner's probably well-formed expectations of what lies behind the face. Devices such as those illustrated in Figures 3 and 4 reduce hazard by reducing surprises. They allow high resolution mapping while mining and drilling to be integrated almost seamlessly into the ore production cycle. In contrast to long range reconnaissance BHR surveying, they offer short-turn-around payback, for it is a laborious process to correct the dip or bearing of a mine stope once it has strayed from the desired or optimal contour.

[0051] An individual BHR could thus be used to let UG2 or kimberlite faults, stumbled upon at stope level, be stalked individually, and might allow splays, partings or grabens to be probed from short drift boreholes. In turn, the angles of a stope's approach to faults can be optimized if fault orientation is known by this technique. Automating data harvesting and possibly interpretation means that much of this could be done without special skills and without significantly disrupting production.

[0052] Figure 6 (not to scale) illustrates BGS mapping before blasting of a 3m blast-hole near the top of the UG2 reef. In accordance with the present invention the BGS modes are transceived and recorded by the bolt-on unit depicted schematically in Figure 4, and the survey is performed during drilling of the blasthole so that no

additional sequential steps are required and mine production is not slowed. Figure 6 shows a section through a typical part of the UG2 reef with overhead triplets. Imaging options include short range radar, reflection imaging or the like, with the goal of locating the interface to competent roof strata as it is critical that all roof bolts are

5 securely held. Thus, short range imaging functionality is critical, as it can be of the order of centimetres in distance between the drill bit and critical overlying features such as the thin weak chromitite planes that separate pyroxenite layers in Figure 6. As shown in figure 6, when using BGS imaging the EM “bubble” during reflection can be envisaged as surrounding the end of the drill. Taking the difference between two

10 measurements as the drill bit moves, i.e. a differential measurement, reduces steady state signatures (such as the EM signatures of drill rod joints and vertical faults) and brings out the features which are changing relative to the slowly moving drill bit. As the bit is moving relative to the rock as it deepens the borehole, fractures and/or triplet deviations passed by the drillbit can be brought out, for example by spatially filtering to

15 emphasize change.

[0053] This embodiment further enables the possibility of using data harvested by retrofitted TDR-MWD devices, either stored locally or communicated back to base with WiFi, ZigBee, BlueTooth or the like, and processed together with local in-stope blast-rig geo-registration, either measured or deduced by dead-reckoning with the aid

20 of a drilling plan, to map on a hole by hole and blast by blast basis the proximal fracture patterns and triplet elevations on every breast-mine stope; all without disrupting production. Such maps could be particularly useful on the Merensky Reef or the UG2, where potholes are hidden, and dangerous to approach for thin UG2 host layers selectively, and weakness planes in the roof shift unforeseeably. Further it is

25 noted that axially propagating BGS mode reflections are particularly well suited to the detection of vertical fractures, which might rise in density if a fault confines normal cracking behind the face (Fig 1B) to herald an impending rock-burst, or house water under dangerous pressures. An adapted low-profile mechanized “Jumbo” or even a suitably equipped airleg drill could profile UG2’s triplets, continuously and pre-

30 blasting, in full 3D. Establishing roof integrity routinely with a Jumbo, by locating triplet locations in 3D pre-blasting, could significantly improve miner safety.

[0054] Figure 7 illustrates another embodiment exploiting the fact that underground blastholes in narrow stopes are usually in close proximity to one another. This embodiment recognises that a borehole radar can be positioned in an already-drilled 3 metre blasthole 710, during drilling of a 7 metre cover hole 720. BGS modes can be
5 launched on the drill string as it drills hole 720, by way of proximity coupling from the borehole radar positioned in the adjacent or nearby blasthole 710. Electromagnetic mapping during drilling of hole 720 can thus be effected. In more detail, Fig 7 shows a DD220L blasthole rig driving a 7m hole into a face. A BHR radar of the type shown in Figure 3 lies 50cm below the 7m hole, out of mechanical harm's way, in the first of a
10 set of 3m blastholes that will eventually be drilled as part of a "burn cut". The BHR signals proximity couple to the drill steel above it. It is noted that good short-range performance of radars like that illustrated in Figure 3 are essential. Conventional radars currently in service have minimum ranges of at least 2m i.e. longer than the heights of many stopes. They cannot readily support the evanescent scanning system illustrated in
15 Fig 7.

[0055] The embodiments of Figure 6 and 7 may be simply adapted to provide automated mapping, in 3D, of hazards in the roof-strata immediately above tabular ore bodies. This can be effected by mounting a high resolution short-range tactical radar in the carousel of the mechanized blast hole rig. After drilling a 3m blast hole, the rig can
20 retrieve the radar and a spacer rod, and insert these into the hole. The hole can then be scanned, with measurements being recorded onboard the radar and geo-registered to the local site, and this data from that blast-hole being returned to an in-cab processor for conversion into a 3D map. Such a 3D map can be iteratively constructed as drilling and blast stages progress, in substantially real time, and may thus be suitable to warn
25 blasters and rock bolters of water in-rush hazards or roof weakness-plane elevation changes, or potholes, or unusual patterns of mining induced fractures in time to enable them to take remedial action, say by selecting longer resin-bolts.

[0056] In Figure 8 we show a BHR image of faults imaged by the device of Figure 3, as seen from a shaft pilot hole. Sub-vertical reflectors can be tracked easily over a
30 radial distance of out to 25+m from the borehole. That their echoes close to the

borehole are precise, devoid of ghosting or reverberation is owed to the borehole radar antenna design freedom that is opened up by small, high energy density batteries. The echoes can be tracked almost to the apices of the sharp peak features (“Λ’s”) at their borehole wall intercepts, at which location it is noted that wireline images and cores
 5 can give positive identification to complement the survey and orient at least some reflecting planes in three dimensions. It is noted further that because many cover holes and shaft pilot holes track close to the trajectory of intended development, the fact that the radar of Figure 3 can yield useful images of the rocks through which miners intend to pass (i.e. those within 5m of the hole) is important

- 10 [0057] Fig 9(a) is a BHR profile, shot with the bi-static of the form of that shown in figure 3 pushed on the rods into a kimberlite borehole. Sharp apex Λ’s in the zoomed in gather in Fig 9 (b) further confirm its close-in performance. Fig 9(b) shows, usefully, that the echo highlighted in Figs 9(a) still is “heard” when the radar submerges into kimberlite. Echoes in kimberlite in Fig 9(c) confirm the kimberlite dyke’s
 15 translucence.

[0058] The present embodiments recognise that if mapping while drilling in underground stopes is to be of any use, it must become operationally transparent. This might be effected for 2m blast holes by using either Rogowski coils or tapered coaxial horns fixed to the boom, encircling but mechanically decoupled from the drill steel, to
 20 either reflect very wide band (say ~100-500MHz) EM pulses from the drilling bit, or to work monochromatically at lower frequencies, driving the drill rod say into quarter-wave resonance. High resolution short range radars of the type shown in Figure 3 could work in harness with low profile mechanized blast-hole drills and similar semi-automated rigs to illuminate the task facing blasters and roof-bolters. With such radars
 25 loaded in their carousels, they could make hanging wall weakness plane 3D maps effortlessly, updated instantaneously for the better guidance of roof-bolters.

[0059] The borehole radar of Figure 3, having a reduced minimum range, makes it possible for a wideband borehole radar in a blasthole in proximity to a drill rod to transceive broadband electromagnetic pulses onto that drill rod without significant loss

of bandwidth. Further, this device permits the rock properties pertinent to the safe, efficient economical operation of a tabular underground mine to be deduced by recording and then translating recorded EM traces. Measurements can be converted into a map of faults, be they near-normal to, or quasi-parallel to, blast holes drilled in patterns at the end of a drift or on the breast of narrow stopes. Such a map can be extended in near-real time, using WiFi or other means of relaying traces from the radar transceiver(s) to a remote computer loaded with a-priori data. In turn, such a map can be applied tactically almost immediately, and before blasting, to the prediction and mitigation of hazards that might otherwise overwhelm ground control measures.

- 10 [0060] Comparable or supplementary maps might be created in some embodiments of the present invention by replacing or supplementing the BHR with other imaging devices such as a low frequency toroid or a dielectrically UHF coaxial horn.

[0061] Figure 10 illustrates the essential differences between BHR and BGS data. The two gathers of BHR (left) and BGS (right) traces were shot in succession in a vertical borehole in the Bushveld platinum fields, using the same borehole radar, suspended on a dielectric cord and a conducting wire respectively. The most prominent feature on the BHR gather is labelled 1002 in Figure 10 It is a radar echo from a thick water-bearing fracture, which converges slowly on the borehole, meeting it 220m from the collar at 1004, terminating there, apparently in a ~20m thick conducting, mineralized layer through which the borehole passes, near-normally. Reflections from the base of this and other near-parallel interfaces intersected by the borehole form the family of near parallel, angled, nearly straight lines designated 1008 on the BGS gather in Figure 10 So-called tau-P projections onto the borehole allow the intersections with the borehole to be located precisely. Slight bends or “kinks” in the lines, and amplitude variations can, taken together be translated into maps of effective dielectric permittivity and/or conductivity; and thereon, subject to various assumptions, into variations in the height of say the second triplet above the axis of the hole in Fig 6.

[0062] Maps deduced from BHR and BGS gathers, singly or together, can reveals the density of fractures before blasting a stope face and can, therefore enable \advance

planning of say required roof bolting, or the selective use of overhead protective strike netting, or other such measures in the rock-fall susceptible sections. Selective use of overhead protective strike netting gives a significant benefit as compared to the time and expense of constant use when the scale of operations in South Africa alone is about
5 700,000 blast holes a day.

[0063] It is noted that a key difference between BGS reflectometry radar and borehole radar is in the orthogonal alignment of the generated E field. Conventional borehole radar does not see conventional fractures because they are parallel to the plane of radiation and borehole radar radiates toroidally. However axial targets are seen well
10 by time domain and/or frequency domain reflectometry. Combining multiple imaging techniques thus improves the overall picture obtained of the surrounding formations. Other imaging options include enhancing the detection of change in the state of rocks in the vicinity of mining operations by say the subtraction of traces or trace gathers, shot at different times to monitor processes such as the injection of grouts or the flow
15 of broken rock down ore passes, and/or to warn miners say of faults or foliations that develop as mining stresses in the vicinity of stopes shift either by intent or by accident.

[0064] Figure 11 illustrates another embodiment, in which electromagnetic wave radar resistivity (EWR) is effected by fitting a Rogowski coil 1102 to the underground drill rig 1100. The Rogowski coil 1102 is an air-cored solenoid, fed from one end.
20 Normally one lead is connected to the coil directly while the other lead is run back up the centre of the solenoid to reduce EM pickup from stray EM fields. The solenoid is provided as an open loop which can be passed either side of the drill pipe, and which can then be bent to close the solenoid loop and for example held together with a suitable releasable snap-fit arrangement. Once encircling the drill pipe 1104, the
25 magnetic fields generated by the solenoid 1102 align with axial currents in the drillpipe 1104 itself, permitting the generation of EM probe signals travelling down the drill pipe 1104 to or towards the drill bit. The air core of the Rogowski coil 1102 is beneficial in this embodiment because this leads to low inductance and therefore good responsiveness. Air cored Rogowskis may thus be particularly suitable in this
30 application in some embodiments of the invention in the low VHF band.

- [0065] Figure 12 illustrates a further embodiment of the invention relating to drilling efficiency. If a drillbit bounces free during its rebound from the end of the hole, input mechanical energy will resonate between the ends of the drill rod, reducing fatigue life. Though their respective cutting actions differ markedly, both percussion and tricone drill bits both engage rhythmically with the rock at the bottom of the borehole. During contact, electrons can pass between bit and rock, and so insight into the state of play downhole can be secured by synchronizing SPR and BGS measurements with drill rod rotation and/or percussion. A suitable synchronizing signal could be derived with the aid of filters, limited, clippers, amplifiers, from an accelerometer on the rig.
- 10 [0066] Percussive drilling is efficient in hard, brittle rock. The kinetic energy of a relatively slow moving piston is transformed –through an effective taper or step – during impact of a reciprocating piston with the out-by end of the drill rod, to strain energy in a fast moving strain pulse within the drill steel. Rock beneath the bit spalls, probably in tensile brittle failures both along arches between the PCD buttons on the bit
- 15 and during the rebound at the end of the hole, to the strike of the strain pulse. The transfer of strain pulse's energy into broken rock is inefficient. Drilling rate in narrow-seam short-hole blasting is limited by the need for 4kW top-hole hammers light enough to be manually handled & still deliver $\sim 10\text{W}/\text{mm}^2$ to the bit. Rod handling, and loss of 3% percussive energy per joint, plus the need not to collapse temporarily unsupported
- 20 cantilevered roof after blasting, limits shot hole length to roughly the height of a worked section. Heavy $\sim 20\text{kW}$ top-hole blast-hole hammers can lift drilling rates to $>2\text{m}/\text{min}$.

- [0067] The embodiment of Figure 12 aims to synchronise the use of time domain radar so as to “address” the rock at times at which the bit is actually in contact with the
- 25 rock. The EM “bubble” obtains a measurement in much less time than that for which the bit contacts the rock. In this embodiment, such measurements are made at different times during the percussion cycle. For efficient drilling, the driller's aim is to prevent the bit from breaking free from the rock (as shown in the “under thrust” trace of Fig 12B) because that return energy is wasted and wears out the drill. However, by
- 30 watching the resistivity it can be determined, either manually or automatically how

sustained is the contact of the bit with the rock, and therefore whether the drill is operating in an under thrust state which should be corrected, and potentially, change thrust automatically.

[0068] While preceding embodiments have focussed on BHR and TDR, it is noted
5 that other imaging techniques may additionally or alternatively be applied in other embodiments of the invention. For example, the digital store might be used either singly or while simultaneously accumulating radar data to accumulate seismic and other BHR imaging near equivalent echoes, where the seismic might be pulsed or derived by striking the end of the drill string with an intelligent percussion hammer,
10 which might even be programmed to either sweep frequency or otherwise impulse-equivalent encode percussive beats as a pseudo-random sequence, could be used to scan strata elastically. Near-monochromatic (CW) radar may be employed in some embodiments where it is desired to detect deviations in roof strata that near-parallel a drill bit. Pulse radar, swept or stepped frequency radars or fluxes of electrons or
15 gamma rays or active and/or passive magnetic field detectors may alternatively be employed in some embodiments, singly or simultaneously.

[0069] Figure 5c confirms the surprising result that a tabular dipping, granite-hosted, gently dipping kimberlite ore body of about 3 metres thickness is borehole radar transparent. While intra-dyke two-way losses are large, they prevent imaging only if
20 the top dyke is thick enough for loss to approach the BHR system's dynamic range. The present embodiments also recognise and verify (Figs 9a-b) that many reefs and dykes such as the UG2 reef and the Snap Lake dyke are similarly translucent, and in turn recognise that the triplets & other planes of weakness are open to borehole radar profiling from blast-holes, before blasting ever occurs, using propagation modes
25 transceived by a small & short range borehole radar or the like.

[0070] Figure 13 illustrates the need, during roof-bolting, of insight into micro-faulting. Leaf-spring-like Vivaldi horns, indicated at 1302 and illustrated further in Figure 13b, are embedded in a dielectric slab either side of the drill collar. While a percussion blasthole drill rod might carry 20kW of vibrational power, it can pass

through such leaf-spring antennas without touching either. Terminals on the left and right springs, respectively launch up-going waves and receive down-going reflections as shown in Figure 13c. Notably, when seeking to “look ahead” of a drillbit, FDTD simulation suggests that asymmetric modes launch readily in end-fire, hit the plane reflector, & are recaptured by the receiving antenna.

[0071] As shown in Figure 13c, an impulse applied between the left leaf-spring antenna (Tx) and the drill rod, creates a clearly asymmetric up-going pulse, guided by the drill rod 1304. A receiver, attached to the right hand leaf spring antenna (Rx), detects the down-going reflection from at or beyond the drill bit. Note that the drill rod, between the antennas, slightly but usefully shields the Rx from the Tx thereby assisting receiver isolation. Such leaf spring antennas can be modified as required, for example by being shaped such as Vivaldis, by carrying loadings to minimize reverberation, by being corrugated to raise efficiency, and/or by being immersed in a dielectric plastic plate one edge of which could usually be pressed against the plane roof of a stope, irrespective of the angle of the drill rod to the stope.

[0072] In another embodiment similar to that of Figure 13, BGS mode excitation may be launched by a nearly conventional horn, by using a particular form of horn excitation. In this embodiment, two terminals are provided at the top of the horn, one on the horn and the other on the drill rod. Exciting these terminals creates a dimple in surface current, and produces the assymetry that is evident in the guided wavefield shown in Figure 14. This is advantageous as it has been recognised that asymmetric modes launch relatively easily from the drill bit.

[0073] We refer now to the problem of imaging roof-bolt holes. Such holes are typically narrow in diameter and no more than 28 mm in diameter. The features of interest when roof bolting are typically thin, such as the triplets in the UG2 reef, making them difficult or impossible to image without an antenna or the like being positioned within the bolt-hole. However conventional borehole radars do not fit within a small 28 mm bolt-hole. Figure 15a illustrates a coaxial cable antenna which may be beneficially employed for imaging a narrow borehole, such as a 28mm

diameter roof-bolt hole. A suitable transmitter source (not shown) drives an electromagnetic pulse onto the central coaxial guide 1502 of a “triaxial” cable. The central guide is surrounded by a ground sheath 1504, and is terminated by a chain of resistors 1506 which are configured to maximise the field energy radiated from and
5 present at the active tip of the cable when the pulse is applied, as shown in Figure 15b. The resistors 1506 are reactively linked capacitively and inductively to the outer sheath 1508 of the triaxial cable, which then carries the resulting waveform back along the coaxial cable to a receiver (not shown). The elements 1506 in particular comprise a lumped element “antenna” comprising a coiled leaky-feeder, a capacitor, and a short
10 Wu-King resistor chain. In this configuration the electronics of the transmitter and receiver need never enter the narrow borehole. The coaxial cable may be protectively mounted in an electromagnetically suitable flexible hose to provide robustness for repeated insertion into multiple roof-bolt holes. The triaxial configuration shown, providing a ground sheath 1504 separating the transmit path 1502 and the receive path
15 1508, may be particularly suitable for assisting in providing sufficient isolation of sensitive receiver electronics from a high power transmitter pulse.

[0074] Figure 15b shows a snapshot of the E_Y field that develops at the end of the coaxial cable of Figure 15a when a pulse is fired by a transmitter 1512. Figure 15c is a sequence of FDTD strobe-shots of E_Y (Y horizontal) at 400 ps intervals during
20 development of the “end-of-probe” pulse, in the triaxial antenna of Figure 15a. As shown, the energy separates into three portions 1520, 1522 and 1524. Energy 1520 is tightly guided between 1504 and 1508 and is down-going, energy 1522 is weakly guided, or even leaky GBS guided, outside sheath 1508, while energy 1524 propagates freely upwardly. Each of these three modes may interact with the surrounding
25 formation, such as the triplets of the UG2, in a measurable way. Thus this device, critically from the view point of roof-bolt drillers in the UG2, can map weak planes that are too thin to be detected reliably by conventional freely propagating pulses from a borehole radar, while using holes that are too thin to be entered easily if at all by a conventional borehole radar.

[0075] It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects as
5 illustrative and not restrictive.

CLAIMS:

1. A method of imaging a formation from an underground borehole, the method comprising:

during drilling of the borehole from the underground stope, obtaining an electromagnetic map of the borehole which images features of the formation which are less than substantially 5 metres away from the borehole.
2. The method of claim 1 wherein the borehole is a 2-10m long blast hole.
3. The method of claim 1 wherein the borehole is a 7-150m long coverhole.
4. The method of any one of claims 1 to 3 wherein the electromagnetic mapping method comprises at least one of: time domain reflectometry (TDR); frequency domain reflectometry (FDR); short range borehole radar (BHR); single point resistivity (SPR); and guided Barlow-Goubau-Sommerfeld (BGS) modes.
5. The method of any one of claims 1 to 4, employed to provide a near-real-time stope rock fall hazard reduction tactical mapping tool.
6. The method of any one of claims 1 to 5, further comprising storing measurements of the electromagnetic map together with related time stamped drill bit positional information, for translation into strip fault maps before faults are exposed by blasting.
7. The method of any one of claims 1 to 6, wherein the electromagnetic map is used in mapping roof-bolt boreholes during drilling so as to map potential partings in the roof by roof-bolting machines as they operate.
8. The method of any one of claims 1 to 7 further comprising, after drilling, manually pushing a tactical bistatic BHR with a good small minimum range ($R_{\min}$), into the drilled borehole.
9. The method of claim 8 wherein manual deployment of the BHR is speed-controlled by a mechanical clutch, motor or governor at the collar of the drill rig.
10. The method of any one of claims 1 to 9 wherein, to obtain the electromagnetic map, electromagnetic signals are launched along the drill rod by a horn antenna encircling or immediately adjacent to the drill rod.

11. The method of any one of claims 1 to 9 wherein, to obtain the electromagnetic map, electromagnetic signals are launched along the drill rod by a proximal coupling from a BHR located in an adjacent borehole.

12. The method of any one of claims 1 to 9 wherein, to obtain the electromagnetic map, electromagnetic signals are launched along the drill rod by either: a Rogowski coil encircling the drill rod; or electromagnetically driving an in-line gap of the drillstring which is resistant to force from the drill.

13. A method of monitoring the operation of a drill rod as it drills a borehole, the method comprising:

launching electromagnetic signals along the drill rod and recording resulting electromagnetic measurements;

time-synchronizing the measurements to a stroke of the drill; and

assessing the time-synchronized measurements to determine drill bit contact with the drilled rock face.

14. The method of claim 13, further comprising adjusting the drill stroke in a feedback loop, based on the determined drill bit contact with the drilled rock face, to optimise operation of the drill.

15. The method of claim 13 or claim 14 wherein the drill is less than substantially 10 metres long at maximum drilling depth.

16. The method of any one of claims 1 to 15, wherein the electromagnetic map is obtained repeatedly over time, and further comprising detecting a change in state of the formation by comparing a first electromagnetic map obtained at a first time to a second electromagnetic map obtained at a second time.

17. The method of claim 16 further comprising issuing an alarm upon detection of a detected change in state of the formation.

18. A system for imaging a formation from an underground borehole, the system comprising:

at least one drill rod for driving a drill bit from the underground stope;

at least one paired electromagnetic transmitter and receiver which are electromagnetically coupled to the drill rod at or proximal to an entrance to the borehole, and configured to launch electrical or electromagnetic signals onto the drill

rod within the borehole and to store a response so as to obtain an electromagnetic map of the borehole imaging features of the formation which are less than substantially 5 metres away from the borehole.

19. A borehole radar for short range imaging, the borehole radar comprising:

a power source comprising one or more compact high energy density batteries;

a receiver configured to remain on during transmitter operation, and having a front-end rectifier chain configured to ensure soft receiver saturation in the presence of large transmitter signals and to provide a high receiver dynamic range; and

one or more resistively (and/or capacitively and/or inductively) loaded antennas for radiating broadband BHR and BGS signals produced by the transmitter and for detecting similar electromagnetic reflections for the receiver.

20. The borehole radar of claim 19, wherein the antennas are isolated electromagnetically either spatially or by ferrite loading.

21. The borehole radar of claim 19 or claim 20, wherein the borehole radar is elongated to fit within boreholes and is less than substantially 2 metres in length.

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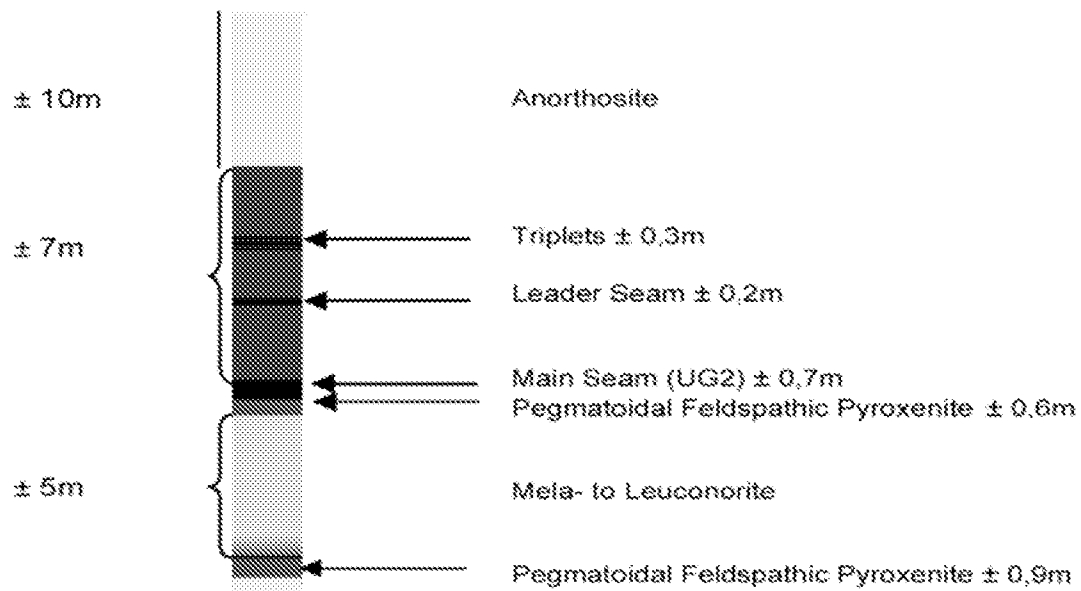
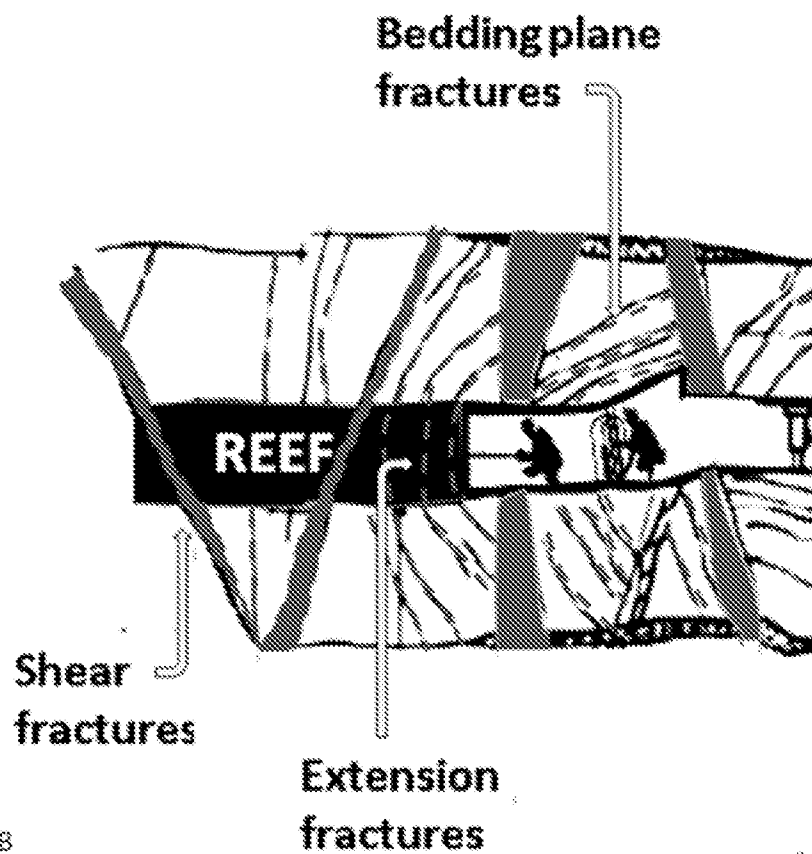
**Figure 1A**

FIG 1B

Figure 1B

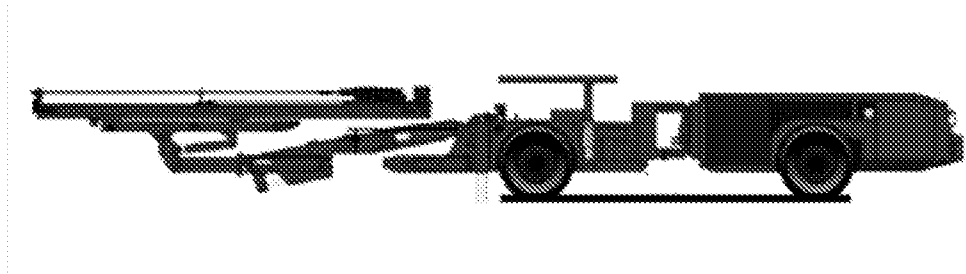


Figure 2

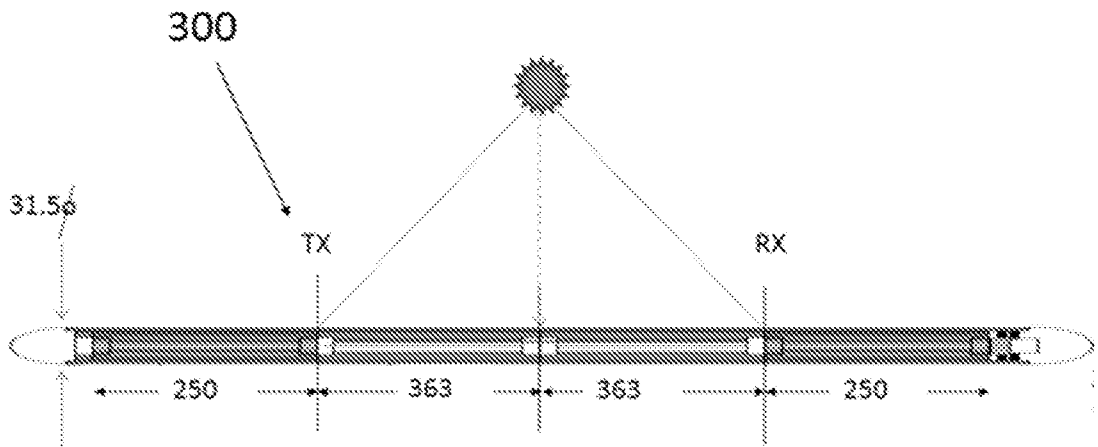


Figure 3

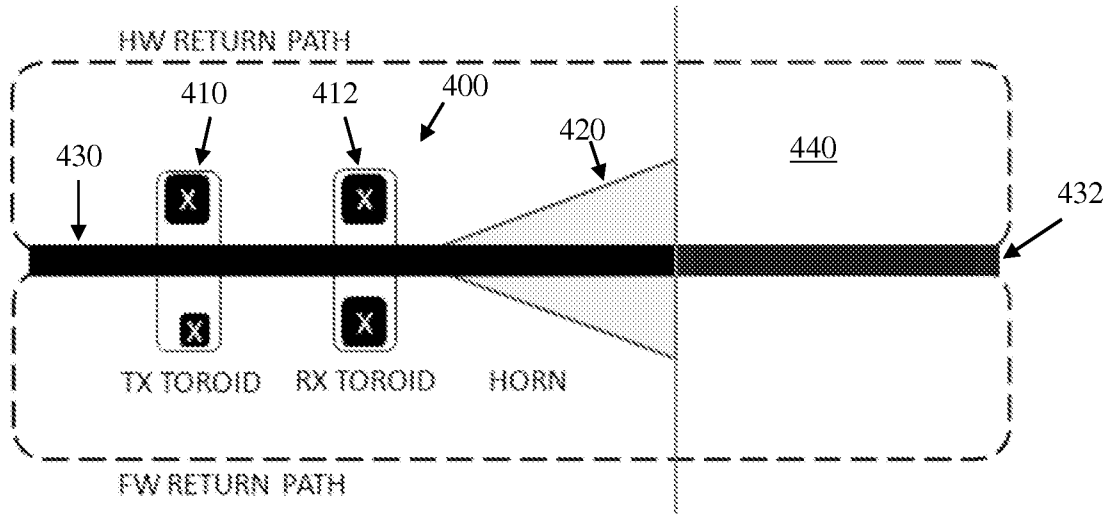


Figure 4

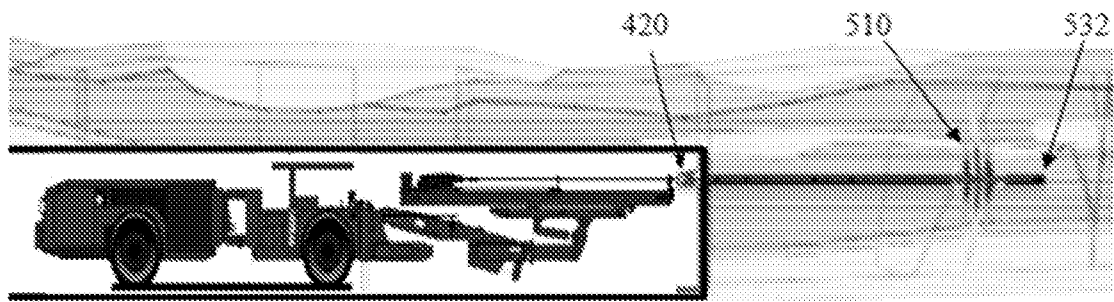


Figure 5a

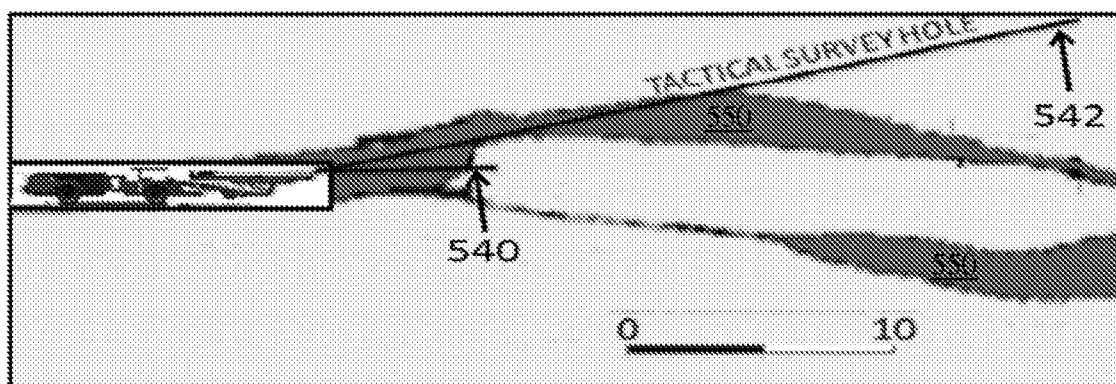


Figure 5B

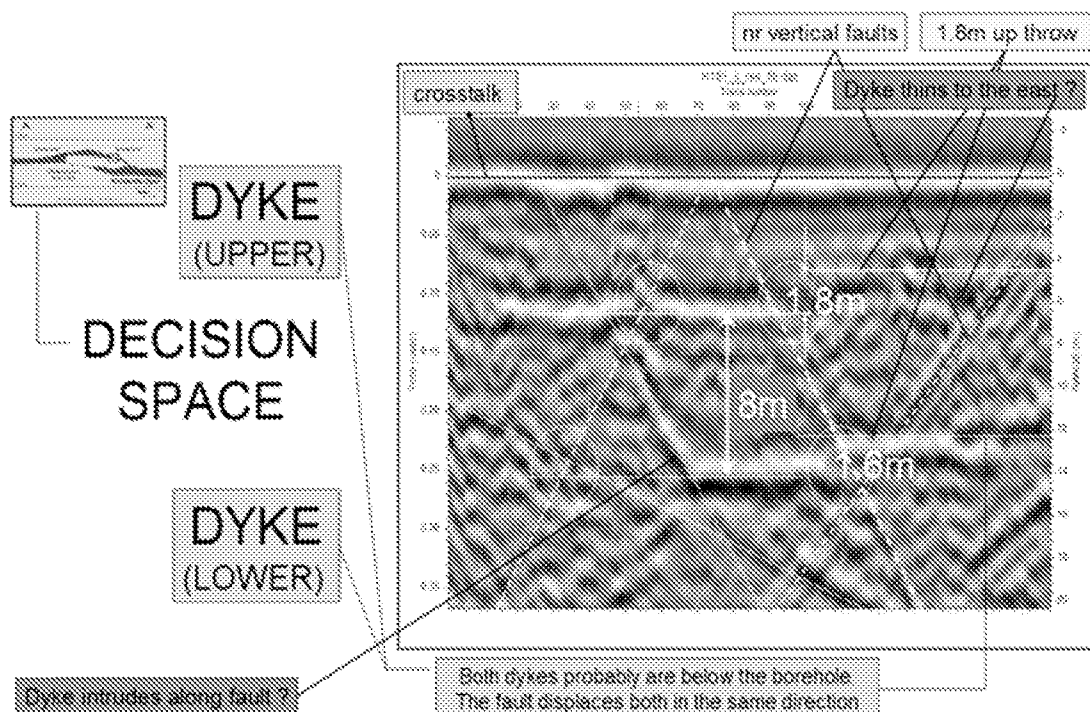
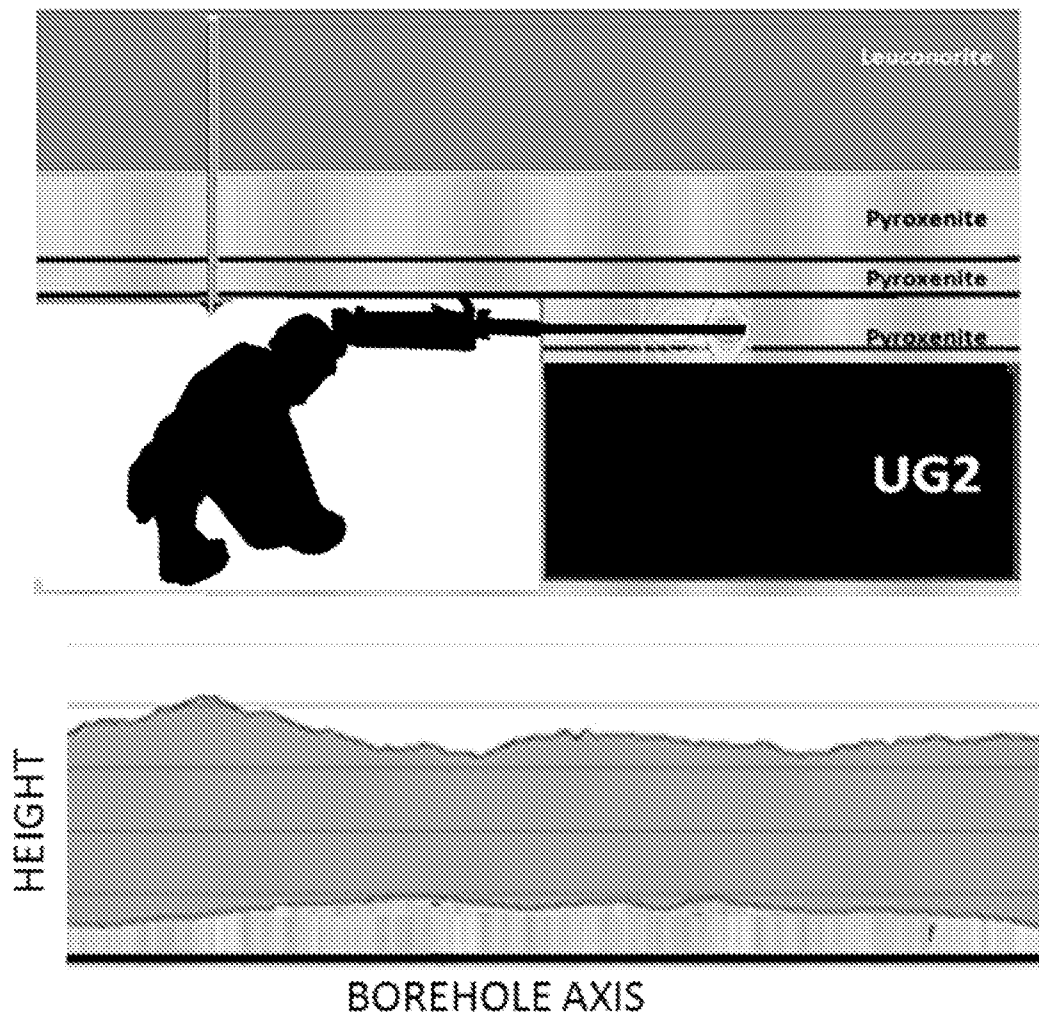


Figure 5c

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**Figure 6**

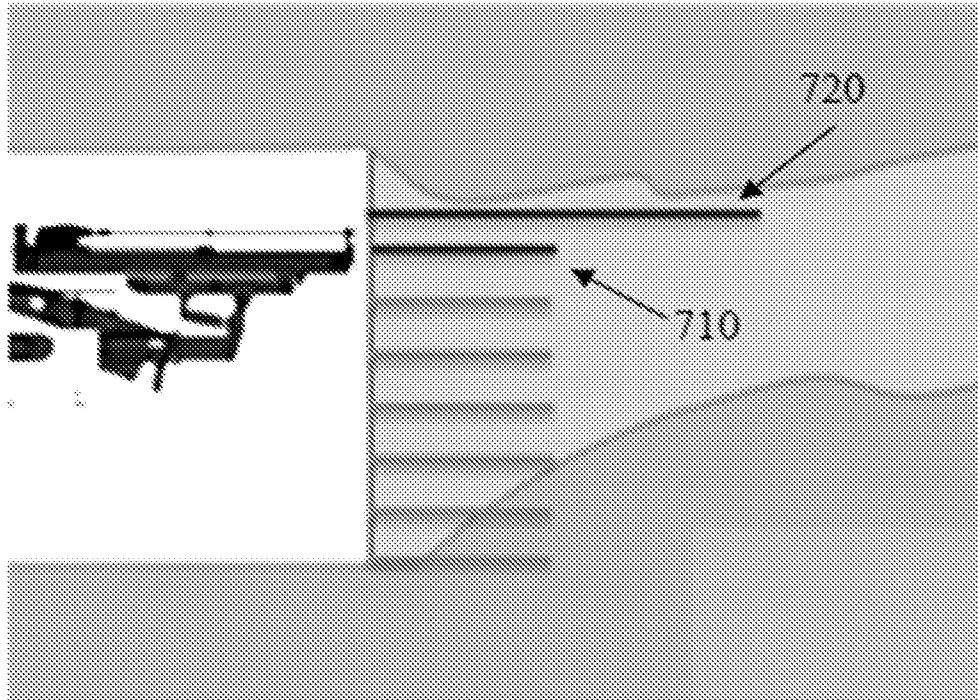
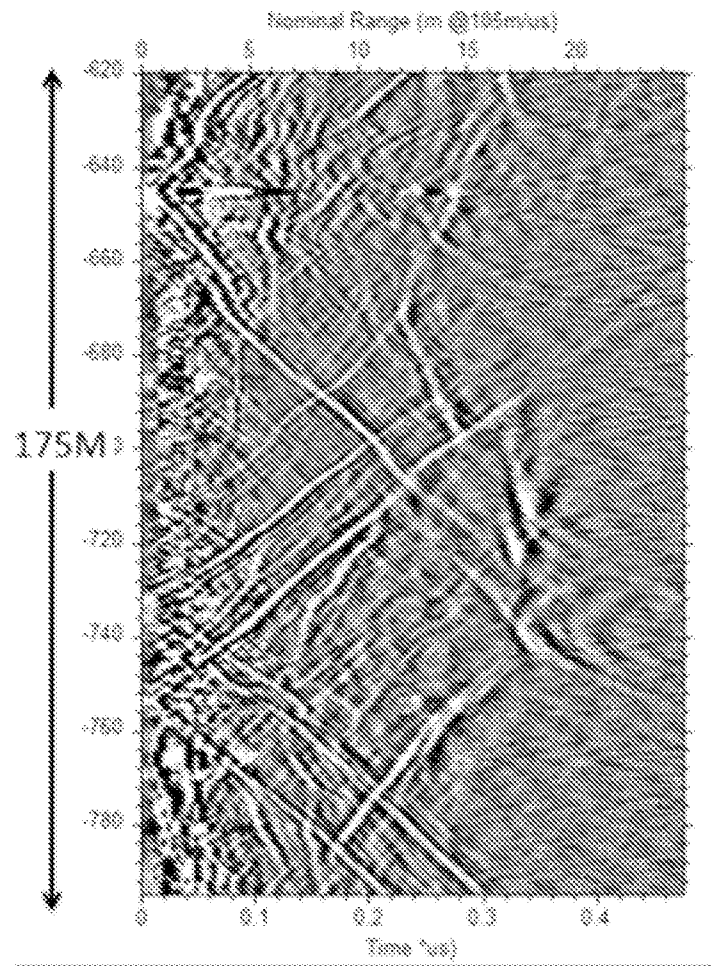


Figure 7

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**Figure 8**

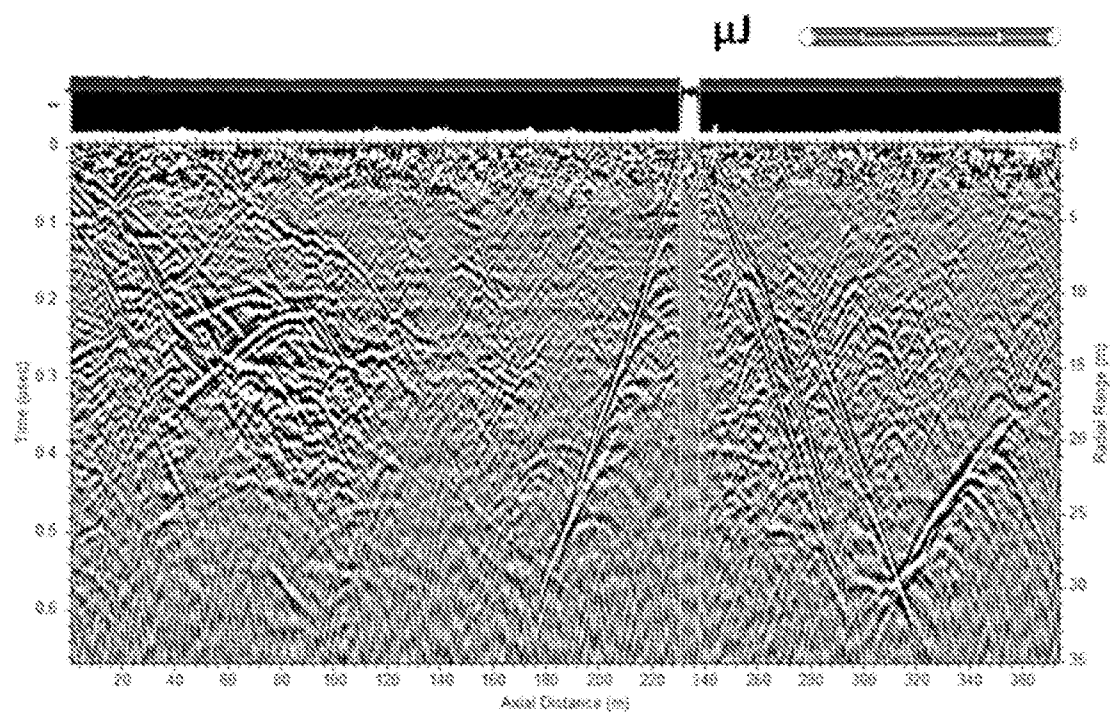


Figure 9a

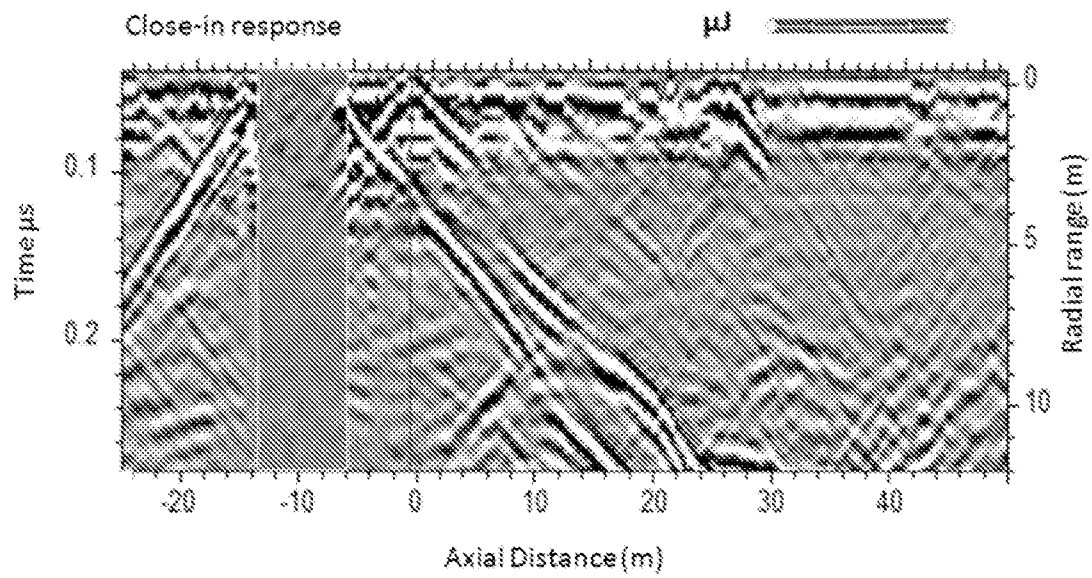
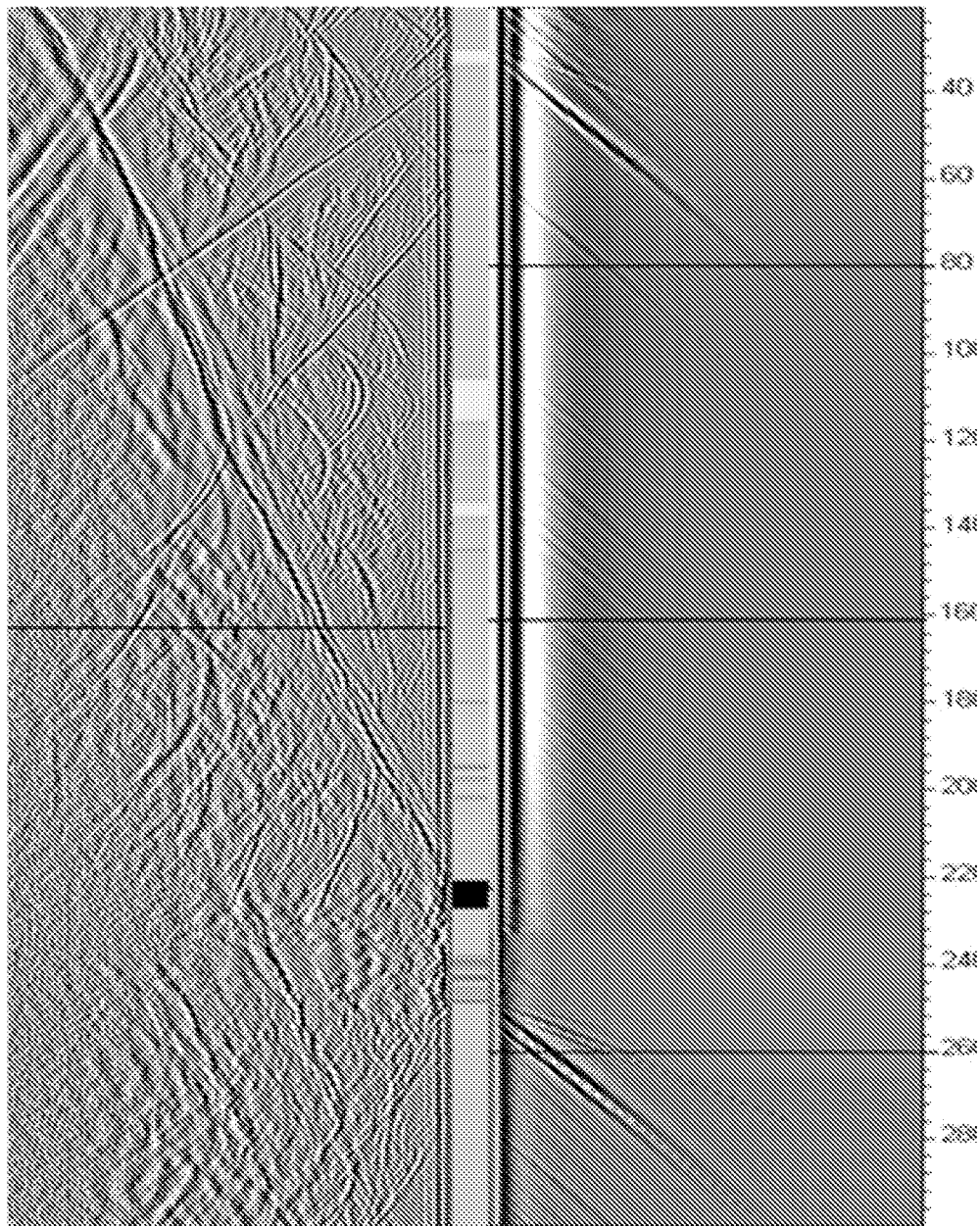


Figure 9B

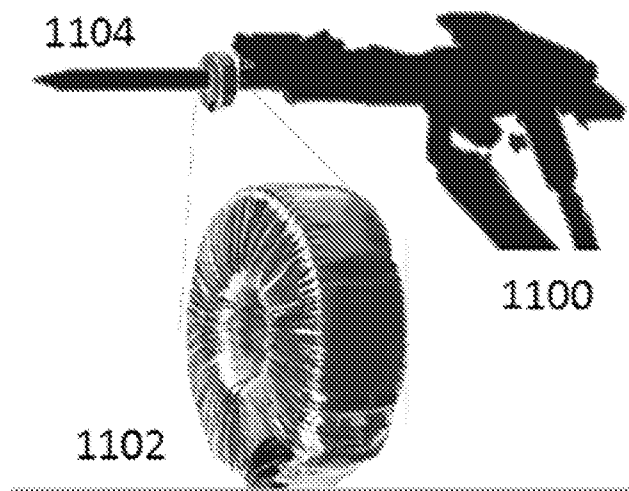
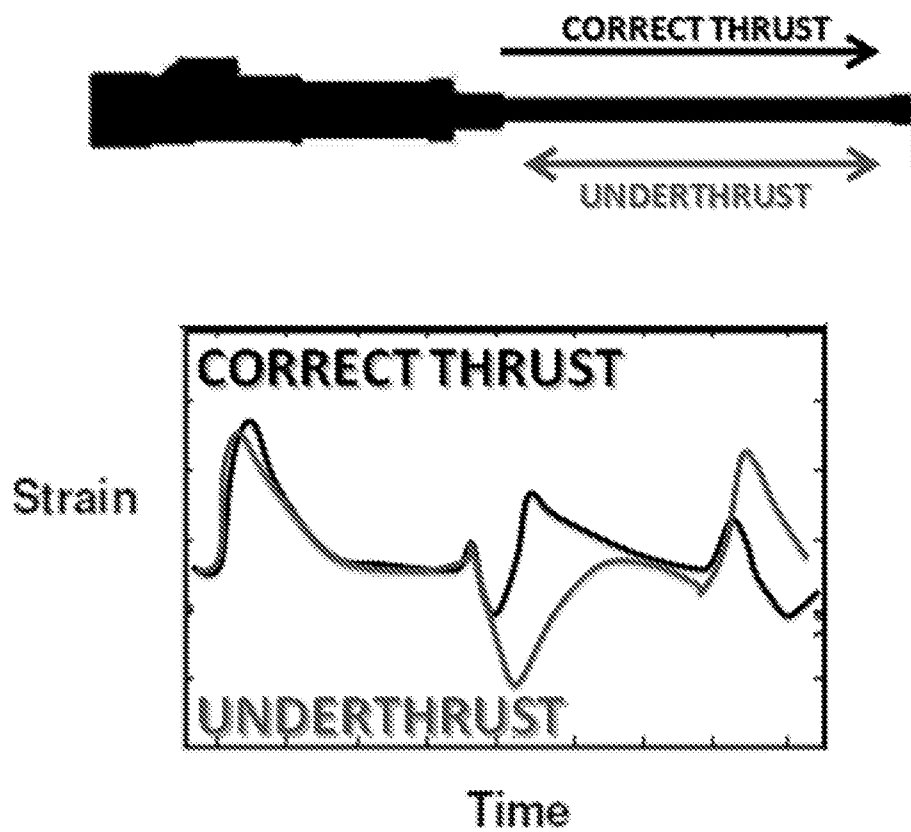


BHR

BGS

Figure 10

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**Figure 11****Figure 12A & B**

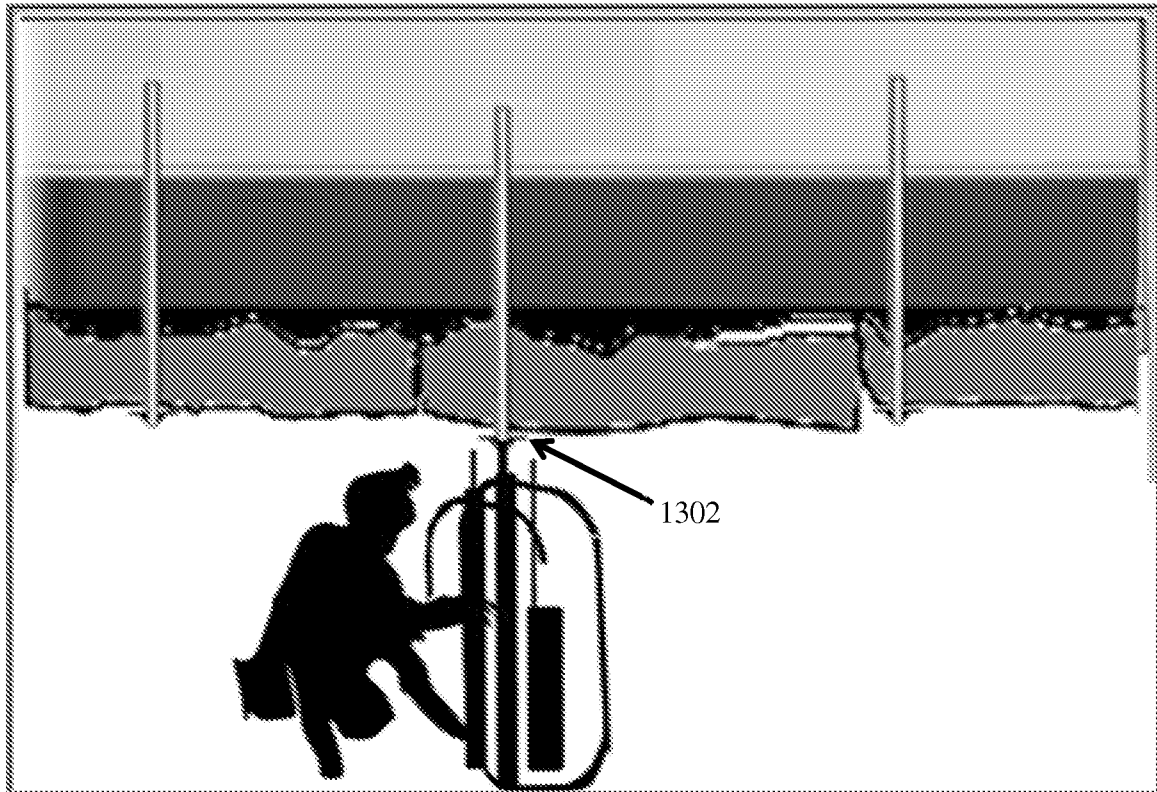


Figure 13a

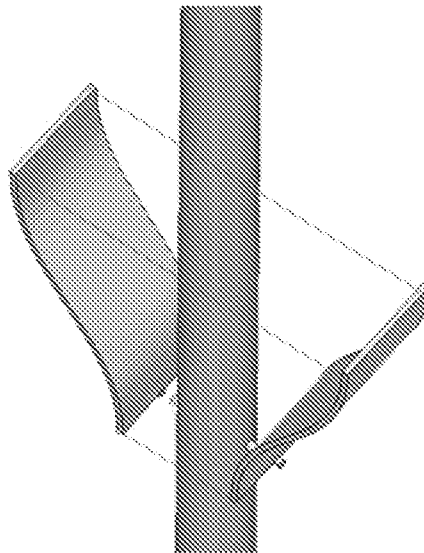
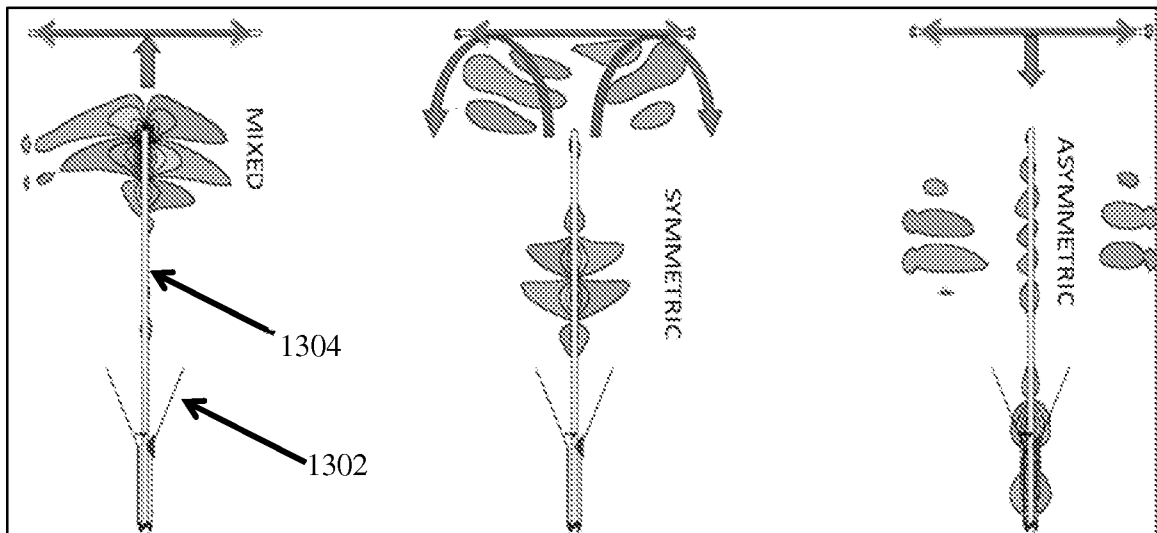
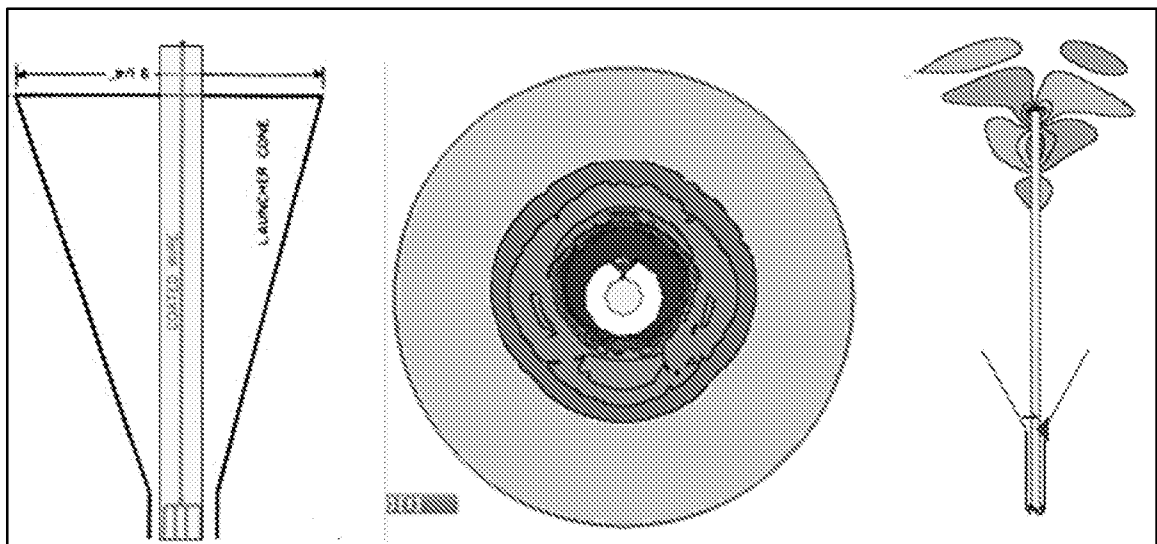
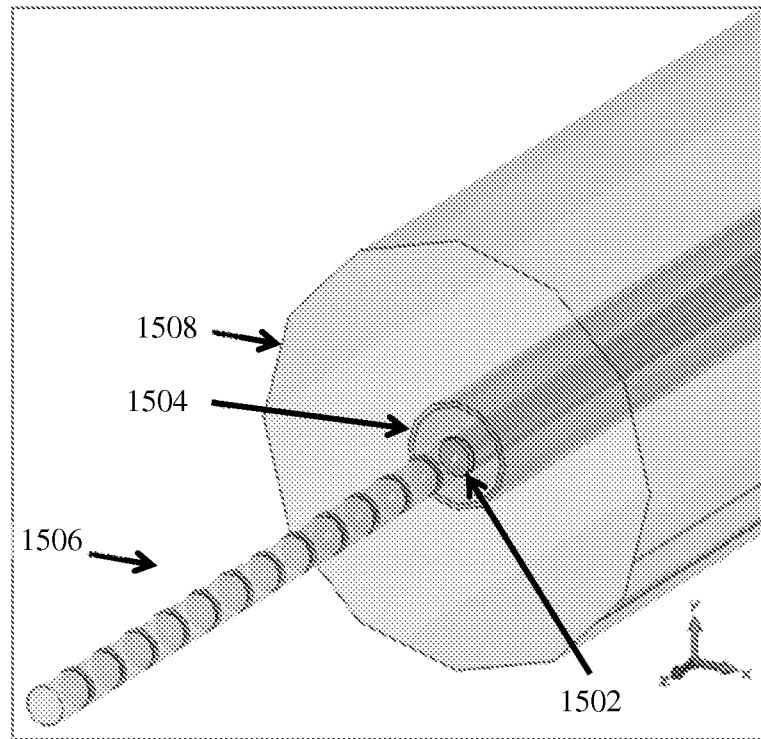
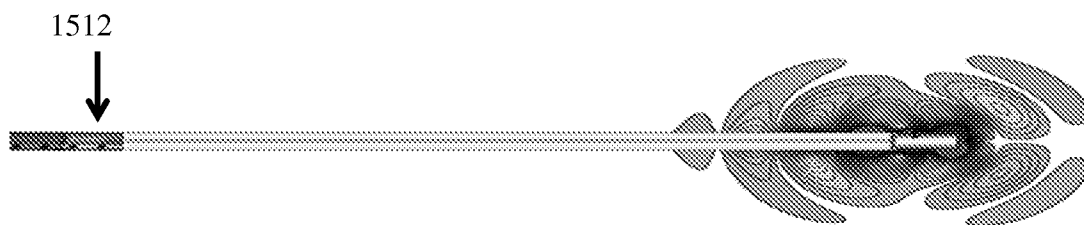


Figure 13b

**Figure 13c****Figure 14**

**Figure 15a****Figure 15b**

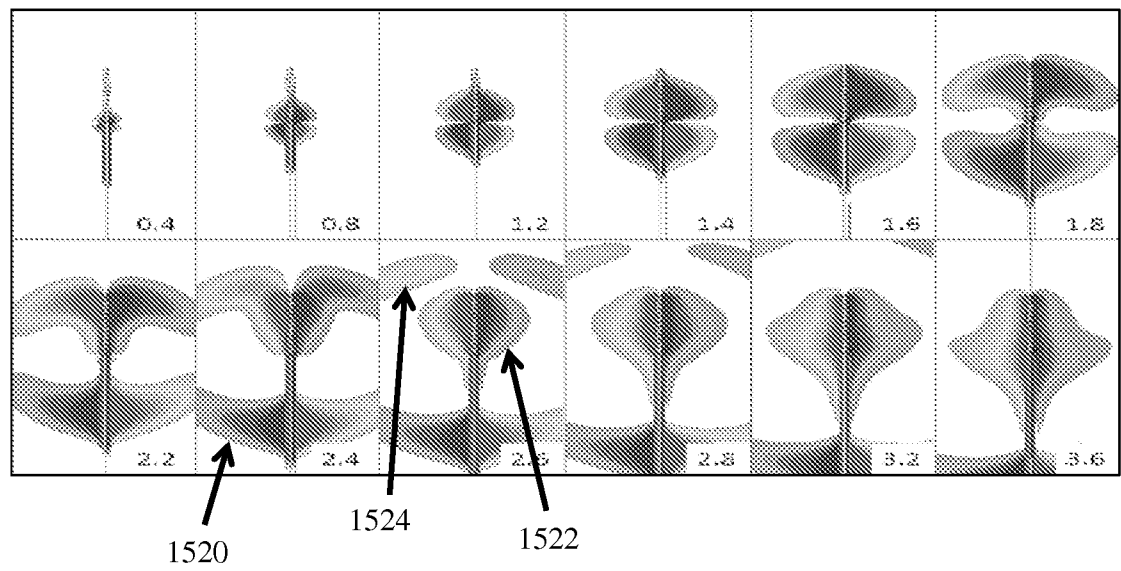


Figure 15c

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2013/000360**A. CLASSIFICATION OF SUBJECT MATTER****G01V 3/12 (2006.01) G01V 3/38 (2006.01)**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC, Google, GooglePatents, Espace:G01V3/IC/EC/CC, ELECTROMAGNET, DRILL, MINING, MAP, GRAPH, IMAGING, RANGE, BORE, MONOSTATIC, BISTATIC, STOPE, WORKFACE, ANTENNA, RECEIVER, TRANSMITTER, TUNNEL AND SIMILAR KEYWORDS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:	
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
13 June 2013Date of mailing of the international search report
13 June 2013**Name and mailing address of the ISA/AU**AUSTRALIAN PATENT OFFICE
PO BOX 200, WODEN ACT 2606, AUSTRALIA
Email address: pct@ipaustalia.gov.au
Facsimile No.: +61 2 6283 7999**Authorised officer**Susan Pring
AUSTRALIAN PATENT OFFICE
(ISO 9001 Quality Certified Service)
Telephone No. 02 6283 2210

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2013/000360
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2100544 A (ENSCO INC) 22 December 1982 Fig 3, col 1 lines 25-29, col 2 lines 101-104, col 4 lines 7-31, lines 48-64, claim 47, page 11 line 33, page 8 lines 14-34	1-12,18
A	WO 2006/015402 A1 (GEOMOLE PTY LTD) 16 February 2006 Claim 47, page 11 line 33, page 8 line 32, page 8 lines 14-34	2,3,7-12
A	US 3806795 A (MOREY) 23 April 1974 Col 3 lines 29-55	

Form PCT/ISA/210 (fifth sheet) (July 2009)

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See Supplemental Box for Details

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-12,18

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

Supplemental Box**Continuation of: Box III**

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- Claims 1-12,18 are directed to a method of imaging a formation from an underground borehole during drilling. The feature of obtaining an electromagnetic map of the borehole which images features of the formation which are less than 5 meters away from the borehole is specific to this group of claims.
- Claims 13-17 are directed to a method of monitoring the operation of a drill rod. The features of sending and recording electromagnetic signals along the drill rod and time synchronizing the measurements to the stroke of the drill and assessing these measurements to determine the drill bit contact with the rock face are specific to this group of claims.
- Claims 19-21 are directed to a borehole radar. The features of a power source of high density batteries, a receiver remaining in the on condition and composed of a rectifier chain and designed to ensure saturation when exposed to large transmitter signals and to provide a high dynamic range, and one or more resistively loaded antennas for radiating BHR and BHS signals produced by a transmitter (not defined as being part of the borehole radar) and for detecting electromagnetic reflections for the receiver are specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied *a priori*.

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2013/000360	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
GB 2100544 A	22 Dec 1982	AU 524580 B2	23 Sep 1982
		DE 3124881 A1	09 Jun 1983
		GB 2100544 A	22 Dec 1982
		GB 2100544 B	20 Nov 1985
WO 2006/015402 A1	16 Feb 2006	AU 2004322187 A1	16 Feb 2006
		AU 2004322187 B2	19 Nov 2009
		AU 2005270744 A1	16 Feb 2006
		AU 2005270744 B2	18 Jun 2009
		CA 2576169 A1	16 Feb 2006
		CA 2576273 A1	16 Feb 2006
		PE 07082006 A1	12 Aug 2006
		WO 2006015402 A1	16 Feb 2006
		WO 2006015436 A1	16 Feb 2006
		ZA 200701195 A	30 Dec 2009
		ZA 200701196 A	27 Jan 2010
US 3806795 A	23 Apr 1974	AU 5317573 A	12 Sep 1974
		CA 962330 A1	04 Feb 1975
		DE 2264037 A1	19 Jul 1973
		FR 2169836 A1	14 Sep 1973
		FR 2169836 B1	25 Apr 1975
		GB 1417722 A	17 Dec 1975
		IL 41056 A	13 Mar 1975
		IT 973244 B	10 Jun 1974
		JP S4879101 A	24 Oct 1973
		JP S5544916 B2	14 Nov 1980
		US 3806795 A	23 Apr 1974
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			