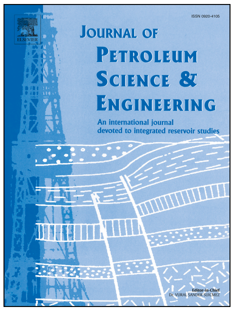

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Application of Resonance Enhanced Drilling to Coring

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Abstract

This paper aims to evaluate the applicability of Resonance Enhanced Drilling (RED) technology to coring operations. A series of coring experiments on sandstone and granite using diamond impregnated and polycrystalline diamond compact (PDC) bits are carried out on a specially designed vertical laboratory drilling rig. We present a comparison between the efficiency and quality of cores obtained using RED technology against conventional coring. Based on this analysis, improvements in penetration rates of up to 180% compared to conventional coring for the same drilling conditions were achieved. All cores retrieved are in good condition showing consistent diameters, generally smooth core surfaces and no evidence of fracturing or other visible core damage. Our preliminary assessment suggests that the RED coring technology provides significant improvements in Rate Of Penetration (ROP), while maintaining consistent core quality compared to conventional coring.

Keywords: Coring; Drilling; Core quality assessment; Experimental studies

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Nomenclature

BHA	Bottom Hole Assembly	DI	Diamond Impregnated
ROP	Rate Of Penetration [mm/s]	PDC	Polycrystalline Diamond Compact
TOB	Torque On Bit [Nm]	LVDT	Linear Velocity Differential Transducer
MSE	Mechanical Specific Energy [MPa]	RED	Resonance Enhanced Drilling
TSP	Thermally Stable Diamond	FD	Face Discharge
ECF	Extended Channel Flushing	WOB	Weight On Bit [kN]
RPM	Revolution Per Minute		

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1. Introduction

Coring is a technology that utilizes special hollow drill-bits to obtain representative rock samples (cores) from sub-surface formations, to evaluate their basic mechanical and geological properties and it is widely used in the Oil & Gas industry. In addition, coring has been widely applied in many other fields, such as space [1, 2], medicine [3, 4], as well as for sub-surface scientific research, geotechnical and resource exploration [5–7]. Although these applications have different purposes and means of deployment, the basic principles of the coring operations are similar. Coring forms an integral part of Oil & Gas operations, where rock samples acquired from a reservoir give invaluable ‘ground truthing’ of information that otherwise is obtained by remote sensing techniques such as reflection seismic data or wireline geophysical logs. Core data is therefore regarded as critical for calibrating petrophysical data derived from wireline logs [8, 9]. Core samples can provide both qualitative and quantitative geological and petrophysical data necessary for reservoir characterization and management, completion decisions, drilling, and other applications, in turn, providing means for obtaining a representative description of reservoirs often lying at extended depths [10, 11].

Coring technology has been improving continually since its introduction. It can be categorized into three main methods: conventional, wireline and sidewall coring [12]. Conventional coring is the earliest method comprising a coring bit connected directly to a core assembly and drill-pipes, which in turn enables the collection of a few meters of core, prior to pulling the drill-string out of a bore-hole for core retrieval. To address time and cost implications associated with frequent tripping operations, which become major when operating at depths of several kilometers, a method termed wireline coring was developed. This method involves using wireline/slickline trips in order to retrieve a core sample through the inside of the drilling pipe, therefore removing the requirement to pull the entire drill-string after each core run. Both of these methods can be successfully used to obtain cores from the well. Core samples covering 30, 60, or 90 ft sections are common and provide valuable reservoir geological and petrophysical properties for geoscientists [13]. Many new technologies aimed at improving drilling efficiency and enhancing core quality are being developed based on these two methods, such as logging-while-coring technology [14], new liner systems [15, 16], pressure coring technology [17–20], anti-jam coring systems [21, 22], extended coring technology [10, 23], turbine driven coring systems [24] and wireline continuous coring [25, 26].

The third commonly applied method is sidewall coring, which is also deployed via wireline/slickline, but in contrast to conventional coring is applied after the interval of interest has been drilled conventionally. Sidewall coring is faster than the first two methods and can provide precise depth control and targeting of selected geological elements over much larger intervals. The type of core samples are usually

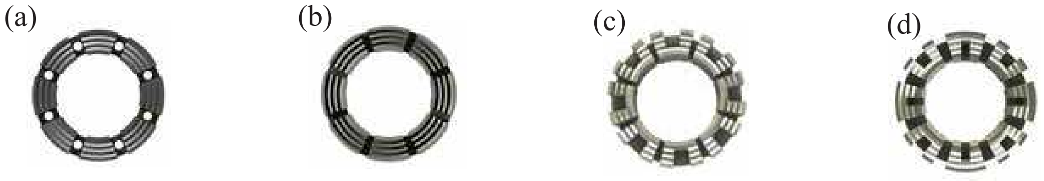

Figure 1: Coring bit profiles: (a) face discharge, (b) extended channel flushing, (c) V profile and (d) jet profile. Taken from [38]

relatively small in length (1-1/8″ to 1-3/4″) and diameter (up to 1″), however, larger sized samples are now becoming more common [27, 28]. This coring method can be classified into two types: percussion (core is obtained by firing core bullets propelled by explosive charges into the formation) and rotary (core is obtained by small conventional rotational coring motors). Rotary sidewall coring is more widely used because it generally delivers better core integrity, especially in harder formations [29, 30].

In conventional drilling operations, the coring drill-bit forms a key element of the coring system. A vast range of different coring bits have been designed for different rock-types, drilling assemblies and other aspects [31]. For conventional and wireline coring, coring bits can be divided into four types by the composition of cutters: natural diamond, polycrystalline diamond compact (PDC), thermally stable diamond (TSP) and impregnated drill-bits [32]. Also, depending on the amount of drilling fluid that passes through the bit, the coring bit profile can mainly have three forms: face discharge (FD), extended channel flushing (ECF) and V and Jet profiles (see Fig. 1). Additionally, in order to improve rate of penetration (ROP) in hard and abrasive formations, some new coring bits have been developed to include hybrid bit technology combining rock roller and PDC technology [33]. Deschamps *et al.* [34] and Tian *et al.* [35] presented a specific drill-bit design that generates micro-cores of formation during conventional drilling operations, which are returned to the surface with the drilling fluid and cuttings. Guarisco *et al.* [36] designed a PDC core bit to minimize vibrations while coring and reduce the chance of core jamming. Sun *et al.* [37] developed a high matrix diamond coring bit manufactured using combined hot pressing and welding methods to improve overall drilling efficiency.

Regardless of the coring technology and bit used, cost effectiveness is a crucial factor for coring operations, which in turn is directly proportional to the rig time. The quality of core samples is another important factor to consider, with the primary purpose of being able to retrieve representative and undamaged samples of the formation of interest. With the growing global demand for Oil & Gas resources and a move towards deeper and more complex reservoirs, robust core characterization of complex reservoirs has never been more important. Coring of hard and/or unstable reservoirs may result in low ROP, core jamming and ultimately higher operational costs coupled with reduced recovery rate and poorer quality of the core. Therefore, in order to ensure the quality of the core samples and in order to improve the efficiency of coring, an innovative coring method utilizing RED, tested for conventional drilling [39–41], is proposed in this paper.

RED is a new technology developed at the University of Aberdeen [41], which aims to improve drilling performance by introducing high-frequency, at or near resonance vibration, to achieve much higher ROPs than those achieved currently by standard rotary drilling techniques, while at the same time ensuring a good borehole stability. The RED technology applies controllable high frequency dynamic stress on the drilled formation, which is induced by axial oscillations of a drill-bit at the resonance conditions. The resonance conditions between a drill-bit and a formation are maintained for varying drilling conditions by adjusting the frequency and amplitude of the dynamic load to produce a steadily propagating fracture zone. Extensive modeling [42, 43], and experimental [44–46] studies have proved that RED can significantly improve the ROP, which is particularly well suited for hard rocks and does not requires a large Weight On Bit (WOB) to drill efficiently.

In this paper, we aim to evaluate the applicability of this method to coring operations. A series of coring experiments on homogeneous sandstone and granite were carried out on the RED Vertical Rig [39], and subsequently the efficiency of RED coring and the core quality are compared against conventional coring. The paper is organized as follows. In Section 2, the RED experimental rig and details of the drill-bits and rocks used are given. The experimental methodology and results are discussed in Section 3, followed by the core quality assessment described in Section 4.

2. RED Vertical Rig

During development of the RED technology, several experimental rigs have been constructed. These range from small scale rigs which are used to investigate fundamental impact dynamics to large scale experimental setups, which include vertical and horizontal RED rigs (see [39]). For the purpose of evaluating the applicability of RED for coring application we utilise the RED Vertical Rig shown in Fig. 2(a). The rig allows experiments with drill-bits having a diameter up to 6″, with a rotational velocity up to 120 rpm and a WOB up to 50 kN. The main components of the experimental rig shown in Fig. 2(a) are the fixed frame, moving frame, torque restraint frame, vertical lathe and hydraulic system to generate WOB. A drill-string is composed of a vibro-isolator spring, magnetostrictive actuator (PEX-30), structural spring, 4 component dynamometer, connector and coring drill-bit. In this setup, a rock sample is fixed to the rotary table which rotates with a fixed angular velocity, while the drill-string is stationary. A close up view on the coring bit connector and its placement is depicted in Fig. 2(b). In this study, we evaluated the performance of two types of coring bits shown in Fig. 2(c), a 3-7/8″ impregnated natural diamond bit and a 4.1″ diameter PDC coring bit, producing cores with diameters of 2.4″ and 1.3″, respectively. For each of coring bit, there is a separate coring bit connector, that allows the drilling of cores with lengths up to 500 mm.

The RED module [39, 41] shown in Fig. 2(d) is used, which is comprised of the exciter, structural spring, vibration isolation unit and drill-bit. In the study we used standard industrial drilling/coring drill-bits mounted into the Bottom Hole Assembly (BHA). The module is subjected to a rotary motion and a Weight On Bit (WOB). The exciter, comprising the high frequency exciter and the structural spring, subjects the drill-bit to an oscillatory motion of given amplitude A and frequency f. The RED module is isolated from the drill-string by a vibration isolation unit, that ensures vibration are not transferred to other parts of BHA.

The Vertical RED Rig is equipped with multiple sensors that allow us to monitor the main drilling parameters such as ROP, WOB, Torque On Bit (TOB) and angular velocity. The ROP is measured using both a Linear Velocity Differential Transducer (LVDT) and a linear encoder attached to the fixed and moving frames. The 4-force component dynamometer (load-cell) placed beneath the structural spring measures the axial force (static and dynamic), two lateral forces as well as reaction torque acting on a drill-bit. The angular velocity of the rotary table is measured by a rotary encoder, mounted on the vertical lathe. The dynamic force is generated by the PEX-30 exciter and passed on to the drill-bit through the structural spring, the load-cell and the drill-bit connector. The magnetostrictive exciter generates a prescribed harmonic excitation of a given frequency f and amplitude A, consequently driving the drill-bit at the resonance conditions. The vibro-isolator filters any vibration from PEX-30 to the hydraulic cylinder and the frame. The level of vibration throughout the experimental rig is measured by various accelerometers attached to the fixed and moving frames. The relative displacement between the moving frame and the drill-bit is measured by an eddy current probe, that allows for robust monitoring of the axial vibration generated by the PEX-30 exciter. All the measurement signals are synchronised and recorded using a purpose-built, Labview based data acquisition system.

3. Methodology and experimental results

In order to test the applicability and efficiency of the RED technology for coring applications, several series of experiments have been carried out. At the start of each coring run, the rock was driven at low angular velocity (10 rpm) to allow for all the cutters to engage and limit effects of lateral vibration which could be generated during the initiation of coring. All experiments have been carried out in two

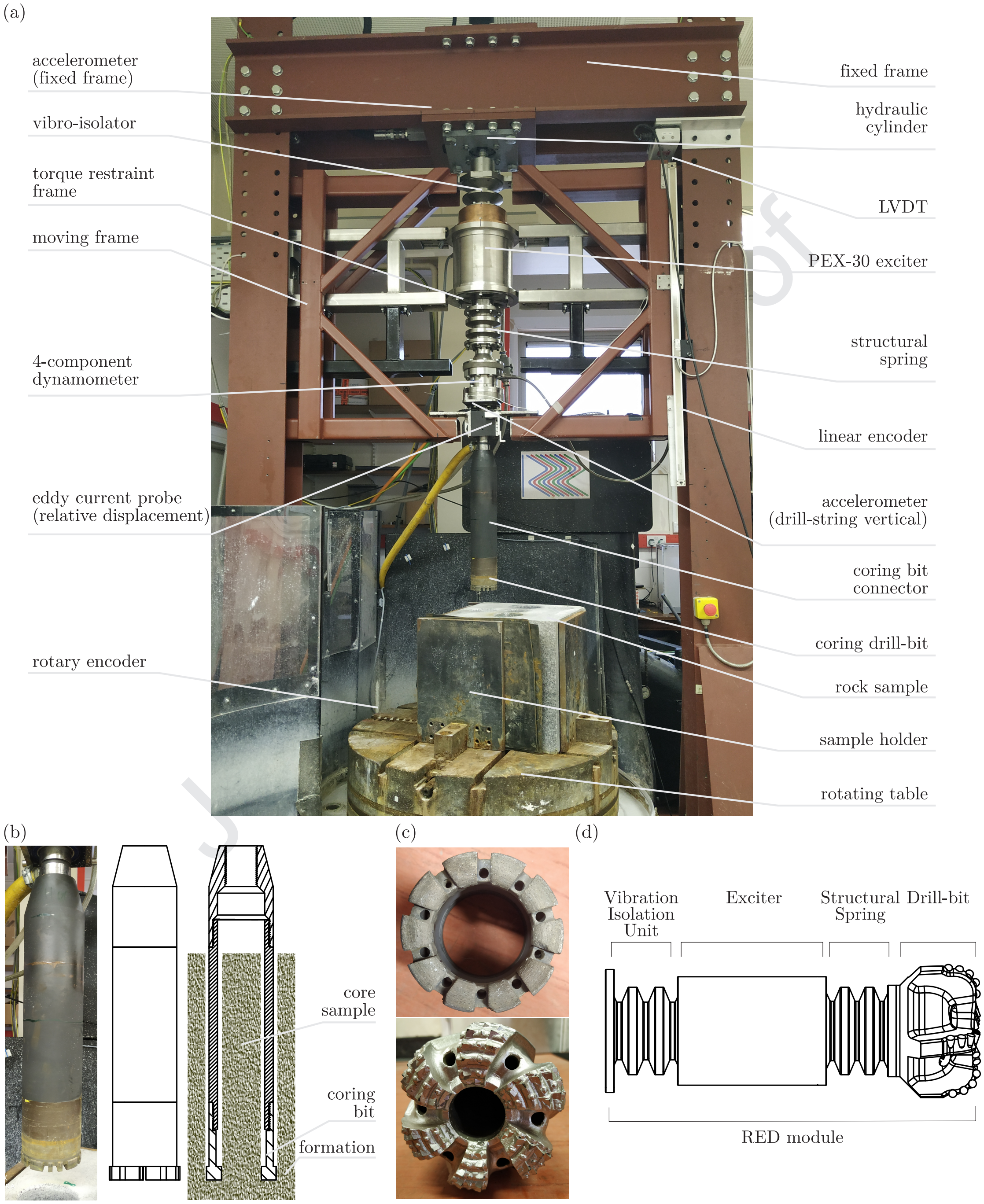

Figure 2: **RED vertical experimental rig**; (a) a photograph of the rig [41] with its main components: sensors (4-force component dynamometer, LVDT, rotary encoder, eddy current probe), fixed frame, moving frame, drill-string (vibro-isolator, PEX-30 exciter, structural spring, coring bit connector and coring bit), rotary table and sample holder; (b) a close view on the coring bit connector and it's operation; (c) examples of coring diamond impregnated and PDC bits used in the setup; (d) a schematic of the RED module with its main components [41].

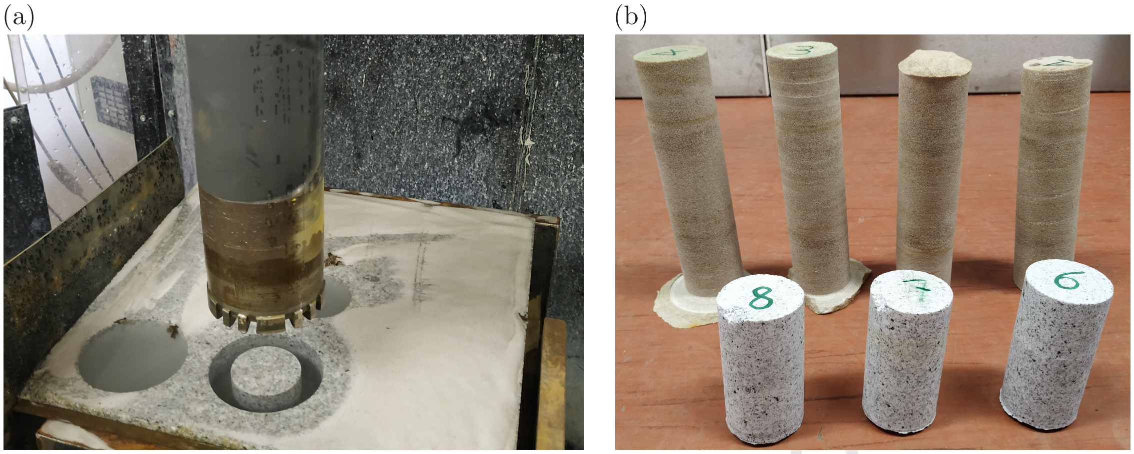

Figure 3: Photographs depicting RED coring operation (a) and (b) examples of sandstone and granite cores, obtained using diamond impregnated coring bit.

consecutive equal distance runs: (a) first we cored conventionally and then (b) we cored with the RED action. In this way, we minimised the influence of depth and possible formation inhomogeneity in our comparisons between conventional and RED coring.

As part of the experimental studies, several cores of granite and sandstone (see Fig. 3) were drilled using two types of coring bits: Diamond Impregnated (DI) and PDC (see Fig. 2(c)). As a first step, we applied the conventional coring method to obtain a sandstone sample (Core 1) with the purpose of validating the data acquisition procedures and to observe the quality of the core sample, which served as a reference for subsequent cores obtained using the RED technology. Then, a series of experiments were carried out using the RED coring for different excitation frequencies. As mentioned earlier each experiment involved a conventional coring first followed by a subsequent RED coring interval (in each interval a drilling distance was the same). For example, Core 2 with the length of 233.3 mm was drilled in 15 intervals as follows: initial test to ensure a proper cutter engagement, conventional coring, RED coring with 190 Hz, conventional coring, RED coring with 193 Hz, conventional coring, RED coring with 196 Hz, conventional coring, RED coring with 199 Hz, conventional coring, RED coring with 202 Hz, conventional coring, RED coring with 205 Hz, conventional coring and finally RED coring with 208 Hz. Overall over 100 experiments were carried out in this study and their details are listed in Table 1.

In Fig. 4, we present examples of typical measurements captured during two experiments of RED coring in granite (Panel (a)) and sandstone (Panel (b)), where a family of time histories including progression, WOB, TOB, bit relative displacement and bit rotational velocity are depicted. In the first case, we core the granite sample with 40 rpm angular velocity and WOB of 2.6 kN, while the RED module, providing axial excitation at f=170 Hz, is switched on at t=59.56 s (marked with a vertical dashed line).

Table 1: Summary of RED coring experiments carried out in sandstone and granite, using diamond impregnated or PDC bit and their operating conditions.

Sample		**Bit**	**WOB**	**RPM**	**RED Frequency**	**Coring Method**	**Coring Length**	**ROP Improvement Factor**
			[kN]	**[r/min]**	**[Hz]**		**[mm]**	**[%]**
Sandstone	1	Diamond Impregnated Bit	3, 4, 5	12, 20, 30, 15	NA	Conv.	271.3	NA
	2		2	40	190, 193, 196, 199, 202, 205, 208	10 mm Conv. & 10 mm RED	233.3	126.5
	3		2	25	165, 170, 175, 180, 185, 190, 195, 200, 205, 210, 215, 220, 225, 230	5mm Conv. & 5mm RED	235.3	151.8
	4		2	25	210	30mm Conv. & 30mm RED	233	116.7
	10	PDC Bit	2.5	25	190, 195, 200, 205, 210, 215, 220, 225	10mm Conv. & 10mm RED	238	119.6
	11		2	25	170, 175, 180, 185, 195, 205, 215, 230	10mm Conv. & 10mm RED	214.4	141.5
	12		2.5	40	NA	Conv.	234.5	NA
Granite	6	Diamond Impregnated Bit	3	10	170, 175, 180, 185, 190, 195	5mm Conv. & 5mm RED	117	121.8
	7		3	10	150, 160, 165, 170, 175, 180, 185, 190, 195, 200, 205	5mm Conv. & 5mm RED	109	115.5
	8		3	10,40	170, 180, 185, 190, 195, 200, 205	5mm Conv. & 5mm RED	113.3	113.5, 139.33
	9		3, 4	40	NA	Conv.	117.5	NA

As soon as that happens, we observe a dynamic load in time histories of WOB (7.14 kN peak to peak) and TOB (122.27 Nm peak to peak) on top of the base values of 2.6 N and 32.4 Nm, respectively. During the interval when RED was on, the coring bit was oscillating axially (with amplitude of 0.14 mm), which was sensed by the eddy current probe measuring a relative displacement of the bit relative to the moving frame. In this particular experiment, we were able to obtain an improvement of 147.7% when using RED coring (in the time interval t from 59.56 s to 100 s), compared to conventional coring (t from 0 s to 59.55 s). The improvement factor, $\eta = \frac{ROP_{conv}}{ROP_{RED}}$, compares the slopes of drill-bit displacement, when coring conventionally and with RED. The change in ROP is clearly visible in the upper panels of Fig. 4. The second example of a typical experiment, involved coring a sandstone sample at 25 rpm, 1.9 kN of WOB and 230 Hz of the RED frequency. As previously, when the RED module was switched on (t=65.41 s), we observed an additional dynamic load in WOB (18.62 kN peak to peak) and TOB (270.7 Nm peak to peak) around the base values of 1.9 kN and 6.6 Nm, respectively. In this case, the drill-bit was oscillating axially with amplitude of 0.59 mm, while the improvement factor achieved was 178.2%. Note, that both examples presented above utilized the Diamond Impregnated drill-bit. These initial results clearly indicate a potential cost benefit of much faster coring, which can much higher of the RED module and the RED coring process are fully optimized.

Subsequently, we carried out a systematic series of experiments aimed at finding the optimal operational parameters for the RED module to provide the best improvement factor for both sets of drill-bits and rocks. In Fig. 5 we present graphs depicting the change in improvement factor as a function of RED frequency f for six different cases: (a) granite, 10 rpm angular velocity, DI bit, WOB of 3.0 kN; (b) sandstone, 25 rpm angular velocity, DI bit, WOB of 2.0 kN; (c) granite, 40 rpm angular velocity, DI bit, WOB of 3.0 kN; (d) sandstone, 40 rpm angular velocity, DI bit, WOB of 2.0 kN; (e) sandstone, 25 rpm angular velocity, PDC bit, WOB of 2.5 kN and (f) sandstone, 25 rpm angular velocity, PDC bit, WOB of 2.0 kN.

In all cases, we observe improvement factors ranging from 105% to 180% confirming the potential of RED in coring ROP. In addition, it can be seen by comparing Figs 5 (a) and (c) that higher improvement factors are obtained for the higher angular velocity at the same excitation frequency, where the DI drill-bit is used to core the granite sample under WOB of 3 kN in both of cases. However, it is interesting to note that the improvement factor decreases with increasing angular velocity for sandstone (see Figs 5 (b) and (d)) with the DI drill-bit and WOB of 2 kN. By looking into the lithology of granite and sandstone, it can be concluded that for the DI drill-bit used in the experiment, a high angular velocity is better for RED coring of hard rocks, which is not that evident for softer ones. Also, we can find that improvement factors are higher in Fig. 5 (e) than those in Fig. 5 (f), where the same PDC bit and angular velocity of 25 rpm are used for coring sandstone in both cases.

4. Core quality assessment

The quality of cores retrieved from sub-surface coring operations is arguably the most important feature of any coring undertaking alongside core recovery e.g. the ratio of expected verus retrieved core length [47]. Simply put, a core barrel full of loose gravel, or alternatively a 300 mm section of pristine core from a 30 ft barrel run will both lead to major and expensive disappointment for the operator. The chosen coring operation must have the potential to deliver useable core material capable of producing the required results from both geological and petrophysical investigations, that will go towards justifying the inevitable additional expense of coring rather than simply drilling the formation [47]. Core damage can take many forms and have many different origins including those associated with (i) geology: such as sub-surface stress state, rock strength/competence, poorly lithified sediments, natural fractures and swelling clays, (ii) coring operations: such as core jamming, core barrel vibrations, fracturing, crushing, cutter shearing, and (iii) core retrieval and storage: pore fluid expansion during rapid ascent, drilling fluid invasion, thermal contraction and poor handling/storage.

Within this section we present a core quality assessment of the cores produced during this study in order to appraise the influence of RED coring technology on core quality. The key goal is to appraise whether the application of RED coring has any positive or negative influences on core quality within the confines of the study setup. In general, all cores cut during the project were retrieved in good condition showing consistent diameters, generally smooth core surfaces and no evidence for fracturing. In some cases, minor surface damage is present consisting of coring bit teeth marks, spiral scratches linked to coring bit retrieval and re-entry, and in a few cases of broader core diameter variations interpreted to represent subtle alignment changes to the coring setup during coring as e.g. is seen in Core 3 (Fig. 6).

Beyond close visual inspection, high precision caliper measurements (0.01 mm precision) were taken of the core diameter for each measurement interval of RED versus non-RED to appraise whether RED coring had any influence on the retrieved core diameters. In total, three sandstone and three granite cores were cut using a combination of conventional and RED coring for different interval lengths, an example of each is presented in Fig. 6. Ten individual diameter measurements at incremental rotations around the core were measured in the middle of each RED versus non-RED depth interval. Independent of RED application, in most cases, a subtle < 1 mm increase in the core diameter occurred with measured depth. We interpret these broad changes to be the result of the un-sleaved core undergoing minor attrition due

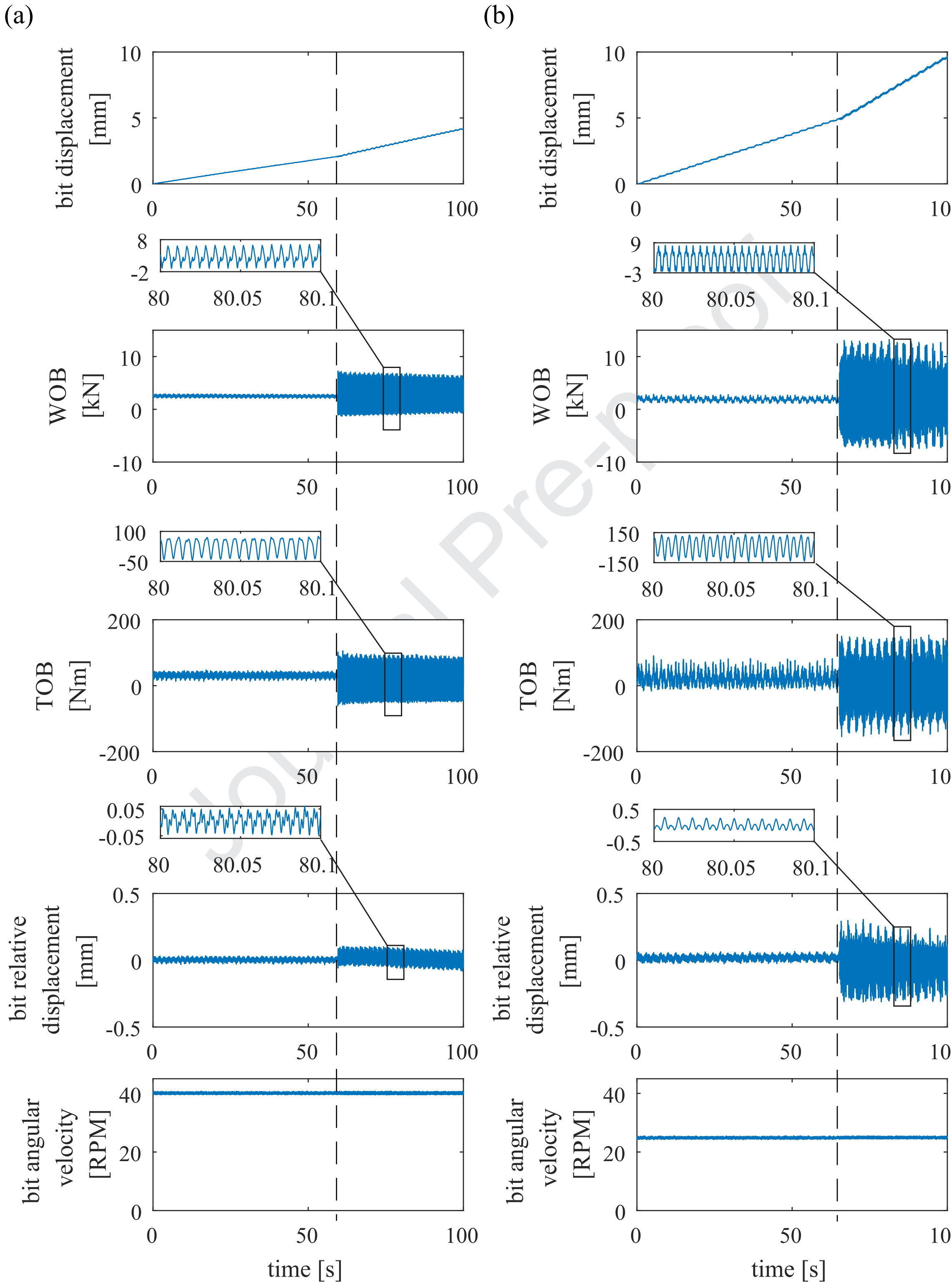

Figure 4: Example time histories collected from the RED Vertical Rig showing (a) 147.7% improvement in ROP whilst coring in granite at 40 rpm angular velocity, RED frequency of 170 Hz and (b) 178.2% improvement in ROP whilst coring in sandstone at 25 rpm angular velocity, RED frequency of 230 Hz.

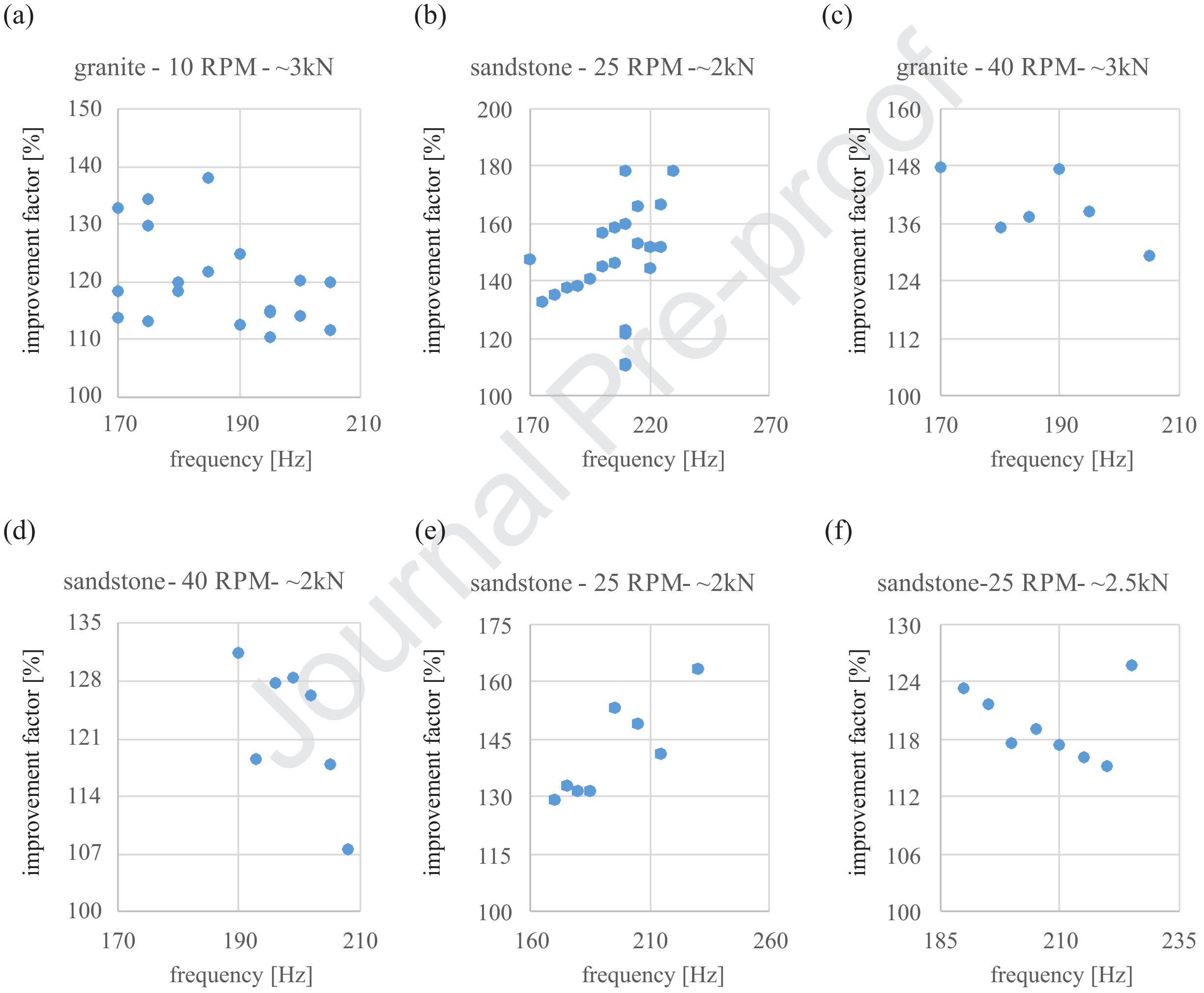

Figure 5: ROP improvement factors using RED technology whilst coring in: (a) granite, at 10 rpm angular velocity, DI bit, WOB of 3.0 kN, (b) sandstone, at 25 rpm angular velocity, DI bit, WOB of 2.0 kN, (c) granite, at 40 rpm angular velocity, DI bit, WOB of 3.0 kN, (d) sandstone, at 40 rpm angular velocity, DI bit, WOB of 2.0 kN, (e) sandstone, at 25 rpm angular velocity, PDC bit, WOB of 2.0 kN and (f) sandstone, at 25 rpm angular velocity, PDC bit, WOB of 2.5 kN.

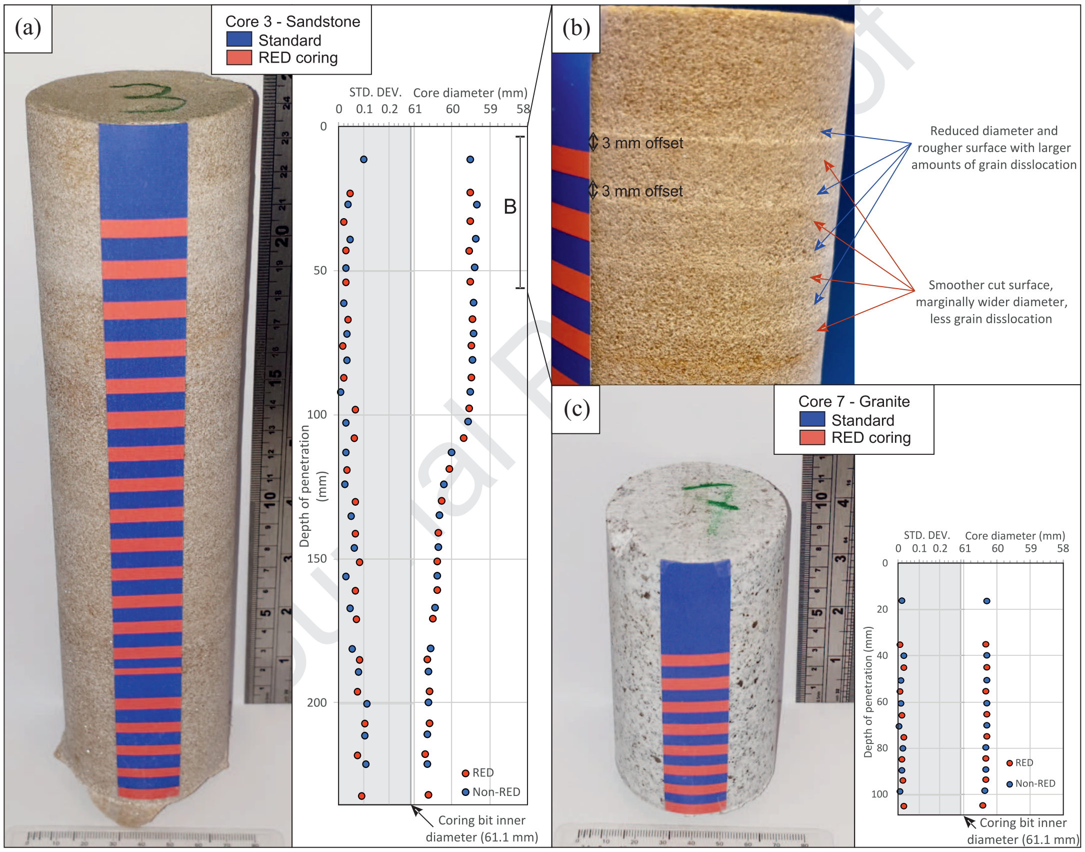

Figure 6: Core quality assessment; (a) a photograph of Core 3 with the intervals cored with conventional and RED coring highlighted. Average core diameter, calculated from 10 high precision (0.01 mm) caliper measurements around the core within each interval are displayed alongside the standard deviation of the 10 measurements are shown scaled to the core photograph; (b) examples of minor diameter variations between RED and conventional coring at the top of Core 3; (c) core example from the granite coring runs alongside the same diameter measurements and standard deviation as in (a). Note, the 3 mm offset is related to the topography of the DI cutter whereby the 'time-zero' deepest part of the coring bit is 3 mm below the internal edge of the coring bit that cuts the core.

to combined core barrel abrasion/fluid circulation effects alongside abrasion during drill-bit cutter passes. In addition, the average diameter of the granite samples was in general larger than the sandstone runs often approaching the 61.1 mm inner coring bit diameter of the DI drill-bit, the likely response to their much harder nature and subsequently lesser vulnerability to the above mentioned features.

Careful examination of the cores was then made with reference to the application of RED versus conventional coring. In general, very little in the way of differences were observed between the intervals cored using the separate techniques. The caliper measurements of the core intervals cut using both conventional and RED coring showed a very marginal increase in the average diameter of core from the RED compared to conventional, ranging from 0.02 to 0.08 mm and from 0.01 to 0.04 mm for sandstone and granite runs respectively. Average standard deviation of the measurements was slightly higher for the RED cored intervals in the sandstone compared to conventional and was marginally higher for the conventional compared to RED in the granite runs. In most cases these minor variations were not systematic between the different coring approaches. One exception shows a subtle difference in the smoothness and diameter of the cored intervals at the start of Core 3 in the sandstone, where the RED cored interval gave consistently slightly larger diameter and apparently less dislocation of grains for the first four RED cored intervals before returning to indistinguishable differences below c. 60 mm penetration. In all other cases including all the granite samples, no systematic visual or measured difference was observed in core quality between RED and non-RED intervals.

Due to the scale of the laboratory set-up, and the short length of the coring runs, we cannot yet comment on how the application of RED may affect longer coring runs. However, based on the initial results, we find that the application of RED coring appears to have no negative effects on core quality. From the investigations of core diameter and core cut smoothness in sandstones, preliminary insights reveal potential improvements in some but not all cases, therefore requiring further testing alongside longer core runs in order to appraise any potential benefits further. At this stage we can conclude that RED coring has no observable negative effects on core quality, and therefore, the associated improvements in ROP appear to come with no adverse implications for core quality.

5. Conclusions

In this paper, a series of coring experiments on sandstone and granite by using the RED technology were carried out to evaluate the applicability of this method to coring operations. Firstly, the RED technology, the RED Vertical Rig and the methodology utilized in the experiment were presented. Subsequently, the efficiency of RED coring was compared against conventional coring for two different coring bits and two different rocks. Finally, a core quality assessment was presented to appraise the influence of the application of RED coring on core quality. Two types of typical coring bits used throughout the experiments were diamond impregnated and PDC bits.

By comparing the coring efficiency of the RED technology for various excitation frequencies with that of the conventional method, we are able to observe that improvement factors ranging from 105% to 180% confirming the potential for RED technology to improve coring ROP and consequently reduce cost of coring operations. By looking into the lithology of rocks, it can be concluded from a systematic series of RED experiments that a high angular velocity is better to RED coring for hard rocks compared with soft rocks.

With regards the core quality assessment of the cores produced during this study, we find that the average diameter of the granite samples is in general larger than the sandstone because of their much harder nature, and very little in the way of differences are observed between the intervals cored using the two separate methods. In general, all cores retrieved are in good condition showing consistent diameters, generally smooth core surfaces and no evidence of fracturing. Therefore, it can be considered that RED coring has no observable negative effects on core quality.

Based on the analysis undertaken, we can conclude that the associated improvements in ROP by RED coring method appear to come with no adverse implications for core quality.

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Application of Resonance Enhanced Drilling to Coring

- Resonance Enhanced Drilling (RED) technology was applied to coring.
- An unique experimental rig and experimental results were presented.
- The experimental results shows a significant improvement in rates of penetrations while maintaining good core quality.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: