



Kicks and their significance in pore pressure prediction

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Abstract: Knowledge of subsurface formation pressures is critical for the calibration of predictions and models needed for safe drilling of deep wells, historically for oil and gas wells. The same details apply to the sequestration of CO₂, ephemeral storage of gases such as hydrogen and for geothermal power. An estimated 10–14% of wells globally experience an unexpected influx of formation fluid, indicative of the controlling mud in the borehole at that time having a lower pressure than the surrounding formation. The drilling events, known as kicks and wellbore breathing, lead to, at best, downtime on the drilling rig which might affect the economic viability of the well, or in the extreme its safety with possible loss of life such as in the case of an uncontrolled blowout. Not all kicks are of equivalent value: dynamic and static kicks can be classified with a high degree of confidence and may become values for true formation pressure. Other types of fluid influx during drilling, including swab kicks and wellbore breathing, need to be identified and will not be accepted in a kick database. These types of influx may be eliminated as potential formation pressure values but, along with mud weights, can be valuable data to constrain the range of possible formation pressures, of significant where no other data exist. A new, rigorous evaluation procedure for determining formation pressure is presented, and compared with direct pore pressure measurements (e.g. RFT, MDT, RCI values). The comparison shows that the proposed methodology illustrates typical uncertainty of about 10 bar (145 psi) pressure over the full range of pressures for which data are available in this study.

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Those involved in pore fluid pressure prediction are constantly looking to improve on the many methods of generating formation pressure curves in shales from both drilling conveyed and wireline tools such as resistivity, compressional sonic and density (Hotman and Johnson 1965; Foster and Whalen 1966; Eaton 1975; Bowers 1995). These estimation/prediction methods typically rely on the presence of shallow data to describe a normal compaction trend (NCT) (Bruce and Bowers 2002); in the absence of shallow data where lithological difference, lack of tool runs or poor data mean no valid data exist then other methods of developing the trends must be utilized (Swarbrick 2002). To calibrate the shale trends, measured formation pressures are sought, either from wireline formation tests (WFT) or drill stem tests (DST). These are unavailable in the shales, due to their low permeability (typically having microDarcy and picoDarcy permeability values); it is necessary to rely on measured pressures in associated higher permeable rocks (i.e. reservoirs) where permeability values are milliDarcy or greater. Normal practice will be to demonstrate a close equilibrium between shales and the associated, but typically rare, reservoir intervals in which direct pressures exist to calibrate the shale interpretations. Many well profiles are drilled without direct reservoir formation pressure measurement over much or all the drilled section. In these circumstances other types of indication of formation pressure have value – one of these data types is ‘kick’ data.

A kick is here defined as an unexpected influx of reservoir fluid (oil, water, or gas) into the wellbore due to borehole fluid pressure less than the formation pressure, a condition known as ‘under-balanced’ drilling. Kicks are associated with enough permeability for a measurable influx. Any such influx could occur either while the drilling fluid is being circulated within the borehole (pumps on)

or during drilling operations while the drilling fluid is static, e.g. whilst making a drill pipe connection (pumps off). Each of these conditions is commonly dealt with in the same way for the purposes of formation pressure detection/prediction, but the implications for interpretation of the kick as a direct indication of formation pressure is very different.

Kicks are used (e.g. Bois *et al.* 1994; Van Ruth *et al.* 2003; Tingay *et al.* 2009; Sagala and Tingay 2012) to analyse formation pressures alongside WFT and DST data, usually with little or no knowledge of the confidence in kicks as measurements of formation pressure. Wireline formation tests such as RFTs and MDTs are measured through the exposure of a probe to the permeable formation and commonly have build-up plots to assess confidence in the quoted measurement. In contrast, uncertainty in kicks is high and needs understanding of the drilling event during and prior to the kick. This paper proposes a revised terminology for drilling events involving an influx of fluid into the borehole leading to a kick and proposes a method to improve confidence in the use of kicks as direct measurement of formation pressure. This methodology can be applied to provide better calibration of formation pressure, both in real-time or when using historical data to estimate and predict pre-drilling formation pressure profiles, which will assist in well safety.

The study was able to compile data from 3835 exploration and appraisal wells, principally from European and North American offshore basins, for which a total of 862 kicks were documented. Some wells recorded more than one kick, with a maximum of 7 in a single well. Although the recorded details of many of these kicks were not available to the study the high number of kicks emphasizes the potential for their use in calibration of pore pressure prediction, based mainly on porosity-based methods (see Swarbrick 2002).

Many national regulatory authorities outside Europe and North America are reluctant to publish data on well incidents, including kicks, and hence there is a bias in the data available to compile statistics.

We have been able to estimate a kick frequency for wells drilled over the past 15 years for the Norwegian Continental Shelf, however, including wells from North Sea, mid-Norway and Barents Sea basins (Carlsen 2021). In the period 2005 to 2020 there was an average of 16 wells out of 100 for which well control incidence was recorded and using the data from 2017–20 it is possible to show that 67% of those incidents were well kicks. Kicks also occur, from the authors' experience, in development wells and in workovers but these were not included in this study.

Data and definitions

The context for this paper is the safe and efficient drilling of deep boreholes, mostly to depths greater than 2000 m (c. 6500 feet). To assist the reader unfamiliar with this context commonly used terms and acronyms are included in Appendix A. Details of drilling operations and further discussion of techniques to evaluate formation pressures can be found in Mouchet and Mitchell (1989).

Direct pressure measurements are critical to calibrate formation pressure profiles for deep boreholes. Tools to measure formation pressures directly place a probe against the borehole wall and allow formation pore fluid to flow into the tool where the pressure build-up is monitored, ideally until the pressure inside the fluid chamber in the tool remains constant, and then assumed to be the pressure of the formation. Many variations of wireline tools have been developed and used over time to record formation pressure, and in this paper are referred to generically as wireline formation tests (WFTs). Historically, the commonly used tools are RFT^{TM1}, FMT^{TM2} and MDT^{TM1}. More recently (since about 2000AD) the possibility of conveying a pressure tool on the drill string has been available. These tools typically require rock permeability of greater than about 1.0 mD to achieve a build-up profile within a short period of time, e.g. about 10 minutes or less.

Influxes, sometime referred to a 'gain' during the drilling of a well need to be evaluated within the context of the drilling parameters and their relationship to the formation pressure surrounding the borehole. When drilling a deep borehole mud of known density is pumped down the drill pipe, returning through the borehole annulus. The density of the mud can be measured with downhole gauges or estimated from surface properties and described as having an equivalent static density ('ESD') when the mud pumps are switched off. During operations when the pumps are on, there is a higher effective density 'ECD' (equivalent circulating density) reflecting the added pressure applied to circulate the mud. Kicks can occur when pumps are both on and off. In each case the fluid influx from any permeable rock units penetrated in the borehole must be examined in relation to the downhole pressure at the time when excess fluid is observed in the rig pits or from measurement of 'fluid in' v. 'fluid out' in MPD (measured pressure drilling) operations (i.e. when specialist surface equipment monitors and controls the effective downhole pressure).

Dynamic and static kicks

Distinction is needed between ESD and ECD fluid influxes. When mud is static the direct indication of a fluid gain will be identified through the automated monitoring of the level of mud in the mud pits. Mud volumes are measured on the inflow and on the return, as well as the level of the mud pits themselves. In modern drilling rigs there may be downhole pressure measuring devices and/or control of downhole pressures with equipment such as MPD. The sensitivity of this measurement is generally no more than 2.0

barrels mud volume, and can be as low as 0.5 barrels of mud with MPD systems installed (Gordon Holm, pers. comm.).

A distinction in terminology for kicks is proposed here such that:

A *static kick* occurs (Fig. 1) under ESD conditions when an influx is observed/measured, indicating the formation pressure exceeds the static density of the mud. **Note:** static kicks during connections or during flow checks at drilling breaks can generally be assumed to be occurring at or close to the bottom-hole depth.

A *dynamic kick* occurs (Fig. 1) under ECD conditions when an influx is observed/measured indicating the formation pressure exceeds not only the static density but also the circulating pressure of the mud.

These will be the two prime categories of kick and data from both events can be used to estimate the formation pressure for the purpose of calibration to formation pressure prediction. Some other drilling events, including swab kicks and wellbore breathing, can occur during operations which masquerade as kicks, but close inspection of the data indicates that a true influx had not occurred, and therefore they cannot be used to estimate formation pressure.

A *Swab kick* or swabbing occurs when there is a forced and temporary influx of formation fluid into the wellbore in response to a reduction in the effective bottom-hole pressure applied by the column of mud in the hole due to the upward movement of the drill-string or tools in the borehole. As drill-string or downhole tools are raised in the borehole, mud is required to replace the void space from the drill-string or tool. If the mud is not able to replace the void space in sufficient volume, the effective borehole pressure drops. If the borehole pressure drops below the formation pressure, a permeable formation will flow into the borehole in order to equalize the fluid pressures. A swab kick indicates only that the formation pressure is less than the ESD at the time of the event. Gains related to swabbing are also not always generated at the bottom-hole and can occur anywhere in the open-hole (section of formation without casing).

Wellbore breathing (sometimes termed ballooning) has no direct relationship to the formation pressure but indicates that the ECD is close to or greater than the fracture strength (Ward and Clark 1998). Wellbore breathing is described here as the opening and

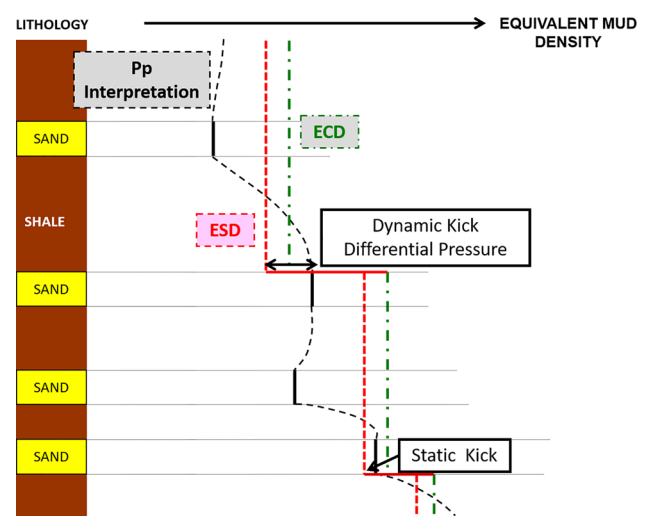


Fig. 1. Schematic equivalent mud weight (EMW) plot demonstrating the relationship between dynamic and static kicks and the MW and ECD. A dynamic kick occurs when formation fluid pressure exceeds ECD pressures of the mud, when mud pumps are on. A static kick occurs when formation fluid pressure exceeds the static mud pressure with 'pumps off'. A kick occurs only when there is sufficient permeability for a recognisable influx of formation fluid, such as a reservoir sand.

supercharging of fractures during circulation, followed by the discharge of the 'lost' drilling fluid when circulation stops. The return of fluid is observed as a 'gain' in the mud pits and hence masquerades as a static kick. If misinterpreted during well control operations as a static kick the likely response will be to increase mud weight leading to further wellbore breathing when drilling is resumed. Logically such interpretation and response could lead to mud losses with potential loss of control of the well. Decreasing flow rates observed whilst monitoring a pit gain plus repeated loss-gain events are diagnostic indicators of wellbore breathing. Wellbore breathing is not valid as a measurement of formation pressure but may be indicative of fracture strength of the near-wellbore rocks. It is required that wellbore breathing be diagnosed and removed from the analysis of kicks and not used for the calculation of formation pressures.

Swab kicks and wellbore breathing have low value in terms of estimating formation pressure but since their occurrence is linked to mud pressures close to formation pressures, their occurrence can assist in restricting the estimate of formation pressure surrounding the borehole.

Method of calculation of 'kick' pressures

For the purposes of pore pressure prediction there are two commonly used methods of calculating the formation pressures from kick data. The first method involves the 'U-tube model' which uses the sum of the downhole pressure exerted by the mud in the drill pipe and the shut-in drill pipe pressure (SIDPP) to calculate the kick pressure. This is the same method used to calculate the kill mud weight (KMW) during drilling and hence is applicable for real-time analysis or when working up historical data from records in wells already drilling. The second method is only applicable for historical data and involves back calculating a kick pressure from the 'kill mud weight' known to have controlled the kick.

U-tube model

The U-tube model assumes that the drill pipe and annulus of a wellbore represent a perfect U-tube. When the well is shut-in on the blowout preventer (following an influx) with no change in measured pressure, then the sum of pressures in each leg of the closed system are equal and reflect the formation pressure (Fig. 2). To ensure this pressure equalization, surface gauges (shut in drill pipe and shut-in casing pressures) are normally given time to stabilize after the well is shut-in on the BOP. When a float valve (ported or non-ported) is present in the drill pipe it is necessary to allow the valve to open, commonly by slow pumping down the drill pipe until a small increase is seen in the shut-in casing pressure (SICP); at this point the increase is then subtracted from the surface gauge on the drill pipe to give an apparent SIDPP.

The SIDPP value is used for calculation of the kick pressure with the assumption that the influx fluid is primarily within the annulus of the well and that the drill pipe contains a constant column of mud of known density. The density of the drilling fluid in the drill pipe is multiplied by the true vertical depth referenced to the kelly bushing (KB) plus the SIDPP to calculate the formation pressure (equation 1).

$$\text{Kick pressure} = (\text{Drilling Fluid gradient} \times \text{TVD}) + \text{SIDPP} \quad (1)$$

The kick pressure calculated above (equation 1) is generally used for calculations of the necessary kill mud weight (KMW) to balance the formation pressure and control the well but the drilling fluid in the drill pipe is presumed to be homogenous and in practice that is not always the case. For example, if the mud weight was in the process of being increased prior to the flow event then the sum of pressures of both columns of drilling fluid needs to be calculated. In addition, the calculation does not consider compressibility of the mud and thermal effects downhole which might lead to inaccuracies in the calculated bottomhole pressure. Other weaknesses are the reliability

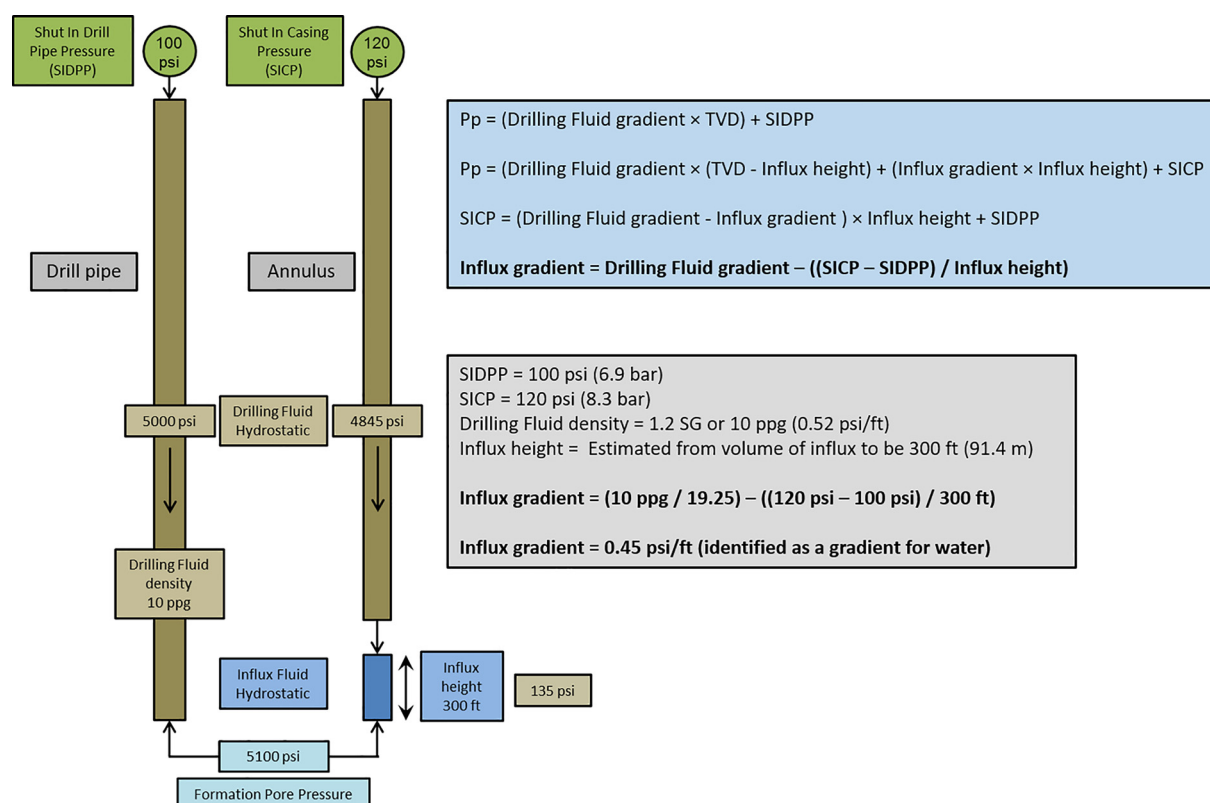


Fig. 2. Schematic illustration of the U-tube of a wellbore with the relationships of pressures between the drill pipe, annulus and formation being shown. An example is shown of common wellbore calculations relating the drill pipe to the annulus.

on the mud system representing a perfect U-tube which is not always the case. Keeping these uncertainties in mind we propose further analysis of the annular pressures as a method to quality control the calculated pressure provided from the drill pipe leg of the U-tube. While the annulus is not typically used to calculate the kick pressure due to uncertainty of the influx fluid gradient, if this is known or if reasonable presumptions are made from local or regional knowledge the relationship between the SIDPP and SICP can be interrogated. If the mud system represents a perfect U-tube and the mud in the drill pipe (equation 1) and annulus (equation 2) are homogenous and of equal density, then sum of pressures in the either leg should equal each other (equation 3).

$$\begin{aligned} \text{Kick pressure} = & (\text{Drilling Fluid gradient} \times (\text{TVD} - \text{Influx height}) \\ & + (\text{Influx gradient} \times \text{Influx height}) + \text{SICP} \end{aligned} \quad (2)$$

and hence:

$$\begin{aligned} \text{SICP} = & (\text{Drilling Fluid gradient} - \text{Influx gradient}) \\ & \times \text{Influx height} + \text{SIDPP} \end{aligned} \quad (3)$$

Since we can presume that the mud density will be greater than the influx fluid density (i.e. water close to 1.00 g cc^{-1} and hydrocarbon densities less than 1.00 g cc^{-1}) then the SIDPP should be less than or equal to SICP (Fig. 2). If this is not the case, then the data require more consideration – e.g. is wellbore breathing occurring? Or is there just a higher uncertainty in the measurements in which case confidence in the kick as a measurement of formation pressure is low? In addition, driller's notes and understanding of the complexity of the kick should be factored in as kicks with multiple phases of control will have a higher uncertainty due to obvious inadequacy of the initial SIDPP calculation and possible U-tube effects during well control.

Worked example

A well takes a 20-barrel kick while drilling ahead to 2931 m (9615 ft) TVD with the mud pumps on and mud being circulated within the hole (i.e. a dynamic kick). The well is shut in and the float valve pumped open.

- SIDPP is 6.9 bar (100 psi)
- SICP is 8.25 bar (120 psi)
- Original MW is 1.2 SG (10.0 ppg)

Using conversion from SG to bar m^{-1} (pressure gradient) of 1.0 SG = 0.098 bar m^{-1}

Kick pressure = $[(1.2 \text{ SG} \times 0.098) \times 2931 \text{ m}] + 6.9 \text{ bar} = 351.6 \text{ bar}$ (5100 psi; Fig. 2).

Equivalent mud density of kick pressure is 0.12 bar m^{-1} or 1.224 SG or 10.21 ppg.

The height of the influx fluid in the annulus can be estimated knowing the volume of mud gained during the influx prior to shut-in and the interior diameters of annulus, casing, and borehole. The influx height subtracted from the drilling depth (TVD reference datum) gives the height of column of assumed mud density, from which the fluid density of the influx fluid/gas can be calculated (Fig. 2). Alternatively, if the fluid density is assumed the influx height can be back calculated.

The method described above was used to determine kick pressures from all influxes where both SIDPP and SICP were documented along with the necessary ancillary data, such as MW.

Kill mud weight (KMW)

In contrast, using the mud weight used to 'kill' the well represents a quick and simple method of estimating a kick pressure. In many cases an upwards revision of the mud density before drilling

recommences provides proof as to whether the kill was successful in controlling the well. Obvious disadvantages of using the KMW are (a) that this method is not applicable in real-time and (b) that during well control a trip margin is typically added to define a higher mud density than would exactly match the formation pressures of the influx zone. Regionally calibrated trends for KMWs can be calculated as shown in Figure 3. With this type of data available a known trip margin or, for example, a typical value of 200 psi can be subtracted from the calculated pressure using the KMW to give a more realistic kick pressure.

Uncertainty in kick pressures

While many uncertainties exist in the calculation of kick pressures it is beyond the remit of this article to discuss every possible event. Factors which may influence the accuracy or reliability of a kick are:

- The type of mud system in use (oil-based mud) can lead to uncertainties in SIDPP when hydrocarbons are introduced into the borehole during an influx, due to absorption of gas into the mud.
- Depth uncertainties with static or swab kicks which require accurate correlation of the kick with the initial zone of influx.
- Other downhole issues occurring at the same time, such as losses during well control.
- Miscalibration of surface gauges.
- Float valve on drill pipe (ported or non-ported) that are designed to prevent flow of fluids from the annulus into the drill pipe will affect the SIDPP values.

A database of direct measurements of downhole formation pressures from Wireline Formation Tests (WFTs) such as RFT, MDT, FMT, RCI tools has been examined and comparisons made between kick values and WFTs reported in these wells at the same depth. For this study, a small dataset was available from the deep, high pressure and high temperature area of the Central North Sea and has been combined with a much larger dataset from the Northern Carnarvon Basin, NW Australian Shelf. In both areas, kicks were first screened for their validity, and separated into (a) static and (b) dynamic kicks.

A plot of the data (Fig. 4) shows that there is a close match between kick and direct pressure measurement for 20 kicks for which there are both WFT and kick pressures at the same borehole depth. These values remained as valid out of a total of 83 reported kicks in the original database of recorded influxes, emphasizing the need to implement a careful strategy to identify kicks with sufficient data to provide reliable downhole formation pressures. This analysis emphasizes the low number of influx zones which are also tested by WFTs.

Statistical analysis of the database of direct pressure measurements and kicks comparing kicks and WFTs in the same reservoir in Figure 4 show a close correlation with most of the values compared within $\pm 10 \text{ bar}$ ($\pm 145 \text{ psi}$). With multiple WFTs in a pressure-connected reservoir the fluid gradient can be shown to offer much higher confidence in the absolute pressure/overpressure of the formation (Swarbrick *et al.* 2005).

Discussion

We recommend that kicks recorded in drilling and geological well records are screened using the above methodology to remove unreliable values from the database. An example well from the Northern Carnarvon basin (Fig. 5) recorded seven influxes, of which only three are categorized as kicks using the new criteria. A post-drill evaluation of shale pressures using the resistivity log estimates pressures increasing between 10 000 and 12 400 feet (3300–3780 m), and indicates ECD (MW is shown as solid black line in Fig. 5) was below formation pressure. Successive increases in

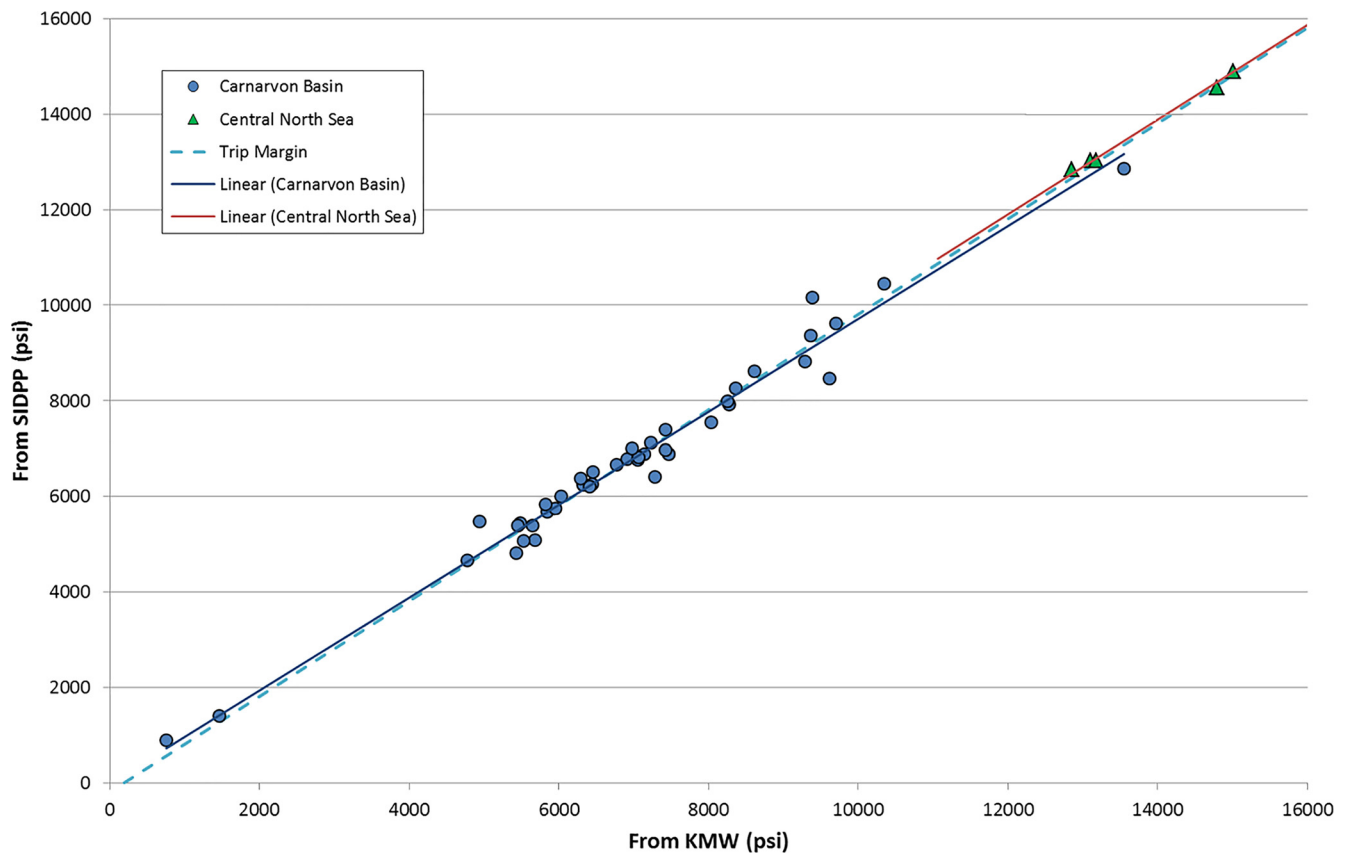


Fig. 3. Plot of kick pressures from SIDPP v. KMW for wells with both information recorded. There is a high degree of correlation in these data from the Carnarvon Basin (blue data) whose range is extended by addition of a small dataset from deep high-pressure wells in the Central North Sea (red data).

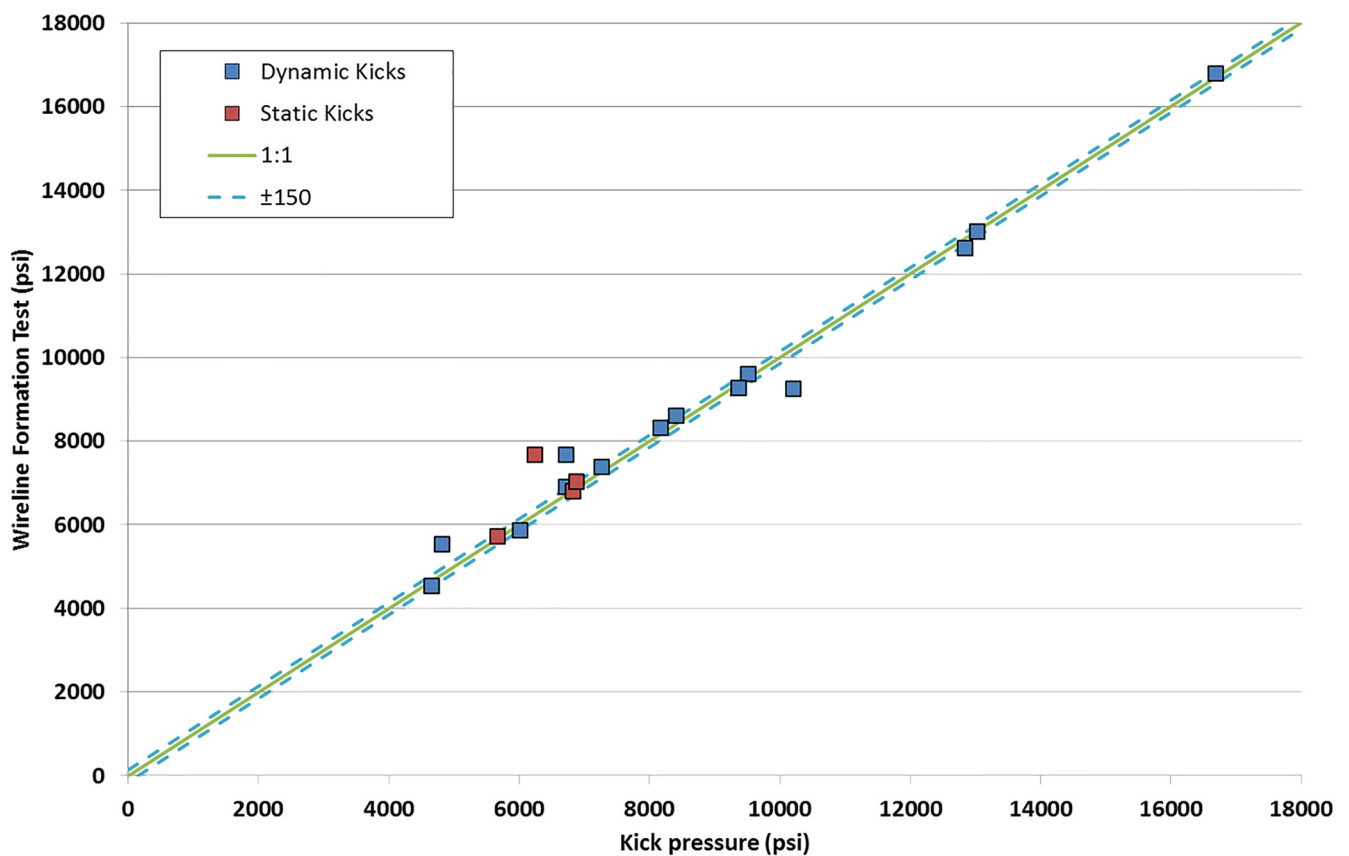


Fig. 4. Kick pressures from both dynamic (blue) and static (red) kicks determined by methods described in this paper, plotted against measured WFT pressure in the same reservoirs. There is a high degree of correlation, with dashed blue lines showing ± 150 psi (10.3 bar).

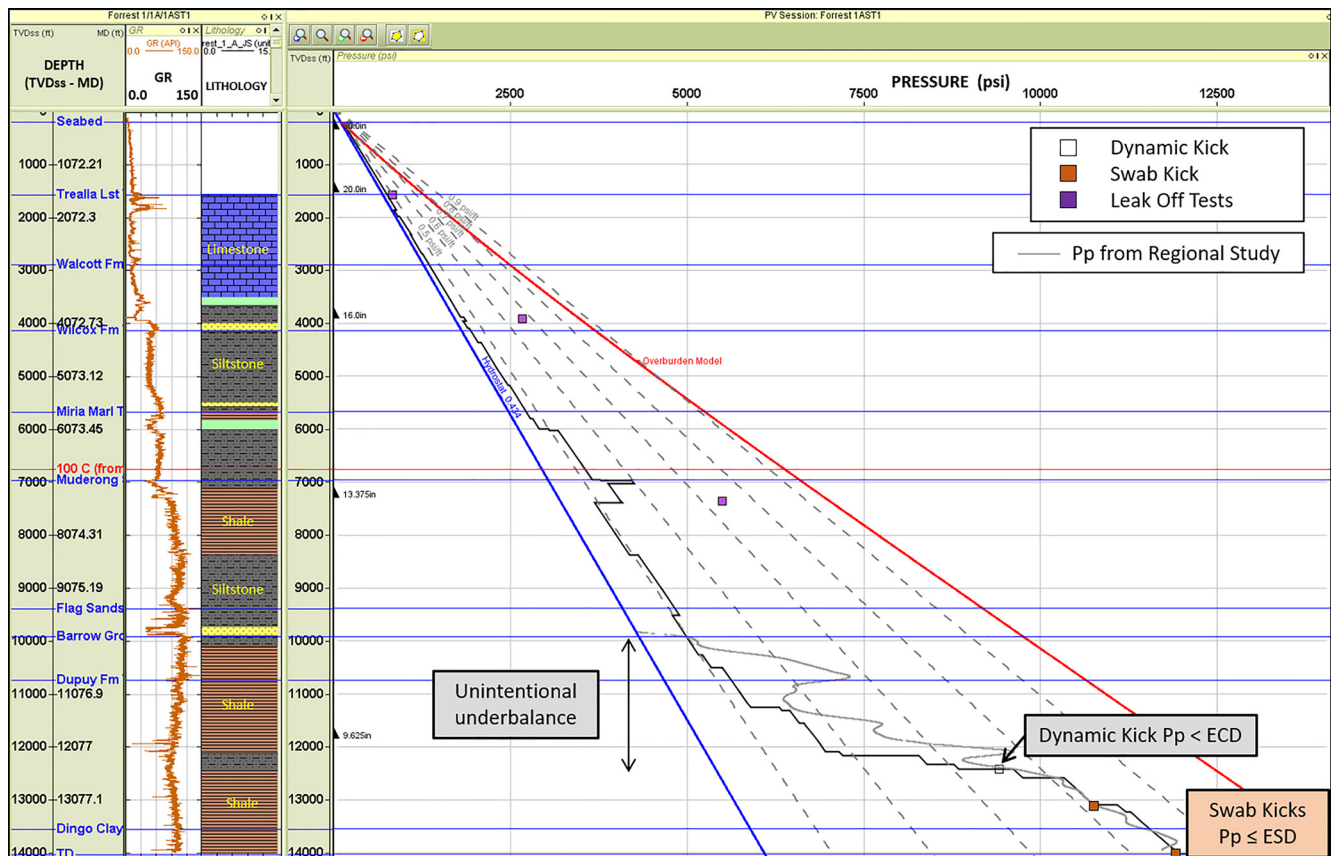


Fig. 5. Pressure–depth plot for Forrest 1AST1 well, drilled in the Carnarvon basin. An example of three kicks is shown out of seven gains found in the well records. Wellbore breathing as well as unspecified gains were discarded. The grey shale pressure profile derived from porosity tool data indicates that the section between 10000–12400 ft was drilled unintentionally underbalance. The kick pressures provide calibration for the interpretation. Solid black line is ESD, i.e. MW with pumps off.

MW indicate the recognition of this pressure transition zone to high overpressure, but it was not until 12 400 feet (3780 m) that a dynamic kick took place, and MW was adjusted to match the requirements for MW to exceed formation pressure. Two of the three deeper influxes are identified as swab kicks. The interpretation of formation pressure closely matches the MW profile at these depths, consistent with swab kicks when drill pipe was pulled up creating temporary condition of effective MW below formation pressure.

Based on the methodology presented above we propose a way to quickly screen data when an immediate interpretation is required for operational reasons. To distinguish the events occurring i.e. swab kick, static kick or dynamic kick the relationship between these different kick events, the MW and ECD (Fig. 1), the following can be applied:

- Dynamic kick pressure > ECD
- Static kick pressure > MW but less than ECD
- Swab kick pressure ≤ MW

Multiple kicks can occur when drilling operations are compromised by a narrow drilling margin. As an example, in the BP Macondo well, drilled in the Gulf of Mexico, there is a long depth interval with a narrow drilling margin and six kicks are recorded (Pinkston and Flemings 2019). The magnitude of formation pressure inferred from the kicks were confirmed independently by direct pressure measurement in three of these kicks (Fig. 2 in Pinkston and Flemings 2019).

The term ‘gains and losses’ refers to a specific set of circumstances where the mud volume required in the borehole increases, recorded as mud ‘losses’, for example when tensile fractures are generated by

mud pressure exceeding the fracture strength of the borehole wall. When the pumps are switched off, the relationship between mud pressure and formation pressure is reversed and excess formation pressure causes fluid influxes (‘gains’) from the formations being drilled inducing a kick (Tare *et al.* 2001).

Formation pressure studies to predict formation pressures in advance of drilling new wells rely on accessing reliable and well documented reports of well operations. The drilling and geological operations records of some wells indicate an influx led to the decision to terminate these wells without further operations. In these circumstances the kick may be the only indicator of formation pressure at the base of the well and will be the only calibration for modelling deeper formation pressures.

Conclusions

While WFTs are common as calibration for formation pressure, often with a high level of confidence, kicks can have higher uncertainty and hitherto have been generally regarded with suspicion for the purposes of defining formation pressure. Systematic re-evaluation of the data for the GeoPOP Research Group led to a classification into static, dynamic and swab kicks described here. Wellbore breathing can be recognized as a distinct event which does not involve formation fluid influx, and therefore excluded from a kick database.

In this paper we have also shown:

- To determine accurate formation pressures both SIDPP and SICP data are required for both static and dynamic kicks. We have proposed a methodology and given the formulae for determining formation pressure values from these data.

- Swab kicks should not be used to determine an accurate formation pressure.
- Comparison of accurately determined kick pressures with independent measurement of formation pressure from WFT at the same depth in several wells shows close correlation of values, with variability assessed to be on the order of 10 MPa (145 psi).
- Correct assessment of kick pressures may be critical to the subsequent design of a re-drill or new well in an area of high formation fluid pressures.

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Author contributions **JL:** data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), writing – original draft (lead); **RS:** conceptualization (lead), formal analysis (supporting), project administration (lead), writing – original draft (supporting), supervision (supporting); **SO:** conceptualization (supporting), project administration (supporting), supervision (lead), visualization (lead)

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Competing 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.

Data availability The datasets generated during and/or analysed during the current study are not publicly available due to proprietary ownership by Ikon Science, London, UK and/or the GeoPoP consortia.

Appendix A: Terms and acronyms used in this paper

Acronym	Term/meaning	Explanation
	Annulus	Gap between drill pipe and borehole wall, and part of the mud flow path where mud from the drill bit returns to the surface. The surface pressure of the annulus is monitored (see SICP).
BHP	Bottom-hole pressure	Pressure at the base of a borehole mainly determined from downhole pressure measurement and/or density of the circulating or static mud column.
	Blow-out	Uncontrolled flow from the borehole into the atmosphere or under the sea as in Macondo Deepwater Horizon incident in April, 2010 (Pinkston and Flemings 2019).
BOP	Blow-out preventer	Equipment located near the wellhead which when activated will isolate the borehole and create a barrier for any borehole fluids to exit the well.
DST	Drill stem test	Controlled flow of fluid to surface to evaluation reservoir productivity and performance.
ECD	Equivalent circulating density	Pressure of the borehole mud when pumps are 'on' and mud is circulating down the drill-pipe and returning via the annulus.
ESD	Equivalent static density	Pressure of the borehole mud when pumps are 'off' and the mud column is static.
FMT TM	Formation multi-tester	Wireline tool used to measure formation pore pressure directly, developed by Western Atlas about 1978.
	Formation pressure	Pressure(s) of the pore fluid (water or both water and oil/gas in a multi-phase fluid) in a rock formation of the borehole wall. Formation pressure can be measured directly (e.g. RFT, FMT, MDT) or inferred from rock and fluid properties of shales (see Swarbrick 2002, 2012)
	Fracture strength	The pressure required to initiate a fracture in the borehole wall, normally when mud pressure exceeds both minimum compressive stress and the tensile strength of the formation.
	Fracture gradient	Fracture strength converted to an equivalent mud weight value or fluid gradient whose origin is a surface reference (e.g. drill-floor, Kelly bushing) or sea-level and land surface datum.
	Gain	Evidence of increase in mud pit level, and/or when fluid-in exceeds fluid-out when operating with MPD.
	Influx	Any fluid gained from the formation.
	Influx height	The height of a column of an influx of formation fluid in the annulus during a kick.
	Kelly bushing	Equipment used near the rig floor to link the drill-pipe and rotary table.
	Kick	An unexpected and unwanted influx of reservoir fluid, oil, water, or gas, into the wellbore due to an underbalanced condition in which pressure inside the wellbore or bottom-hole pressure (BHP) is less than formation pressure.
KMW	Kill mud weight	Mud weight required to stop an influx and estimated from mud weight when there is no gain in the level of the mud pits.
LWD	Logging while drilling	Geophysical tools conveyed on the drill-string giving real-time responses. Tools are located short distances behind the drill bit.
MDT TM	Modular Dynamic Tester TM	Second generation wireline tool used to measure formation pore pressure directly, developed by Schlumberger in 1992.
MPD	Measured pressure drilling	Specialist equipment on a rig/platform which controls the volumes and pressures of the mud column. MPD can be used to induce a kick (by lowering the mud pressure).
MW	Mud weight	Mud density (normally recorded using Pounds per Gallon or Specific Gravity units) present in the borehole. Often the MW value is determined from the mud density in the mud pits; density will vary downhole on account of temperature, pressure, and the presence of any unfiltered rock fragments.
NCT	Normal compaction curve	Reference curve or trend modelled to reflect compaction behaviour of shales at hydrostatic pore pressure under increasing load/effective stress. Used in most formulae to quantify pore pressures from wireline and LWD data.
RFT TM	Repeat Formation Tester TM	Wireline tool used to measure formation pore pressure directly, developed by Schlumberger in 1974.
	Wellbore breathing	A term used to describe mud losses and/or plastic deformation of the borehole by the mud, which occur gradually during drilling (ECD conditions), with a sudden increase in pit level/surface pressure when the pumps are turned off and ESD conditions are resumed.
SICP	Shut-in casing pressure	Mud pressure recorded in the annulus when the well has been closed to prevent fluid escape at the surface.
SIDPP	Shut-in drill pipe pressure	Mud pressure recorded in the drill pipe at the surface when the well is closed to prevent fluid escape to the surface. The base of the drill-pipe has a one-way return valve such that mud can flow out and formation fluid cannot flow in.
TVD	Total vertical depth	Depths for fluid pressures are taken with reference to the surface point vertically above (sub-sea, surface, seabed or depth reference on a drilling rig/platform).
WFT	Wireline formation test	All tests using wireline (and drilling-conveyed) tools to measure formation pore pressure in the borehole.

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