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Cement and steel used in coal seam gas (CSG) well construction in Queensland

GISERA, CSIRO, Australia

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Foreword

This report has been prepared as a component of the CSIRO GISERA project ‘Review of cements, steels and microbial activity for Qld CSG wells’. The scope of this report is tasks 2, 3 and 4 of the project proposal, which cover data collection and collation, summarising and analysing data on the material used in well casing, and summarising and analysing data on the cements and cement additives used in well cement. This study does not assess the suitability of these materials for well integrity.

A companion report, ‘Potential microbial interactions with cements and steels’ (Tran-Dinh et al., 2024), addresses task 5 of the project proposal, which covers a summary and analysis of the available data on subsurface microbial communities in Queensland aquifers in areas of coal seam gas activity.

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Acknowledgments

This research has been funded through CSIRO’s Gas Industry Social and Environmental Research Alliance (GISERA) with contributions from the Australian Government’s Department of Industry, Science and Resources. GISERA is a collaboration between CSIRO, Commonwealth, state and territory governments and industry established to undertake research on the impacts of onshore gas exploration and development on the environment, and the socio-economic costs and benefits. For information about GISERA’s governance structure, projects and research findings visit https://gisera.csiro.au

CSIRO acknowledges the Traditional Owners of the lands, seas and waters of the area that we live and work across Australia. We acknowledge their continuing connection to their culture and pay our respects to their Elders past and present.

CSIRO is honoured to partner and collaborate with Aboriginal and Torres Strait Islander communities across the nation and we acknowledge the contributions of all Aboriginal and Torres Strait Islander people, staff and partners towards our vision for reconciliation.

We thank Neil Huth for facilitating the Cement and Steel Workshop held in Chinchilla, Queensland. We also thank the various stakeholder representatives from local landholders, regional council, state government departments, industry and independent organisations for attending the workshop and for providing valuable feedback that focused the project’s activities and reporting.

Executive summary

The growth in demand for natural gas for both domestic markets and liquified natural gas (LNG) exports has led to a rapid increase in the production of coal seam gas (CSG) from the Bowen and Surat basins. Local communities in Queensland are concerned about the number of CSG wells being drilled per year and the potential failure of their integrity, as well as the possibility of failed wells contaminating groundwater aquifers. A further concern is the lack of readily accessible information on the materials used for constructing the wells, including the composition of cement and casing.

Detailed information on each CSG well drilled is recorded in a Well Completion Report (WCR) prepared by the operating company and submitted to the Queensland Government. After a confidentiality period of 3 to 5 years, these WCRs can be accessed via the Open Data Portal of the Geological Survey of Queensland. However, the information contained in the WCRs is not readily accessible or understood by community members as the reports are written by specialist staff of the operating companies and incorporate considerable technical detail. Therefore, in this report, we have reviewed WCRs for a randomly selected set of wells and synthesised the information on casing and cementing material used in the construction of CSG wells in Queensland. We have attempted to report the information in a way that is accessible to everyone, including those who may not be familiar with technical details of CSG well construction. It should be noted that this study does not assess the suitability of these materials for well integrity.

During this project, WCRs for 131 randomly sampled wells drilled between 2002 and 2023 were reviewed. Reports for 116 wells drilled prior to 2019 were open-file and were downloaded from the Geological Survey of Queensland's Open Data Portal, whereas those for 15 newer wells were obtained from the operating companies. Appendix A.4 details the approach used for well selection in this report. The dataset downloaded was quality checked, including for inconsistencies in reporting and transcription errors.

Information included in the WCRs is written by geoscientists and engineers of the operating companies to document specific information related to drilling and construction of the well, geological data and other observations related to CSG and other hydrocarbon reservoirs, as well as aquifers intersected in the well. The task of extracting data from the WCRs was challenging as different reporting formats were used by various operating companies. The level of detail on casings and cements included in the reports, nomenclature for cement types, additives used by various service providers and the measurement units (imperial and metric) reported were also inconsistent. The consistency of reporting formats appears to have improved over time, in particular for the wells drilled since 2011, when prescriptive requirements for reporting were introduced through the release in 2011 of the 'Code of practice for constructing and abandoning CSG wells in Queensland'.

The review indicates that most CSG wells drilled in Queensland are lined with conductor, surface and production casings. Intermediate casing has also been used in a few deep wells drilled in the Bowen Basin. Steel is the material of choice for the majority of casings used in the CSG wells. The grades of steel used in gas wells are classified by the American Petroleum Institute (API) with reference to yield strength and related mechanical properties. Steel grade K55 accounts for about 60% of the total casings reported in the WCRs reviewed. K55 is routinely used by the CSG industry as it has the necessary mechanical strength corresponding to depths, temperatures and pressures encountered in Queensland. Six other steel grades were also reported (C350, X42, J55, N80, L80 and P110); however, these were used in fewer wells. Non-metal casings, including fibreglass and polyethylene, were used in a few lateral wells drilled in the Bowen Basin. Non-metal casings are generally used in wells where they overlap with coal mining tenure. A few WCRs did not specify the details of the material used for casing; this was more common for shallow conductor casings < 20 m below the surface.

Cementing information in the WCRs was mostly reported with reference to casing type. The majority of surface, intermediate and production casings were reported as cemented. However, in the WCRs analysed, only 41% of the conductor casings were reported as cemented. Cement slurries are prepared by mixing dry cement with water and additives in specific proportions. Cements reported in the WCRs include Class A, general purpose (Type GP), blended (Type GB), shrinkage limited (Type SL), sulphate-resisting (Type SR) and Class G. Approximately three-quarters of all cements reported were general purpose cement. Lightweight cement and gas-tight cement were also reported. These cements contain additives that lower the density of the slurry (for lightweight cement) or prevent migration of gas through the stiffened cement (for gas-tight cement). Ten categories of additives were reported in the cement slurry formulations. There appears to be a marked change in the reporting of cement additives for wells drilled since the early 2000s. Dispersants, extenders and accelerators were the main categories of additives reported for wells drilled prior to 2005. Since 2008, numerous other additives have also been reported, including antifoamers/defoamers and anti-gas migration agents; these are specifically used to prevent the formation of foam and the generation of channels within the cement slurry prior to its curing.

Information presented in this report highlights the complexity of cement formulations used in CSG wells and the increased use of additives over time. Additional details on extracting data from the WCRs, the functionality of various materials added to cements, and properties of casing types are provided in Appendix A.1–A.3.

Glossary

Term	Definition
Accelerator	Additive that reduces the setting time of cement slurry. It shortens the reaction time (duration) of cement with water.
Additive	Chemicals added to cement slurries that modify the properties of the cement slurry or set and hardened cement.
Annulus	The gap between any of the following: tubing and casing, two casing strings, or casing and wellbore. The annulus between the tubing and casing is the primary path for producing gas from coal seam gas wells.
Antifoamer	Additive that prevents the entrapment of air in cement slurry.
Aquifer	An identifiable stratigraphic formation (generally porous rock) allowing significant flow of water. Depending on its quality, this water may be tapped by wells for domestic, agricultural or industrial use.
Casing	Series of pipe installed inside the drilled wellbore to provide structural integrity. Casing extends to the surface and is sealed by a cement sheath between the casing and the subsurface rock formations.
Casing grade	Specific classification and quality standards set by the American Petroleum Institute for casing pipes.
Cement plug	The hardened cement within a well to prevent vertical movement of fluids.
Cement sheath	The hardened cement ring in the annulus between the wellbore and casing, or between casing and tubing, or between two casing strings.
Casing shoe	Bottom of a casing string.
Cement slurry	A mixture of dry cement, additives and water in specific ratios.
Coal seam gas	A form of natural gas (generally composed of mostly methane, CH_4) that is typically extracted from permeable coal seams at depths of 300 - 1000 m. Also called coal seam methane or coalbed methane.
Corrosion rate	Represents the speed at which a material, typically a metal, deteriorates or undergoes corrosion over a specified period of time.
CSG wells	Coal seam gas wellbore (see Wellbore).

Defoamer	Additive that removes the air entrapped in cement slurry.
Dispersant	Additive that increases fluidity of cement slurry.
Extender	Additive that decreases density of cement slurry.
Fibreglass	Refers to composite materials made of reinforced glass fibres, often used for casing and tubing applications to enhance corrosion resistance, and provide durability in specific downhole environments.
Fluid loss additive	Additive that prevents the loss of water from cement slurry into porous rock formations.
Formation fluid	Any fluid within the pores of the rock. It may include water, oil, gas or a mixture.
Formation pressure	The pressure acting on the fluids in the pore space of the subsurface rock formation.
Hydrated cement	The product of the chemical reaction between dry cement and water.
Lost circulation additive	Additive that prevents the loss of water from cement slurry into porous rock formations.
Permeability	The measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the rocks.
Porosity	The proportion of the volume of material (including rock and cement) consisting of pores.
Portland cement	Finely ground Portland cement clinker with small amounts of calcium sulphate (e.g. gypsum, anhydrite or other calcium sulphate-bearing minerals).
Portland cement clinker	Material produced from calcareous and siliceous raw materials (e.g. limestone, clays and shales) heated at high temperatures (~1500°C) in a kiln.
Production zone	The section of a wellbore from which fluids including CSG are produced.
Reservoir	A geological formation with adequate porosity or fractures that can store hydrocarbons.
Retarder	Additive that increases the setting time of cement slurry. It lengthens the reaction time (duration) of cement with water.
Rock formation	A subsurface layer of the same type of rock.

Set cement	Stiffened cement slurry that has not fully developed strength.
Stress	An external mechanical pressure that is applied to a body with units of force per area. Rocks within the earth are subjected to stresses caused by the weight of overlying rocks and tectonics (movement within the earth).
Tubing	A smaller-diameter pipe inserted inside the production casing that is not typically cemented and facilitates the fluid flow.
Well	A hole drilled into the earth from which petroleum or other fluids can be produced.
Wellbore	A hole drilled to investigate subsurface geological formations and natural resources, or to extract the natural resources such gas or water.

1 Introduction

1.1 Background

The growth in the CSG industry over the past two decades has seen a significant increase in the number of wells drilled across Queensland. To date, approximately 14,000 wells have been drilled within various coal-bearing basins in Queensland, and according to the Office of Groundwater Impact Assessment, the total number of wells constructed is expected to reach 22,000 by 2040.[1] The types of wells that have been drilled include CSG exploration, appraisal and development (also known as production wells) as well as water or gas injection wells.

Exploration wells are drilled during the early stages of a CSG project to obtain information on the subsurface geology, presence of gas, reservoir permeability and gas flow rates. If gas is present, further appraisal wells are drilled and tested to determine the volume of gas in the reservoir and its production potential. Subsequently, if the gas resource is proven to be economically producible, development wells are drilled to extract gas from the reservoir. In addition to these, injection wells may also be drilled to re-inject water into aquifers or gas into a depleted reservoir. Wells that can no longer be used for their desired purpose or that are no longer considered economically viable for gas production are generally plugged and abandoned.

Drilling and completion of wells is currently conducted according to the 'Code of practice for constructing and abandoning CSG wells in Queensland' (the Code), published by the Petroleum and Gas Inspectorate, Resources Safety and Health, Department of Natural Resources, Mines and Energy.[2] The Code specifies that '*all wells drilled should be constructed, maintained and abandoned to a minimum acceptable standard resulting in long-term well integrity, containment of petroleum* (the gas) *and the protection of groundwater resources'*. The Code addresses aspects of casing design, tubing and cementing techniques to ensure isolation of the CSG reservoirs from other formations including aquifers. The cement constituents and casing properties are designed to suit the downhole geological conditions, and the operators are required to maintain records of this information for the entire life of the well. Specific information on casing and cements used in the construction of each well is recorded in a WCR and submitted to the Queensland Government within 12 months of completing construction of the well. The reports are stored in the Geological Survey of Queensland's cloud-based database and can be accessed through the online Open Data Portal.[3,4] The casing and cement information included in the WCRs is not necessarily designed for communication with the public, and the details provided in each report vary by operator and date. Clearly communicating the composition of materials used for constructing CSG wells is valuable, as

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[1] https://www.ogia.water.qld.gov.au/__data/assets/pdf_file/0008/1733579/surat-uwir-annual-report-2022.pdf

[2] https://www.resources.qld.gov.au/__data/assets/pdf_file/0006/1461093/code-of-practice-petroleum-wells-bores.pdf

[3] https://geoscience.data.qld.gov.au/

[4] https://www.business.qld.gov.au/industries/mining-energy-water/resources/minerals-coal/online-services/gsq-open-data-portal

it assists the public in understanding what protections are in place to ensure well integrity and to mitigate risks associated with leaks. Therefore, this project seeks to collate and analyse casing and cement information reported in WCRs for a randomly selected sample of CSG wells, with an emphasis on the materials used in well construction and translate this information into easily understood and accessible forms.

1.1.1 Notes on measurement units

Measurement units used in the oil and gas industry worldwide include a mixture of imperial (English) and SI (Metric) systems. However, dimensions for casing types and cement volumes are often reported in imperial units. Cement volumes are generally recorded in gallons, barrels, pounds and sacks. Similarly, casing diameters and lengths are mostly recorded in inches and feet; where appropriate, in this report, they have also been reported in SI units.

1.1.2 Casings in CSG wells

The design of CSG wells involves selecting casings appropriate for downhole conditions. Casings, mostly made of steel, are individual layers of pipe inserted into the well to support its structure and prevent the wellbore from collapsing. There are multiple types of casings, with each designed to serve a specific purpose within various sections of a well.

The first casing layer, called the conductor casing, is the shallowest and largest-diameter casing. It is intended to offer structural support and enhance the stability of the well throughout drilling operations (Figure 1). The second layer, the surface casing, is installed inside the conductor casing and adds extra support, providing stability to the wellbore during the drilling process. Finally, the production casing, the innermost layer, is designed to convey extracted gas from specific rock layers to the surface. In some deep wells with elevated pressure, an intermediate casing, between the surface and the production casings, is also placed as further protection for the shallower part of the well.

Casings are mainly manufactured using a variety of steel, classified based on its strength, metallurgical properties and the manufacturing procedures. The primary manufacturing procedure for casing in the oil and gas industry is governed by the API 5CT standard (American Petroleum Institute, 2019a), introduced by the American Petroleum Institute (API).[5] API casings are primarily carbon steel, a grade of steel that is mainly iron, with a carbon content between 0.1% and 1.4% (Timings, 2005) and other elements present in lower percentages. Carbon steel is commonly used in the oil and gas industry due to its blend of strength, durability and cost-effectiveness. The carbon content in these steels can vary, and other elements such as chromium and nickel may also be added to achieve specific mechanical and chemical properties for the casing. According to the API 5CT standard (American Petroleum Institute, 2019a), there is a range of different casing grades (e.g. K55, N80, P110) to accommodate the diverse underground conditions. Further details on the grades of casing, as well as their chemical composition and physical properties, are provided in Appendix A.1.

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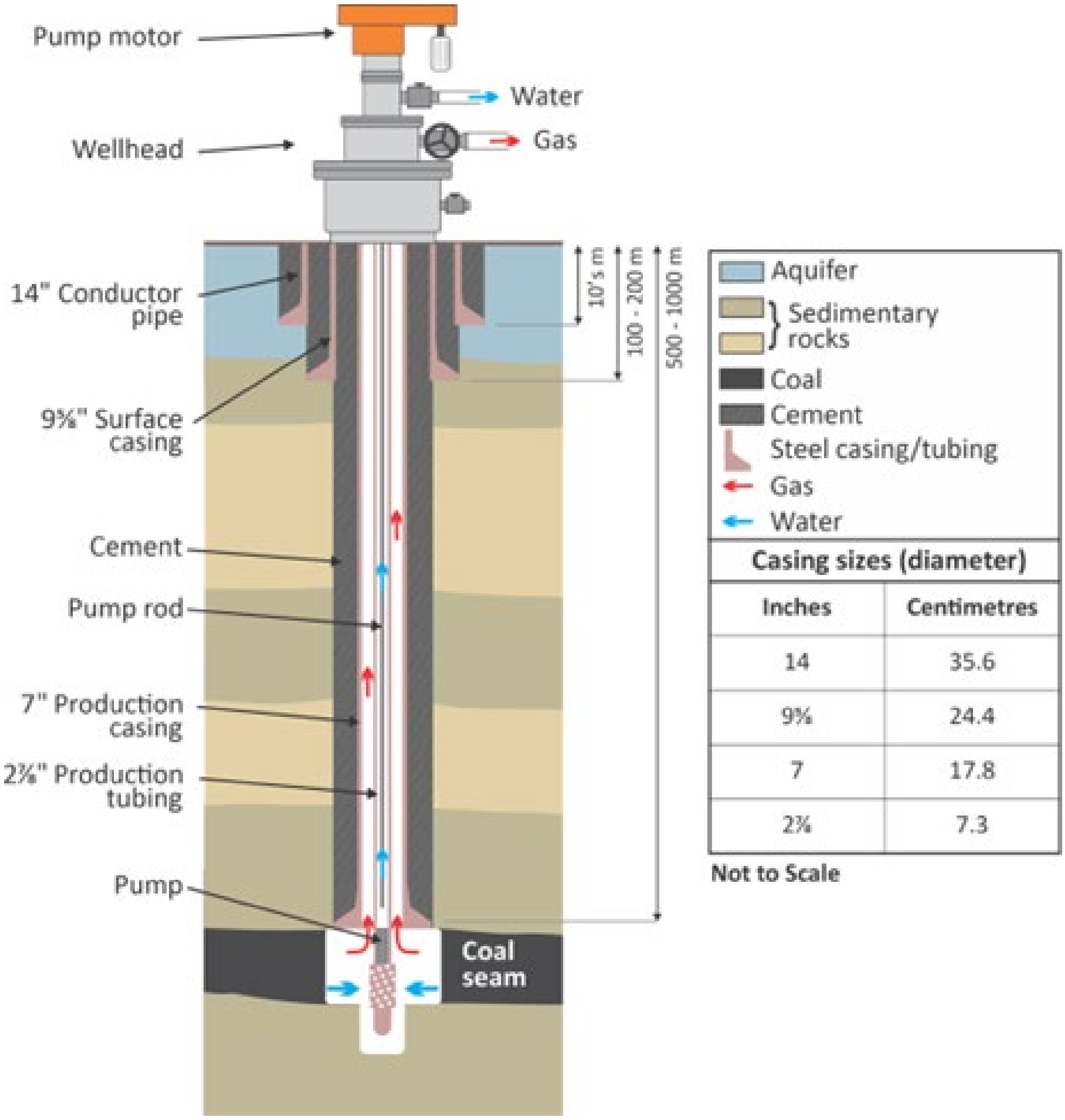
[5] https://www.api.org/products-and-services/standards/important-standards-announcements/standard-5ct



Casing sizes (diameter)

Inches	Centimetres
14	35.6
9⅝	24.4
7	17.8
2⅞	7.3

Figure 1: Schematic showing the types of casing used in a CSG well

(Huddlestone-Holmes & Elaheh, 2018)

1.1.3 Cementing of CSG wells

Cementing is a critical process in the construction of CSG wells for maintaining the long-term integrity of the well. During cementing, the gaps (annuli) between the wall of a borehole and the casing, between the casing and tubing, and between different types of casings (i.e. surface and production casings) are filled with cements that are specifically designed for downhole conditions. The specific functions of cement in wells are to:

- isolate the coal seam from other rock formations, such as sandstone, siltstone and shale layers, to prevent fluid migration between the formations or to prevent fluid reaching the surface
- protect groundwater resources from contamination
- maintain the groundwater pressure of aquifers
- protect the casing from corrosion

- reduce possibilities of casing buckling and collapsing.

Cementing of the well is conducted using cement slurries which are pumped through the casing and flowed back through the gap between the casing and rock formations exposed in the borehole. Cement slurry is a mixture of dry cement, specific chemicals (hereafter referred to as additives) and water. The slurry is designed so that it remains pumpable during its placement and rapidly hardens once in place and prevents the escape of fluids from the well. The composition of the cement slurry is selected according to:

- temperature in the well
- fluid pressures in the rock formations
- chemical composition of the groundwater
- properties of the rock formations (e.g. porosity, rock type: hard rock, soft rock or fractured rock).

Cements used in gas wells are Portland cement–based and are required to meet guidelines established by the API. There are various classes of cements recommended by the API, which include cements with different degrees of resistance to sulphate present in underground water (details in Appendix A.2).

The slurry composition can be altered to ensure the cement:

- remains pumpable during placement
- applies appropriate pressure on rock formations to prevent damage to the wellbore, including rock formations
- prevent the loss of cement or water into rock formations
- hardens rapidly after placement and forms a strong bond with the casing and rock formations
- does not allow subsurface gases to penetrate the slurry prior to hardening.

These properties are achieved through the use of chemical additives. The additives are grouped into categories based on their function. The categories of additives include extenders, weighing agents, accelerators, retarders, dispersants, anti-settling agents, anti-gas migration agents, expansion agents, defoamers, antifoamers and thixotropic agents. Further details of cement grades, categories of additives and their compositions are provided in Appendix A.2.

1.2 Study area and coal seam gas reservoirs in Queensland

Coal seam gas producing wells in Australia are largely concentrated in the Surat and Bowen basins in south-east Queensland (Figure 2). A smaller number of exploration and appraisal wells have also been drilled in the Galilee Basin to the west. The geological characteristics differ across the various CSG reservoirs in Queensland. Coal seams in the Surat Basin are geologically younger and have been subjected to less heating compared with those in the Bowen Basin (Sliwa & Esterle, 2016; Wainman & McCabe, 2017). The majority of CSG wells drilled in the Surat Basin are vertical, intersecting multiple coal layers (also referred to as coal seams). In the Bowen Basin, in addition to vertical wells, numerous lateral wells targeting a single thick coal seam have also been drilled (Figure 3).

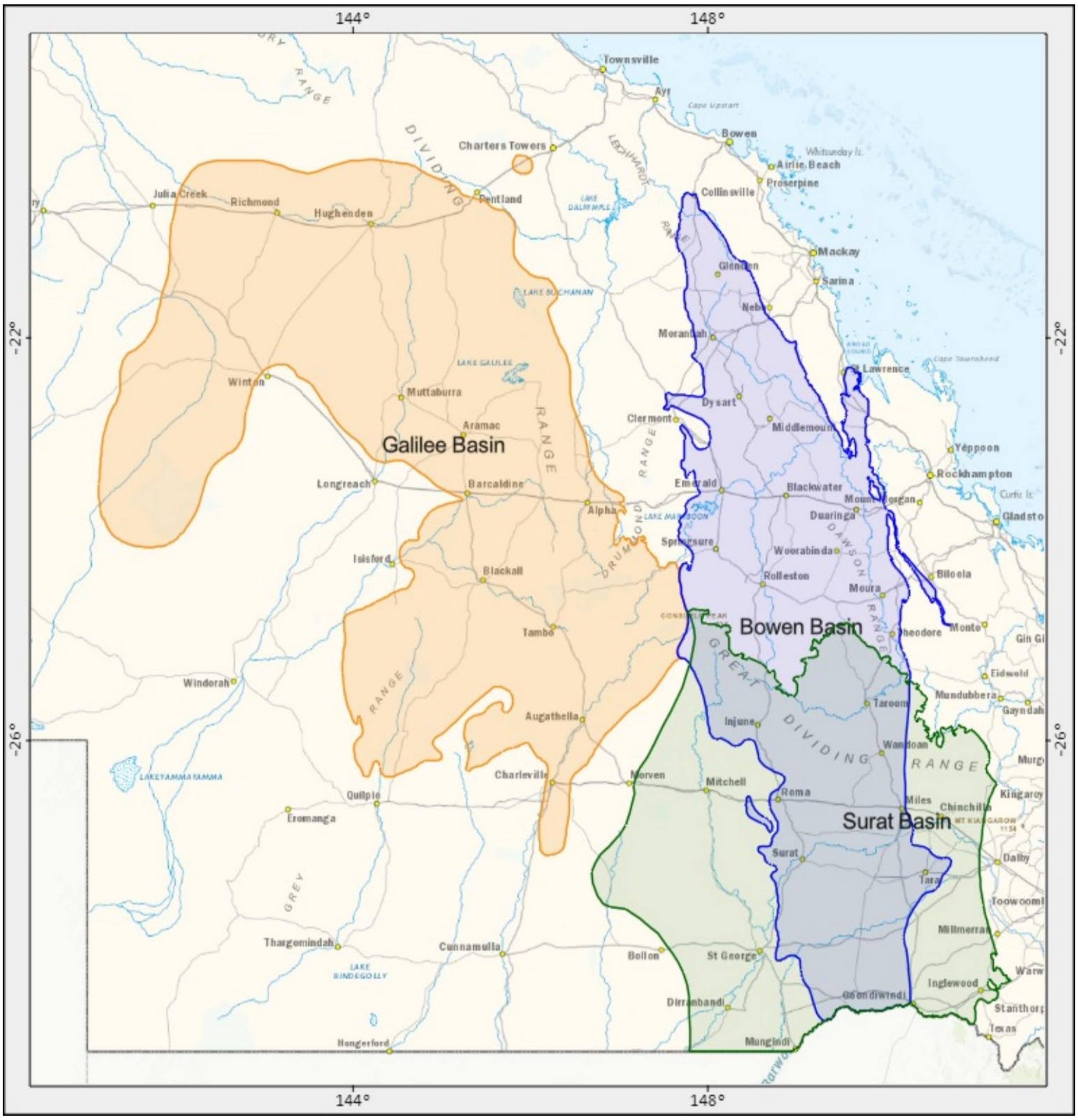


Figure 2: Map showing location of Bowen, Surat and Galilee basins in Queensland

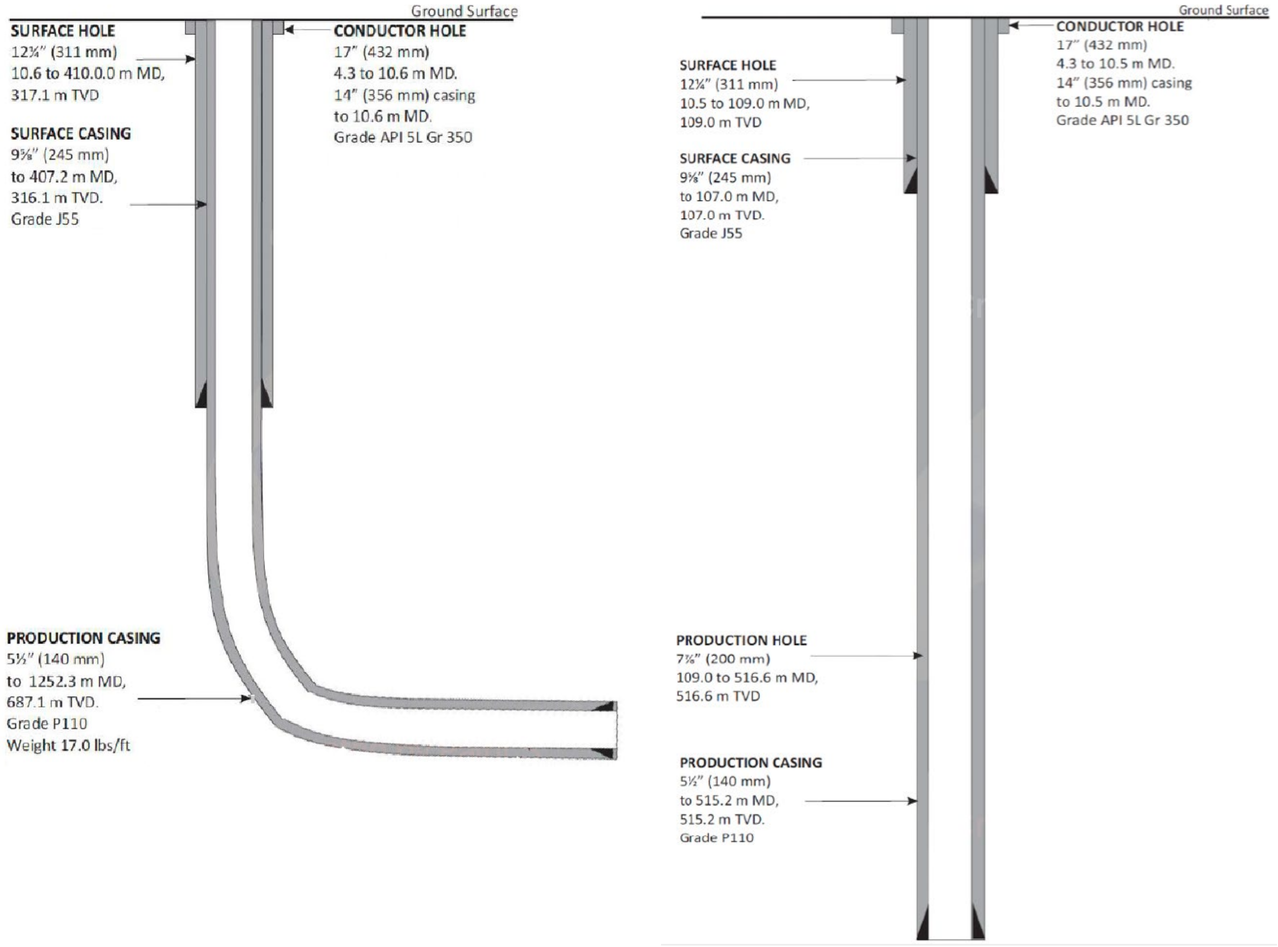


Figure 3: Schematics of a horizontal (left) and a vertical (right) well, showing the position of various types of casing commonly used in their construction

2 Objectives and methods

The overall objective of this report is to provide the community with a broad understanding of the materials used in the construction of CSG wells in Queensland. Discussions with community and landholder groups in Queensland have indicated their interest in understanding the materials used in the downhole environment, as these materials protect groundwater resources and the environment. This study is primarily focused on describing the materials used to case and cement CSG wells in the Surat and Bowen basins. Information on casing and cements was largely derived from publicly accessible WCRs lodged with the Queensland Government,[6] supplemented with a smaller number of more-recent reports directly obtained from the operating companies. The analyses also aimed to identify trends in casing and cement components used over the past two decades, in different geological settings and with different well configurations.

During this study, data for all wells drilled as of February 2023 (13,912 wells) were downloaded.[7] These included exploration, appraisal, injection and development wells drilled in various CSG fields in Queensland. From the downloaded dataset, 131 wells were randomly selected for analysis (random sampling method described in Appendix A.4.5). One hundred and sixteen wells drilled prior to 2019 were open-file and their WCRs were publicly available. Fifteen wells were within their confidentiality period (up to 5 years post drilling) and their data were provided by the operating companies. Total drilled depth of the wells selected for the study ranged from ~254 m to 1919 m, which represents the depth of all the CSG wells drilled in the Surat and Bowen basins (Appendix A.4). Distribution of the selected wells among the operating companies compared to the total dataset is presented in Table 1 and statistical correlations are provided in Appendix A.4.

Table 1: Breakdown of downloaded and reviewed well completion reports categorised by each operating company

Operator	All wells		Reviewed wells	
	#	%	#	%
AGL	16	0.1	–	0.0
Anglo	23	0.2	–	0.0
Arrow	2238	16.1	17	13.0
Junior	471	3.4	3	2.3
Origin	3433	24.7	45	34.4
QGC	4276	30.7	46	35.1
Santos	2973	21.4	18	13.7
Senex	212	1.5	–	0.0
Tristar	64	0.5	–	0.0
Westside	206	1.5	2	1.5
Total	13912	100%	131	100%

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[6] https://geoscience.data.qld.gov.au/

[7] Geological Survey of Queensland (n.d.). ‘Coal seam gas well locations - Queensland.’ Retrieved 09/02/2023, from https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={C45038EB-BB83-4B16-9231-1905ED753D77}.

3 Data sources

3.1 Well completion reports

Data on casing material and cement additives used in the construction of wells were obtained from WCRs prepared by the operating companies. Under the *Petroleum and Gas (General Provisions) Regulation 2017*, WCRs need to be submitted to the Queensland Government, and under section 36 of this regulation, specific information to be reported include:

- total depth (measured depth in metres) of the well
- details of the casing or equipment installed in the well, with a diagram showing their location in the well
- details of the cement used for the well, including the type of cement used and the depth in metres of the top and bottom of each cemented interval.

If the well is plugged and abandoned, the WCR must include further information (an abandonment report) that includes:

- the method of the cementing operations carried out for the well, including the location and type of plugs, the intervals covered by the operations, the volume and type of cement used, any losses of cement due to voids or permeable strata, and the methods used to overcome loss of cement
- the method, materials and volume of cement used to cement voids.

The operating companies are required to submit the WCRs for each well no later than 12 months after completing all well construction activities.[8] The confidentiality period for WCRs is dependent on the type of well. For appraisal and exploration wells, the confidentiality period is 3 years after completion of the well, and for development wells it is 5 years.

Typically, WCRs are lengthy documents, containing a large amount of specialised information on the well. The WCRs are prepared by technical specialists in the operating companies to efficiently record and communicate complex information to other specialists about the construction of the well; their purpose is not intended to inform a general audience. Most general information is found in the initial sections of the report, particularly the well card and well schematics (Figure 4). These sections summarise the main features of the well for quick reference. The detailed and more specialised information, such as drilling reports, well logs and other uninterpreted data are set out in multiple appendices or referenced in separate files that accompany the WCR. Although formats of the WCRs are similar, when compared across different locations and drilling years, they are not identical. Further observations on WCRs and recommendations to improve accessibility are noted in Appendix A.3.2.

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[8] https://www.business.qld.gov.au/industries/mining-energy-water/resources/petroleum-energy/reports-notices/petroleum-wells

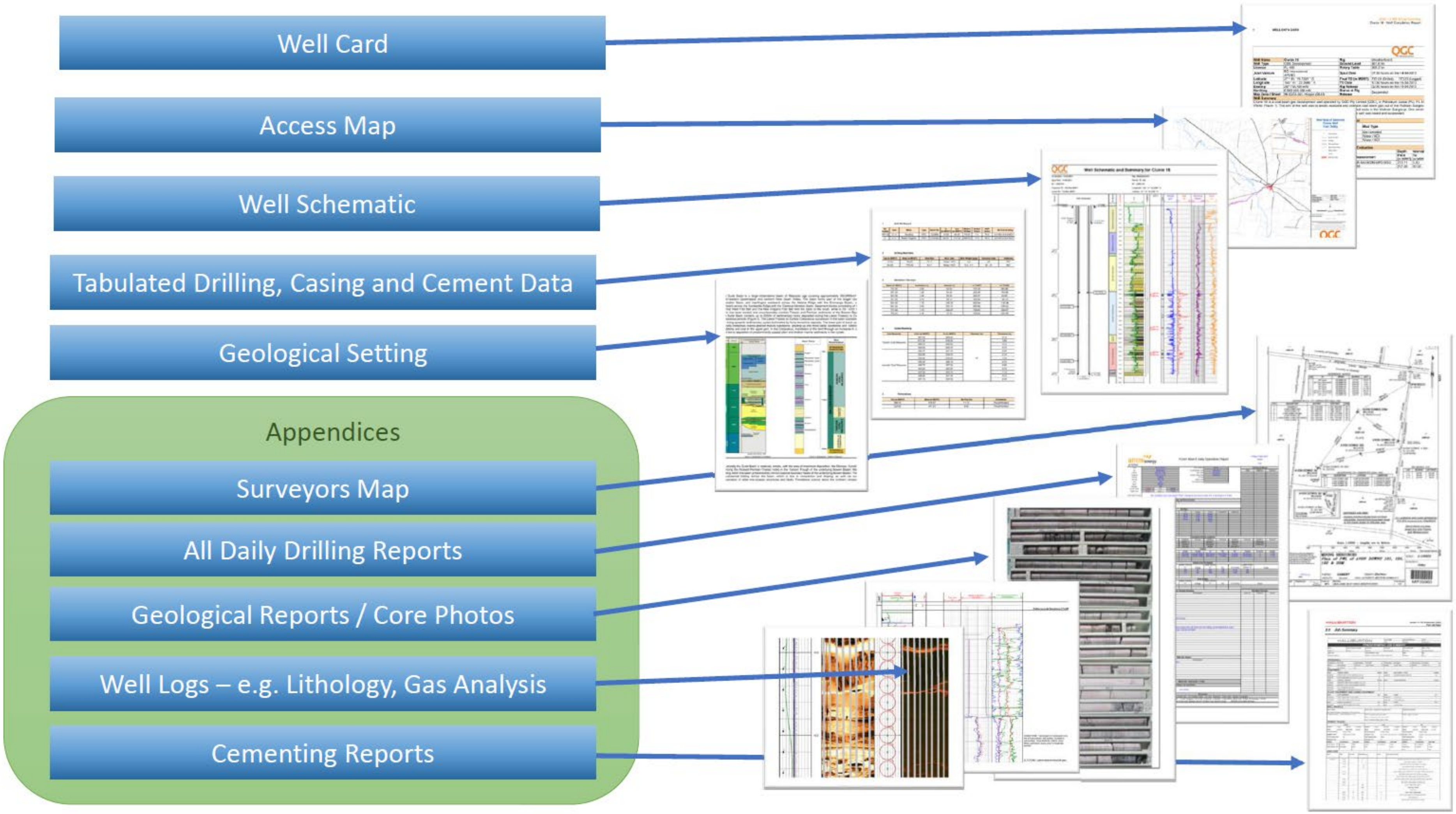

Figure 4: Example structure of a WCR. The first few pages of the WCR generally contain summarised and interpreted information that is more accessible to a general audience. Reports with uninterpreted data, logs and other information intended for communication between specialists associated with drilling and completion of the well are generally found in the appendices, including in the cementing reports

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3.2 Data collection process

All WCRs obtained for this study were read, and required information for this study therein recorded. The information extracted included well location, borehole diameter, casing type and cement class, quantity and additives. The task was conducted manually, without the use of an automated or software-based process (Figure 5). Information required for this project was largely contained within the initial sections of the WCRs, such as the well card and well schematic; however, most detailed information on cement additives was found in the cementing report, which was often included in an appendix, or sometimes in a separate document accompanying the WCR. Where information was incomplete, such as additive concentrations or missing trade names, the cementing reports were examined. The location, year of drilling and the geological basins for the wells studied were also recorded (Figure 6 and Figure 7).

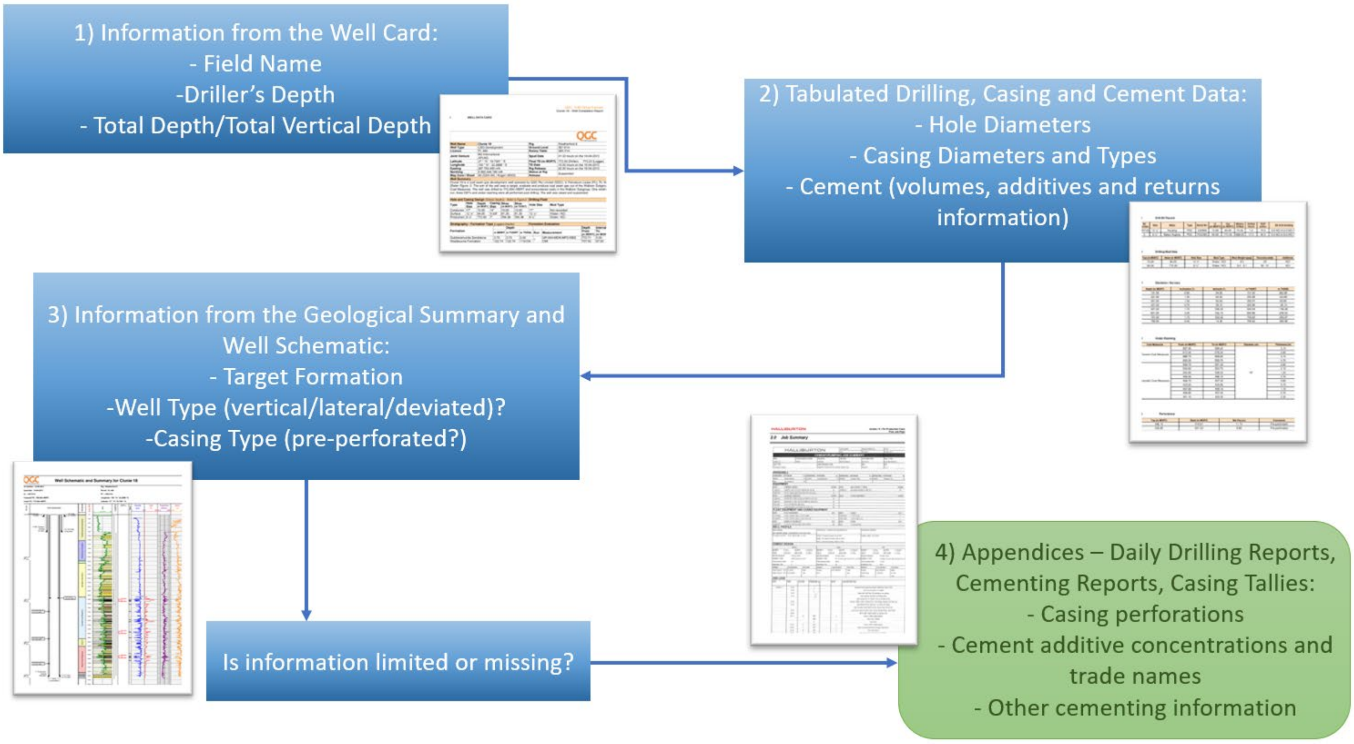

Figure 5: Manual data extraction workflow. Different sections of the WCRs were checked during data collection. Tabulated data in the opening pages of the WCR, and cementing report data in the appendix were used to compile cement additive information

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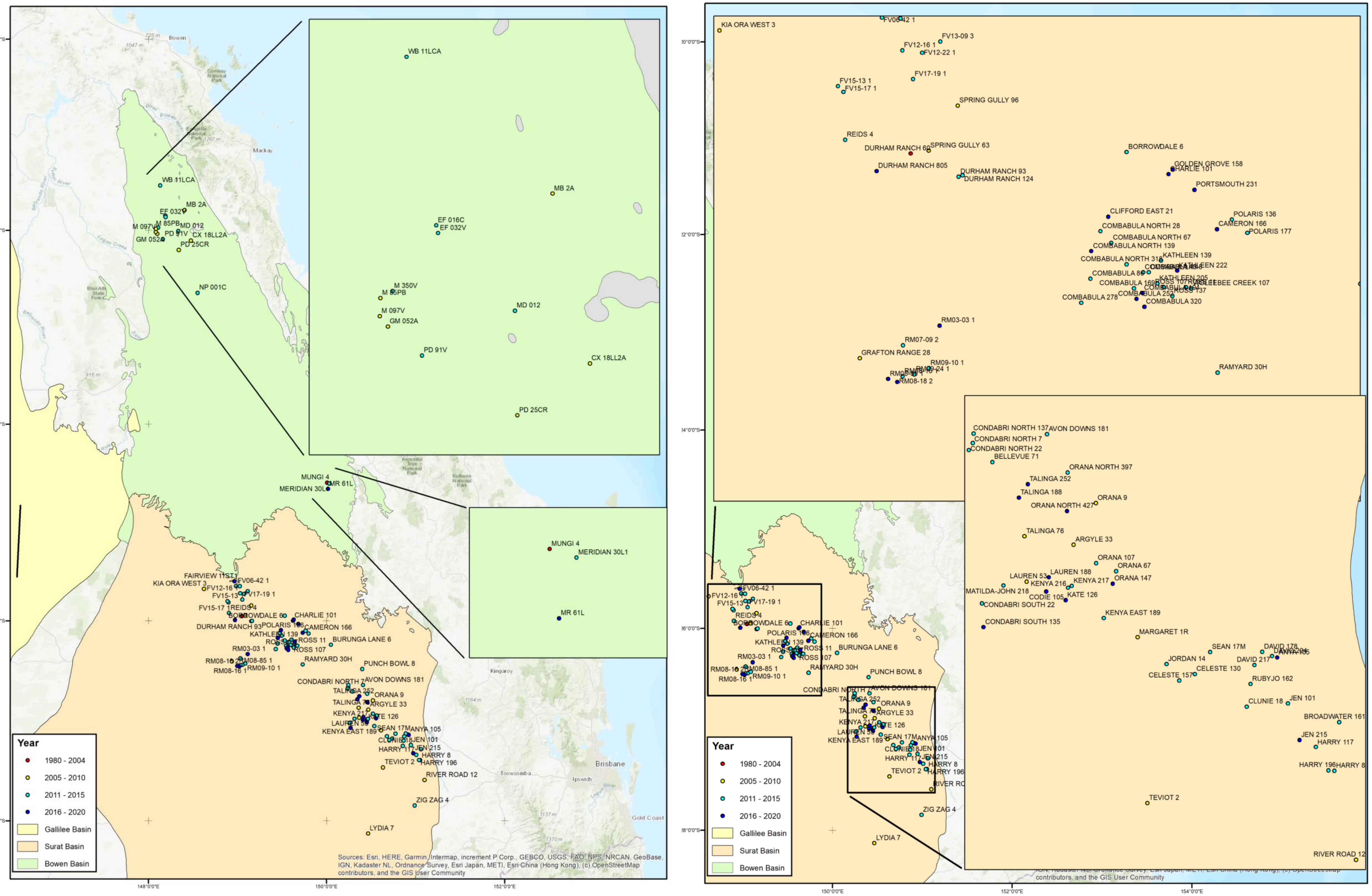

(a)

(b)

Figure 6: Locations of the 131 CSG wells used in this study. (a) Wells in the northern parts of the study area; (b) Wells in the southern parts of the study area

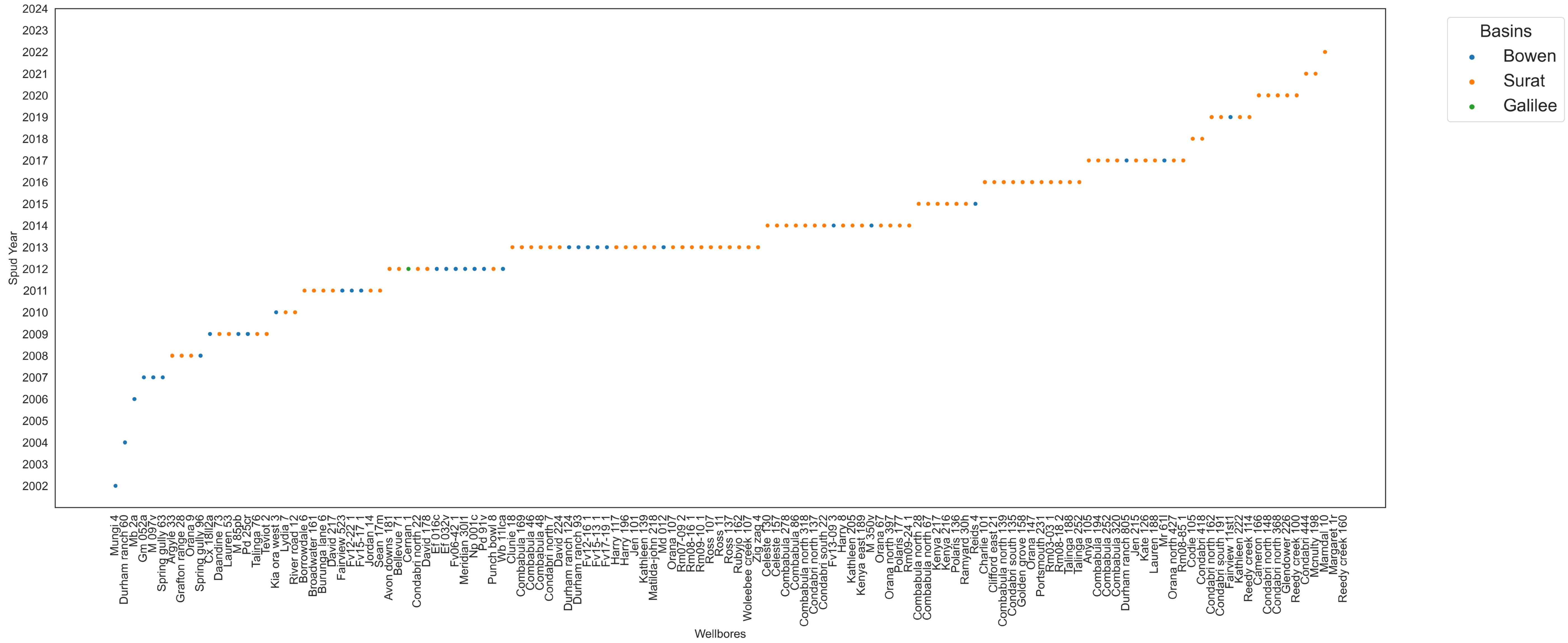

Figure 7: Year of drilling (i.e. spud year) for the 131 CSG wells used in this study, ordered chronologically

3.3 Data limitations and quality control

Information is listed as missing or not recorded if it was not available within the files downloaded from Geological Survey of Queensland’s Open Data Portal. Quality control on the final dataset included:

- searching unique values to locate duplicates and screen for typographical errors
- checking data type entered to screen for transcription and typographical errors
- checking compiled data with original WCRs by multiple project staff
- checking outlier or unusual values collected from WCRs by multiple project staff.

While this manual process was time consuming, it reflects the experience of a non-technical community member seeking information on cement or casing from WCRs. More detailed information related to the reports, including formatting, readability, accessibility and consistency, is provided in Appendix A.3.

4 Casing in CSG wells

Casing data extracted from WCRs for 131 CSG wells were analysed with respect to casing composition, sizes and types of casing used. Integrity of casing is a critical factor in the construction of wells as it is the first line of defence against potential environmental contamination. Over the years, casing practices employed in the oil and gas industry have evolved with advancements in materials and technologies used in manufacturing, as well as changes in industry regulations for well construction. A detailed description of the casing types and grades used in the oil and gas industry are provided in Appendix A.1.

The choice of casing grades used in sections of a CSG well is driven by its total depth, subsurface geological conditions, practical needs and cost considerations. Steel grade K55 is the most commonly used casing material in the CSG wells drilled across the Surat and Bowen basins (Figure 8). K55 steel accounts for about 60% of the casings in the dataset and is used in surface, intermediate and production casings. In mildly corrosive environments (e.g. lacking significant carbon dioxide and hydrogen sulphide), such as in most CSG reservoirs in Queensland, K55 also provides resistance to corrosion (Loder et al., 2024).

In some WCRs the details of materials used for some sections of casing were not clearly stated; In Figure 8, these have been denoted as ‘NCI’ (not clearly identified). The majority of this missing information is related to a short section of conductor casing which ranges in length between 6 and 18 m. Fibreglass and polyethylene materials were used in production casing in four lateral wells in the Bowen Basin where the CSG fields overlap with potential mining tenure. This is in accordance with Queensland Government regulations that steel casing should not be used in lateral wells drilled in regions where the CSG field overlaps with coal mining tenure. The Code also indicates that when drilling single-casing string wells that intersect a single coal seam, steel, PVC-U or fiberglass casing can be used. These materials offer a corrosion-resistant option, and PVC-U, in particular, is suitable for shallow wells with low pressure conditions (RSHQ, 2019).

The majority of the WCRs examined provided information on the material used for three casing sections, including conductor, surface and production casings (Figure 9). Ten wells, however, also had an intermediate casing (Figure 10 and Figure 11). The depth at which different casing types are set is determined by the stratigraphy of various geological formations, including aquifers and the target CSG reservoirs. Additionally, well design strategies and operational needs are also considered to optimise casing depth in well configurations. For example, additional casing may be installed if there are significant well stability issues while drilling the wellbore.

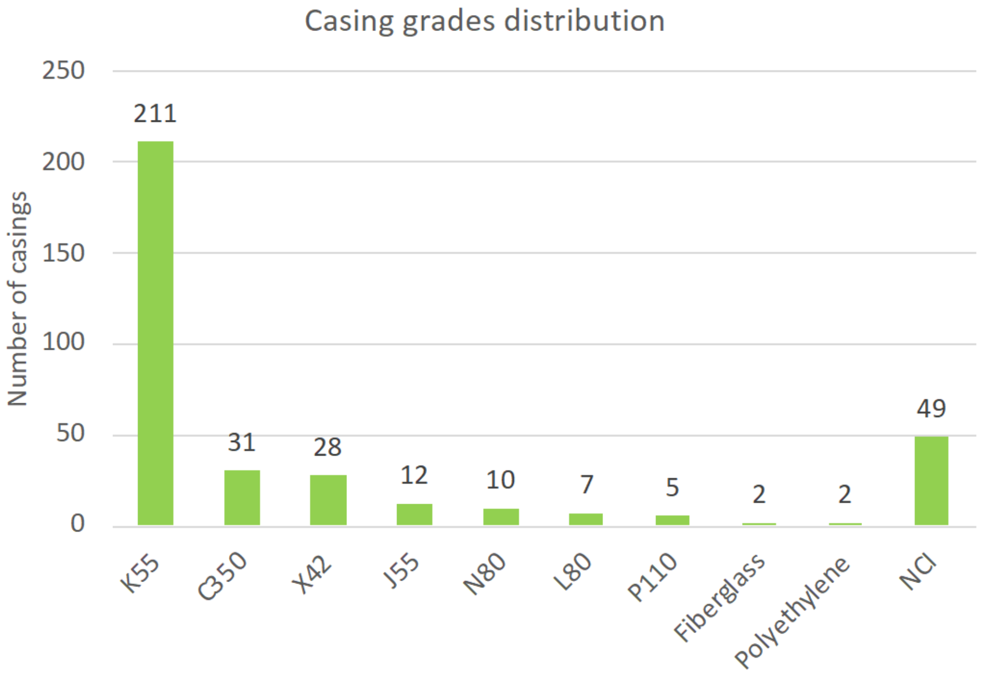

Figure 8: Distribution of casing grades in the CSG wells studied. NCI – casing material not clearly identified; the majority of these are related to shallow conductor casings

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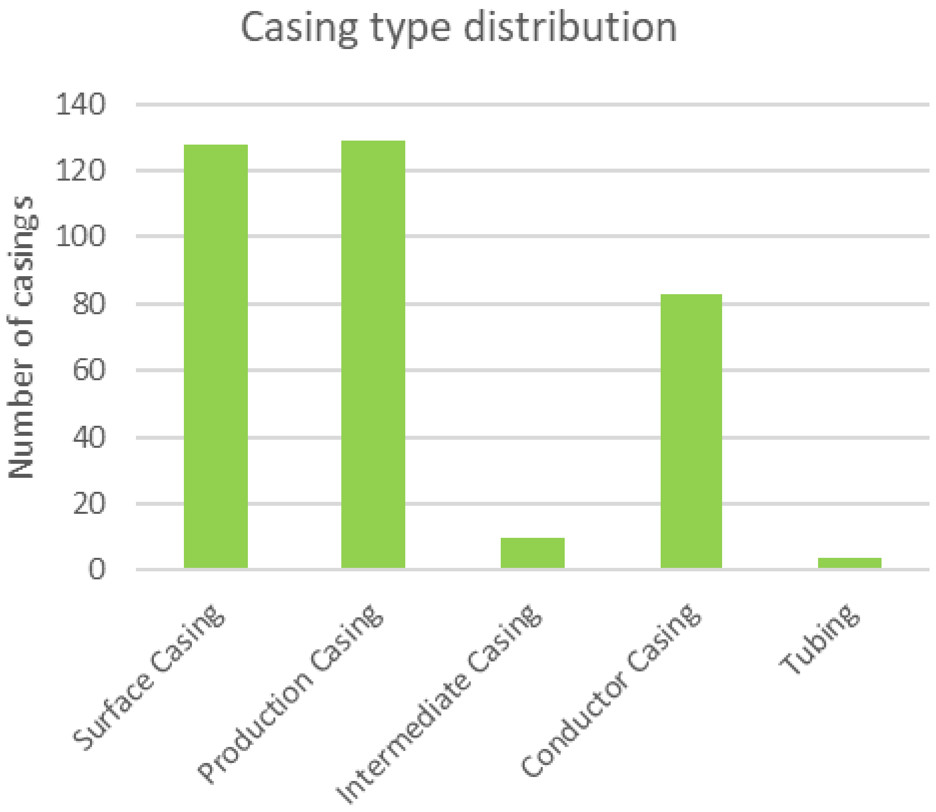


Figure 9: Casing types used in the CSG wells studied

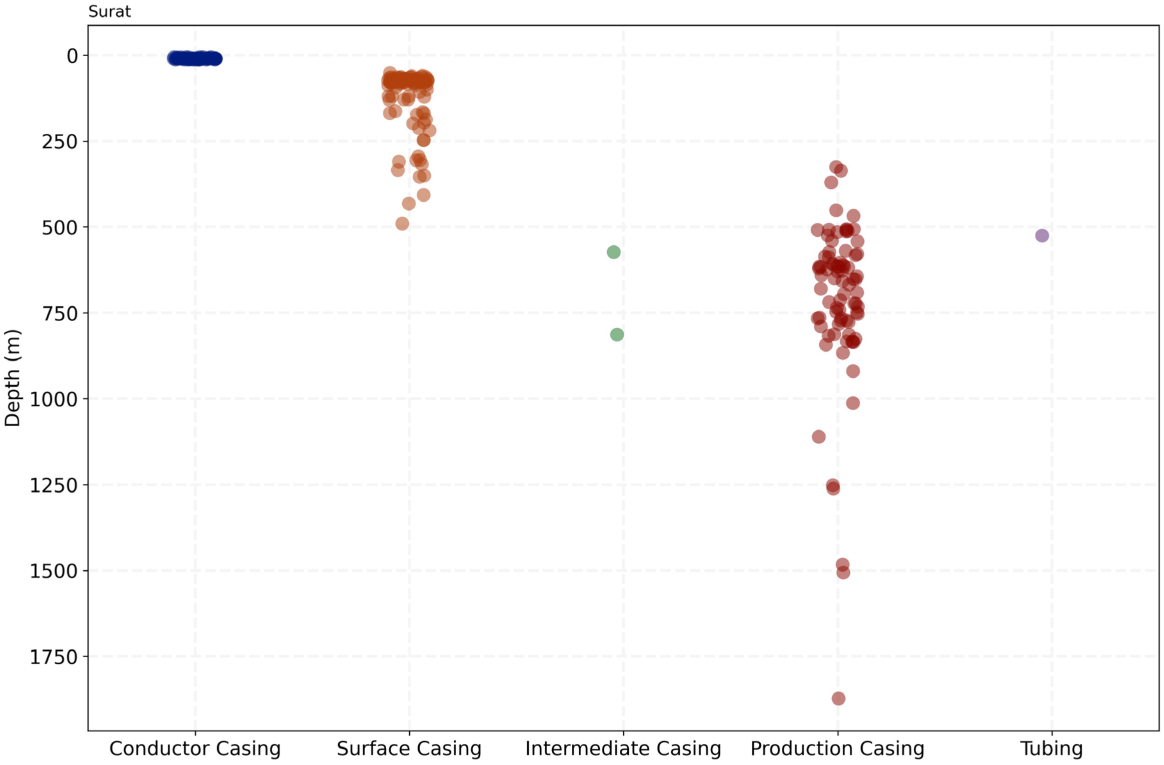


Figure 10: Casing shoe (i.e. bottom of casing) depth for Surat Basin wells

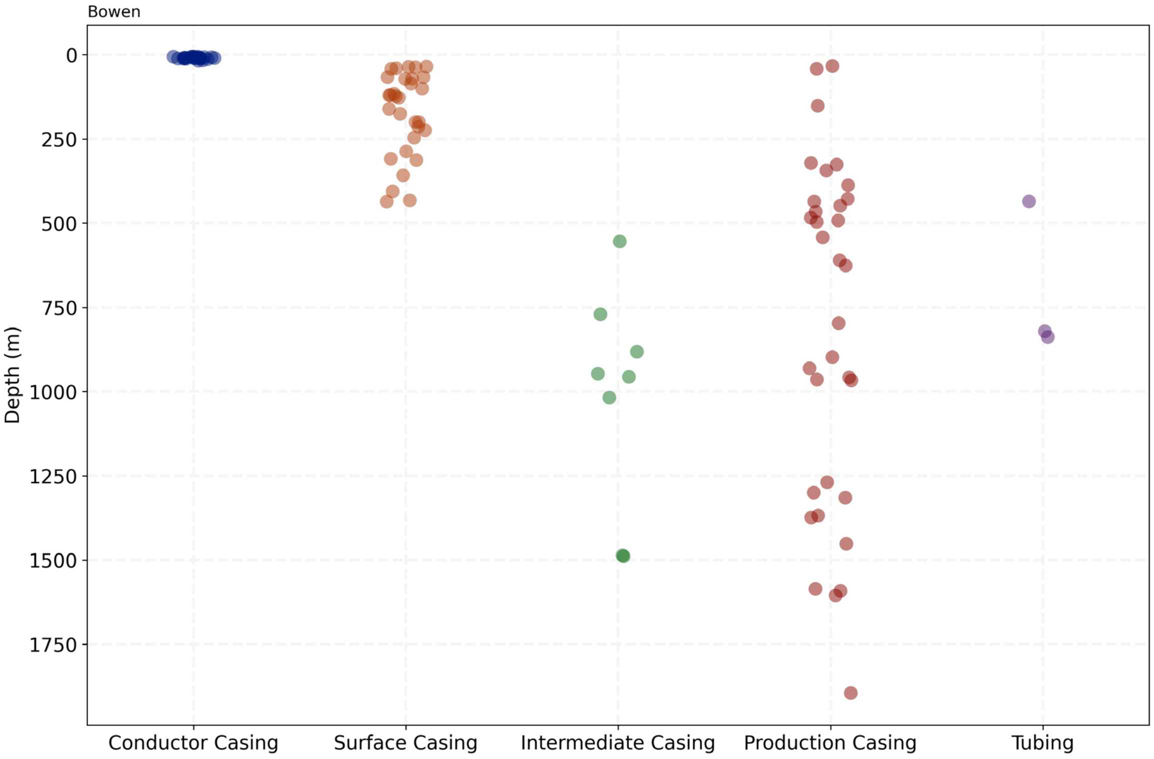


Figure 11: Casing shoe (bottom of casing) depth for Bowen Basin wells

The data were also analysed to investigate how the casing materials may have varied over time (Table 2). The percentile distribution of various casing materials reported in the dataset indicate that K55 is the dominant steel grade used in the wells drilled in the Bowen and Surat basins (Figure 12). The K55 casing is not only used for surface casing applications but is also commonly utilised as intermediate and production casing. Conductor casing typically employs steel grades like X42 and C350, whereas production casings often incorporate grades such as N80, L80 and P110. A specific evolution pattern in the casing steel grades used in the CSG wells drilled between 2002 and 2022 is not evident.

Table 2: Distribution of materials used in casings from the 131 CSG wells drilled between 2002 and 2022. More details on the properties of various casing grades are provided in Appendix A.1.2

Year	Steel grade or material									
	K55	C350	X42	J55	N80	L80	P110	Fiberglass	Polyethylene	NCI
2002					1					1
2004	1				1					
2006								1		2
2007	1	4		1		1			1	3
2008	7	2			1	1				1
2009	5	5				1				7
2010	1	2	1							2
2011	14	1		1		1				5
2012	19	7		2	2				1	6
2013	49	3	6	3	3		2			12
2014	32	2	6	1			1			3
2015	14		3		2	1				
2016	18	2	3	2			2			
2017	19	1	4	2				1		5
2018	2		1							
2019	2		1							1
2020	4		1							1
2022	2		1			1				

NCI – not clearly identified.

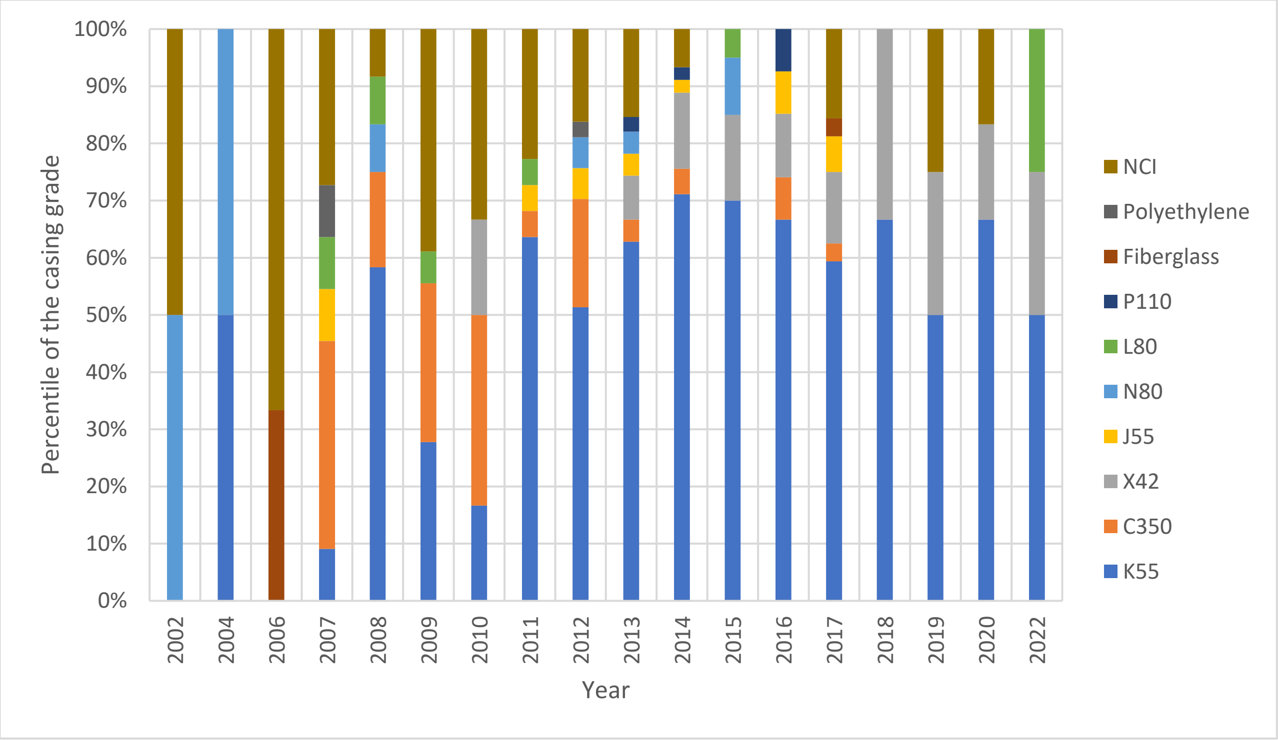


Figure 12: Percentile distribution of steel casing grades used between 2000 and 2022 in casings for the 131 CSG well sampled; NCI – not clearly identified

5 Cement in CSG wells

The composition of cement slurries used in the sample dataset was extracted from well data cards, cementing reports, drilling reports and other sections of the WCRs (Figure 4). Most of the information was obtained from the well data cards and cementing reports. In some WCRs, however, a cementing report was not included. The formulations of the cement slurries for seven wells were not found in the WCRs and, therefore, the cements used in these wells are unknown. These wells were constructed before the release of the Code in 2011.

5.1 Well cementing

In the WCRs analysed, only 41% of conductor casings were reported as cemented, whereas about 95% of surface, intermediate and production casings were reported as cemented. In addition to primary cementing, secondary cementing was reported for 15 wells, for plugging and suspending specific sections of the wells (see Appendix A.2).

In some wells, the surface, intermediate and production casings used two cement slurry formulations called lead and tail slurries (see Appendix A.2). Lead slurry is used in the upper part of the casing, whereas the tail slurry is used in the lower parts, where the temperatures and stresses are greater and the cement is more frequently exposed to coal seam fluids. In addition, the types of additives and their concentrations in these slurries also differ between wells (Table 3).

Table 3: Examples of lead and tail cement slurry compositions used in production casing in Combabula North 318 and intermediate casing in Durham Ranch 805

Well name	Casing section and cement slurry	Ingredient	Function	Concentration	Units[A]
Combabula North 318	Production lead slurry	Class A	Cement		
		$CaCl_2$	Accelerator	1	%BWOC
		NF-6	Defoamer	0.25	gal/10bbl
		Econolite	Extender	1.5	%BWOC
	Production tail slurry	Class A	Cement		
		$CaCl_2$	Accelerator	0.5	%BWOC
		NF-6	Defoamer	0.25	gal/10bbl
		CFR-3	Dispersant	0.5	%BWOC
		Halad 344	Fluid loss	0.4	%BWOC
Durham Ranch 805	Intermediate lead slurry	Class A	Cement		
		LiteCrete	Lightweight cement	94	lbs/sacks
		D167	Fluid loss	0.4	%BWOC
		D065	Dispersant	0.55	%BWOC
		D047	Antifoamer	0.05	gal/sack
		D029	Lost circulation	0.2	%BWOC
		D013	Retarder	0.15	%BWOC
	Intermediate tail slurry	D901	Cement	94	lbs/sack
		Cement: Fly ash 80:20	Lightweight cement	94	lbs/sack
		S001	Accelerator	1	%BWOC
		D167	Fluid loss	0.5	%BWOC
		D065	Dispersant	0.4	%BWOC
		D047	Antifoamer	0.01	gal/sack
		D029	Lost circulation	0.2	%BWOC

[A] BWOC – weight percentage (by the weight of cement); gal/10bbl – gallons/10 barrels; lbs/sack – pounds/sack; gal/sack – gallons/sack.

5.2 Well cementing service providers

Cementing of CSG wells was mostly conducted by service providers (e.g. Schlumberger, Halliburton, Wagners, BJ Services Australia or TRICAN) contracted by the operating companies (Table 4). Most of the wells (98 out of 124) drilled between 2002 and 2022 were cemented by Halliburton and Schlumberger. However, 11 wells drilled between 2011 and 2013 were cemented in partnership with the drilling contractor, and the drilling contractor cemented the shallow (< 100 m) conductor and surface casings (Table 4; Figure 13).

Table 4: Total number of wells cemented by different cementing companies and drilling contractors

Well cementing provider	No. of wells	Well cementing provider	No. of wells
Halliburton	78	**TRICAN**	1
Schlumberger	20	**Major Drilling**	2
Halliburton and Wagners	4	**AJ Lucas**	1
Halliburton and BJ Services Australia	1	**Drillstralis**	1
Halliburton and Nitro Drilling	1	**Ensign**	1
Halliburton and Schlumberger	1	**John Nitschke Drilling**	1
Halliburton and TCL	1	**Johnson Drilling**	1
Halliburton and Wallis Drilling	1	**Mitchell Drilling Corporation**	1
Schlumberger and TCL	2	**Mitchell Drilling Services**	1
Schlumberger and Wagners	1	**Mouzouris Drilling**	1
BJ Services Australia	2	**Queensland Drilling Services**	1

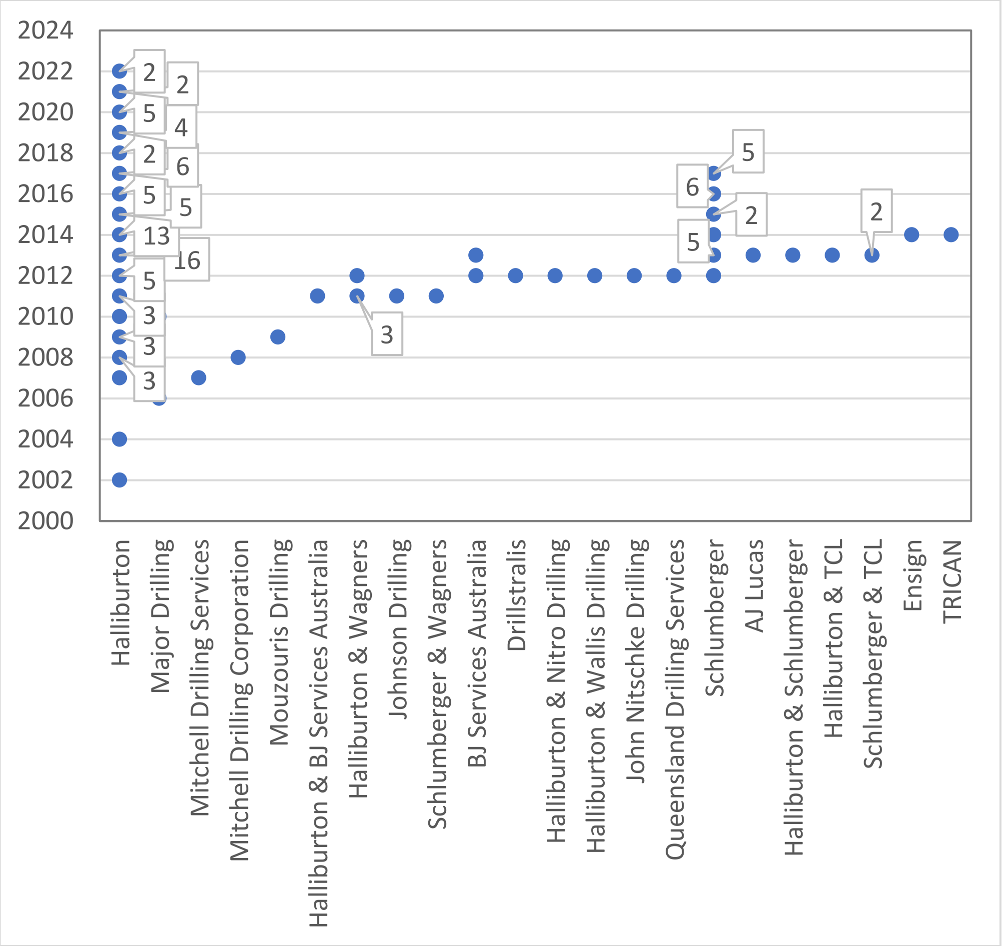


Figure 13: Construction years of the wells cemented by various service providers. Also annotated are the number of wells cemented (where it is more than one) during each year

5.3 Cement composition

5.3.1 Cements

Various cements have been used in the Queensland CSG wells, and these include Class A, general purpose (Type GP), blended cement (Type GB), shrinkage-limited (Type SL), sulphate-resisting (Type SR) and Class G. The compositions of Class A and Class G cements are specified in the API SPEC 10A standard (American Petroleum Institute, 2019b), and the compositions of the other cements are specified in the Australian standard AS 3972-2010: General purpose and blended cements (Australian Standards, 2010). The main constituent of these cements is Portland cement, with various amounts of other mineral additions (Harrison, 2019). More detailed information on the composition of Portland cement and API cements is presented in Appendix A.2.

There are only small compositional differences between the general purpose (Type GP) and Class A cements. Type GP cement, as specified by the Australian standard, contains a higher proportion of mineral additions (max 7.5%) compared to that in Class A cement (max 5%) (Harrison, 2019). Overall, the most common mineral additions are limestone and cement kiln dust, while fly ash and slag are only included in Type GP cement. These cements were reported in the WCRs as Class A, Portland GP cement and Standard cement (Table 5). Class A cement was the commonly used cement as reported in the WCRs reviewed (86 wells; Figure 14).

The shrinkage-limited (Type SL) and sulphate-resisting (Type SR) cements are special-purpose cements that meet more stringent performance requirements. Type SL cement shrinks less upon drying, while Type SR has higher resistance to sulphates present in underground waters. These cements are prepared using either general purpose (Type GP) or blended cement (Type GB). The shrinkage-limited cements reported in the WCRs were SL cement and D901 (Table 5).

Blended cement (Type GB) is a general purpose cement with greater amounts of mineral additions than Type GP. It contains over 7.5% fly ash or slag or both, and up to 10% amorphous silica. D910 cement and Builder’s cement reported in the WCRs, are both special purpose cements. D910 is a Type SL cement prepared using Type GB cement, while Builder’s cement is both Type SL and Type SR cement but is also prepared using Type GB cement (Table 5).

Class G cement is manufactured to have either moderate or high resistance to sulphates present in underground waters. Its use was reported in only one WCR reviewed during this study.

The cements used by the operators of the wells were manufactured according to specifications in the Australian or API standards or based on Halliburton and Schlumberger proprietary formulations.

Other cements reported in the WCRs were lightweight cements and gas-tight cements (Table 5). These cements contain additives that lower the density of cement slurry (lightweight cements) or prevent migration of gas through the stiffened cement after the placement of the slurry (gas-tight cements). The lightweight cements were prepared by mixing Portland cement with extenders (e.g. fly ash, lightweight microspheres, silica, sodium metasilicate) in specific proportions (Table 5). Some lightweight cements were proprietary products (e.g. EconoCem, HalCem, Tuned Light, VersaCem, CBM, Tuned Light Blend and LiteCrete). Their compositions are not openly available. In most cases where lightweight cement was used, it was mixed with other cements and various additives. A smaller proportion (3%) of cement slurries were prepared with only lightweight cement and additives (Figure 15). The gas-tight cements were reported in only three wells, where they were used in the tail slurries.

Several wells (39%) were cemented using at least two types of cements. For example, in Durham Ranch 93, four different types of cements (VersaCem, HalCem, Tuned Light and Portland GP) were used for cementing various sections of casings in the well.

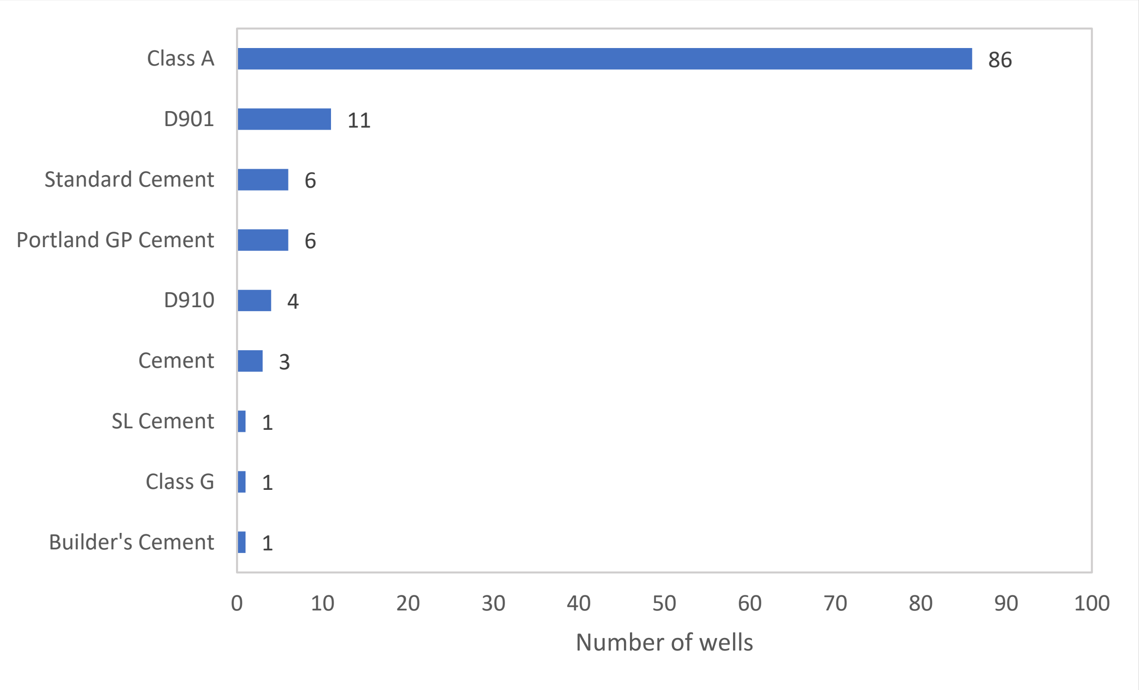


Figure 14: Different cements used in the dataset. Note that multiple wells had at least two types of cements used for cementing casings

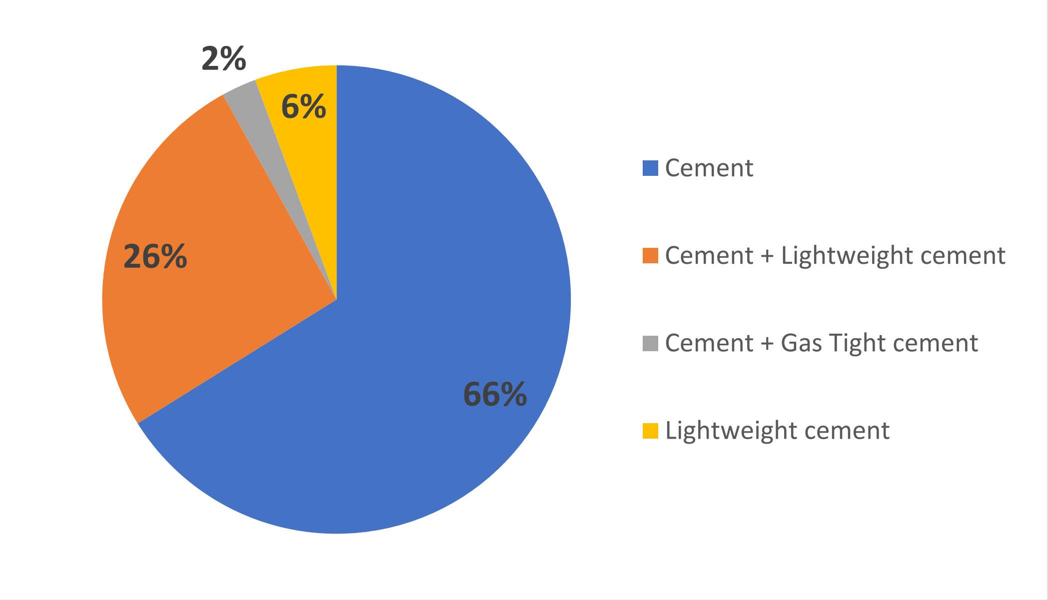


Figure 15: Percentage of cement slurries prepared using different types of cements

Table 5: Types and composition of cements used in the CSG wells studied

Name of cement	Cement type	Manufacturer/service provider	Comments
Portland GP cement	Cement	Generic	General purpose cement (Type GP)
Standard cement	Cement	Halliburton	Cement Standard Class A Portland cement (60–100%) blended with extender (silica) (Composition is withheld as proprietary)
SL cement	Cement	Generic	Shrinkage limited cement for special purpose, complying with AS 3972, Type SL.
Cement	Cement		Reported in 3 wells by BJ Services Australia and Schlumberger
D901	Cement	Schlumberger	Cement Class A – Type SL
D910	Cement	Schlumberger	SL GP blend
Builder's cement	Cement	Generic	• *Cement Australia*: Portland cement blended with fly ash, Type GB, meeting the requirements as Type SL and Type SR • *Boral*: Portland cement blended with ground granulated blast furnace slag
EconoCem cement	Lightweight cement	Halliburton	Portland cement (30–60%) blended with extender (silica) (Composition is withheld as proprietary)
HalCem cement	Lightweight cement	Halliburton	Portland cement (60–100%) blended with extender (silica) and lime (CaO) (Composition is withheld as proprietary)
Tuned Light cement	Lightweight cement	Halliburton	Portland cement (60–100%) blended with extender (lightweight microspheres) (Composition is withheld as proprietary)
VersaCem cement	Lightweight cement	Halliburton	Portland cement (30–60%) blended with extender (silica) (Composition is withheld as proprietary)
CBM	Lightweight cement	Halliburton	Portland cement (60–100%) blended with extenders (silica and sodium metasilicate) (Composition is withheld as proprietary)
Tuned Light Blend	Lightweight cement	Halliburton	Portland cement (30–60%) blended with extender (lightweight microspheres) (Composition is withheld as proprietary)
POZMIX 65:35 **65/35 Pozblend**	Lightweight cement	Halliburton	Cement-pozzolan blend 65% cement and 35% POZMIX A (fly ash)
35:65 Poz GP cement **35:65 Pozmix GP**	Lightweight cement	Halliburton	Cement-pozzolan blend 65% GP cement and 35% POZMIX A (fly ash)
35:65 Poz standard cement	Lightweight cement	Halliburton	Cement-pozzolan blend 65% standard cement and 35% POZMIX A (fly ash)
POZMIX 80:20	Lightweight cement	Halliburton	Cement-pozzolan blend 80% cement and 20% POZMIX A (fly ash)
80:20 GP cement:fly ash blend	Lightweight cement	Schlumberger	Cement-pozzolan blend 80% GP cement and 20% fly ash
80 SL cement/20 fly ash blend	Lightweight cement	Schlumberger	Cement-pozzolan blend 80% SL cement and 20% fly ash
65 SL cement/35 fly ash blend **SL cement 65/35 blend**	Lightweight cement	Schlumberger	Cement-pozzolan blend 65% SL cement and 35% fly ash
LiteCrete	Lightweight cement	Schlumberger	Composition unknown
Gas-tight cement		Halliburton	Composition unknown

5.3.2 Additives in cement slurry

A wide range of additives were reported in the WCRs reviewed, including antifoamers, defoamers, accelerators, dispersants, extenders, retarders, and fluid loss, lost circulation, thixotropic, expansion and anti-gas migration agents (Table 6). Some of the key properties of cement that can be adjusted using these additives include viscosity, density, pumpability, bonding characteristics, strength and setting time. A detailed description of the additives is given in Appendix A.2.4. Antifoamers, defoamers, accelerators, dispersants and extenders are the most commonly used categories of additives reported in the WCRs (Figure 16 to Figure 19; for details see Appendix A.2).

In the wells drilled prior to 2005, dispersants, extenders and accelerators are the only categories of additives reported in the WCRs (Figure 17 to Figure 19). Antifoamers and defoamers appear to have only been in use or reported since 2008. The use or reporting of the other categories of additives is apparent since 2011, which coincides with the year the Code was first released. Expansion and anti-gas migration additives appear to have only been used in a few Surat Basin wells drilled in 2014 and 2016 (Figure 19).

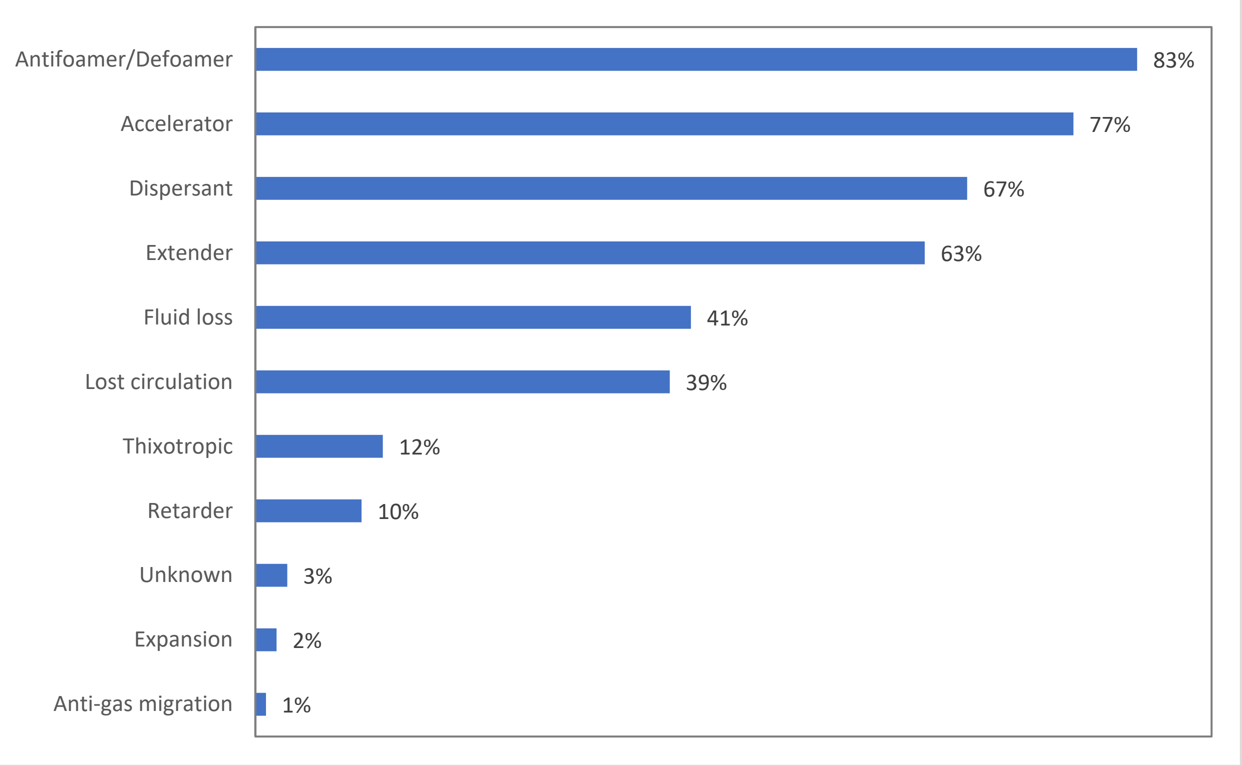


Figure 16: Percentage of different types of additives added to cement in wells studied

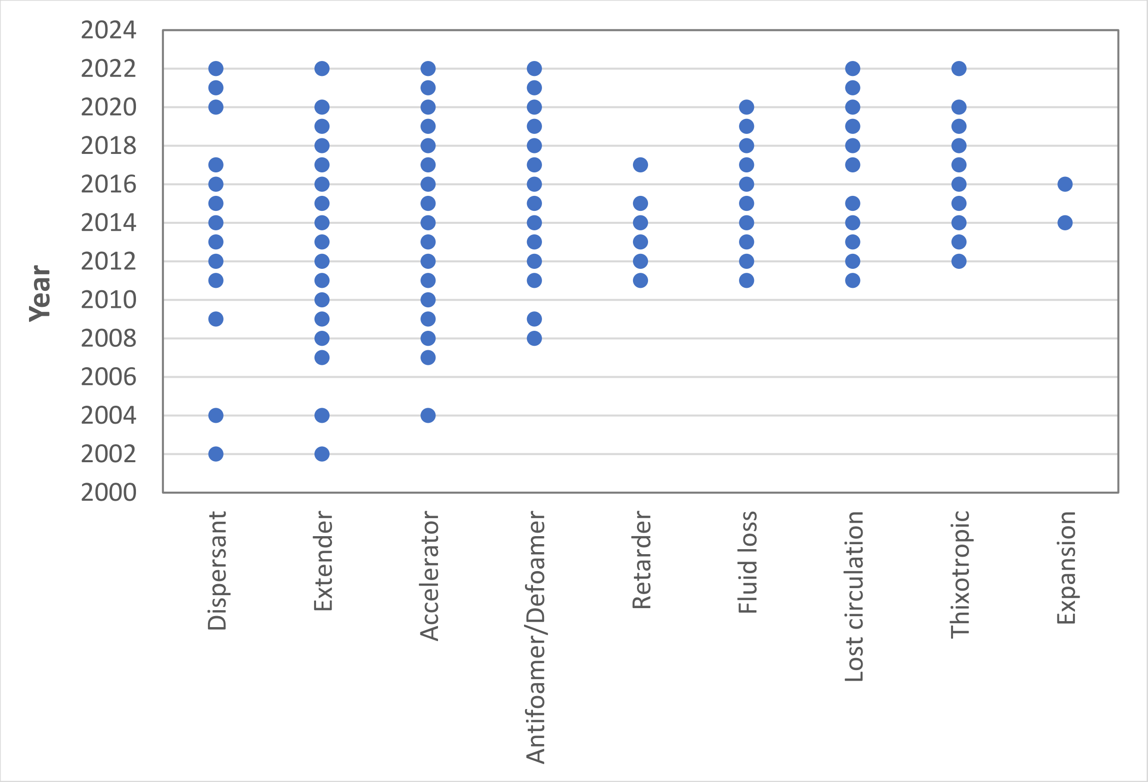


Figure 17: Categories of additives actively used in cement slurries in the CSG wells each year

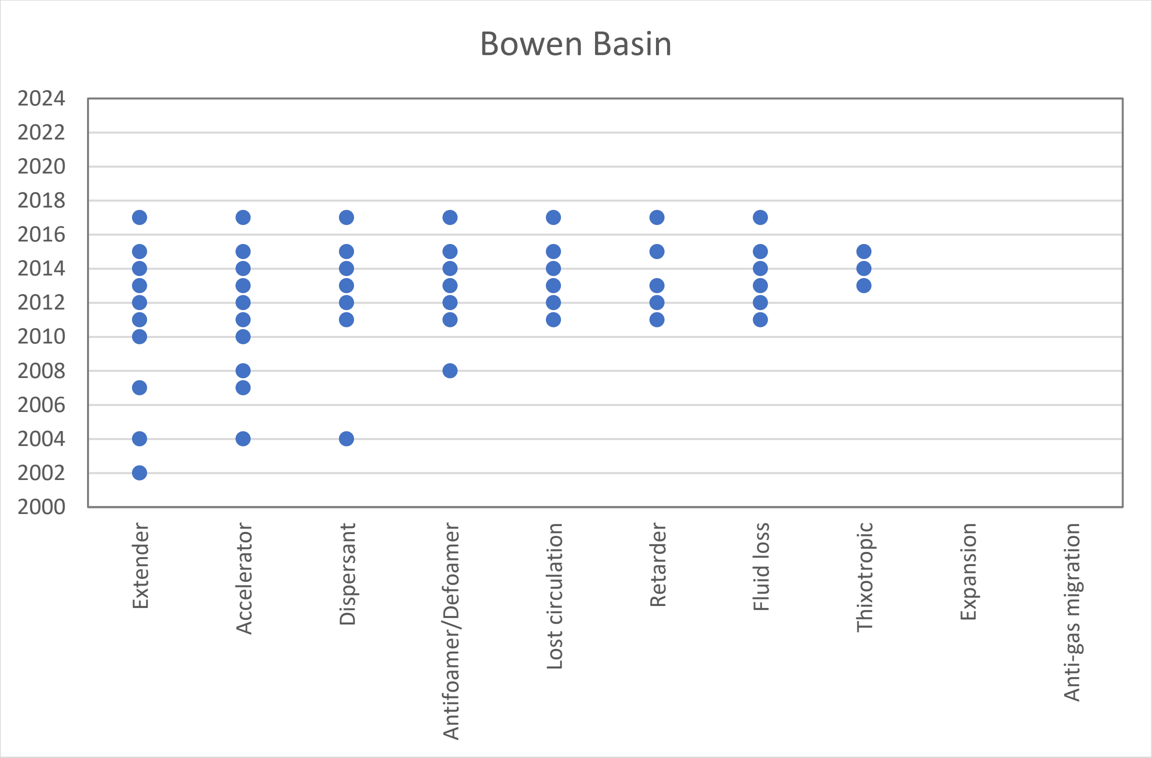


Figure 18: Categories of additives actively used in cement slurries in the Bowen Basin wells analysed

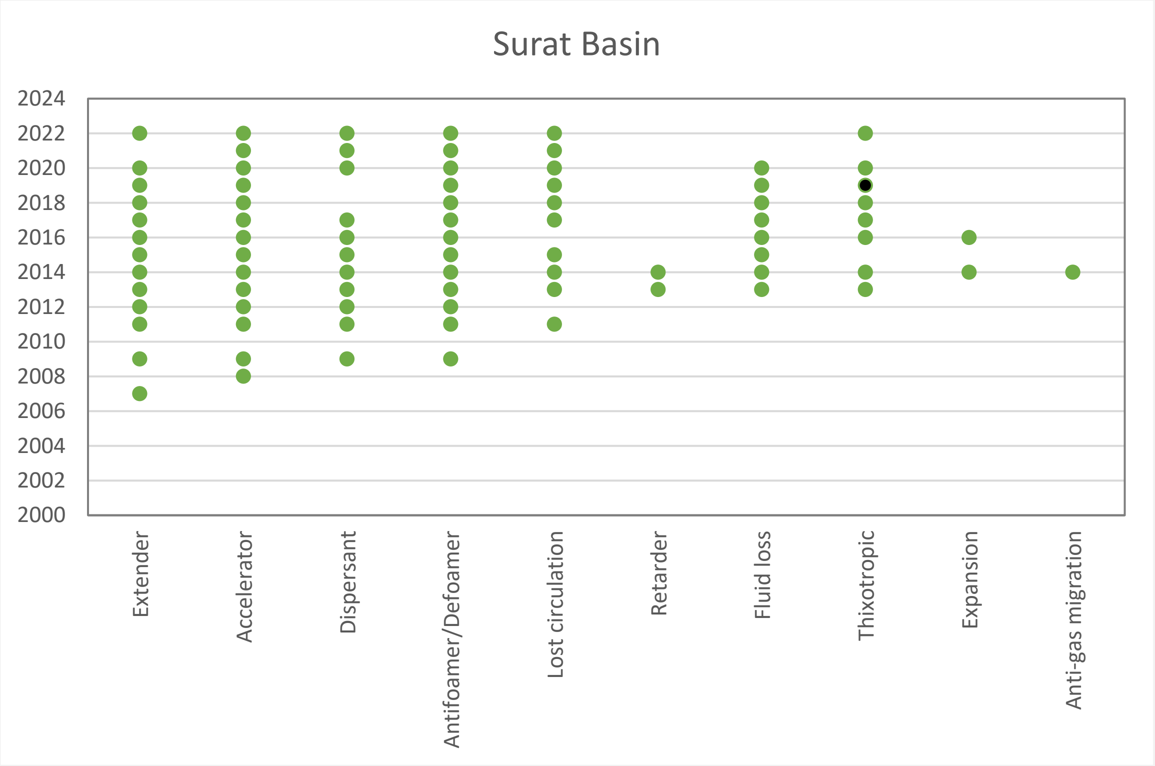


Figure 19: Categories of additives used in cement slurries in the Surat Basin wells analysed

Approximately 70 different additives have been used in cement slurry formulations (Table 6). In some WCRs, only the category or function of the additive was reported instead of its composition or specific name (Table 6). The most commonly used functional categories of additives include antifoamers, defoamers, dispersants, extenders, retarders, and fluid loss and lost circulation agents. The composition of most non-generic additives is not available (proprietary information of the manufacturer or the service provider). Prior to 2011, only a limited number of additives were reported, including bentonite, fly ash, $CaCl_2$, Cement Friction Reducer (CFR), Halad 322 and NF-6 (Figure 20). Since 2011, the number of additives and the complexity of slurry formulations being reported have considerably increased.

Table 6: List of additives and their functionalities in the cements for the CSG wells studied

Category/ functionality	Additive	Manufacturer
Accelerator	$CaCl_2$	Generic
	Cal Seal 60	Halliburton
	S001	Schlumberger
	FS Cement Accelerator	
	Accelerator*	
Antifoamer/Defoamer	A-330L	BJ Services Australia
	FP-13, FP-13L	BJ Services Australia
	D-Air 3000, D-Air 3000L	Halliburton
	D-Air 3500, D-Air 3500L	Halliburton
	NF-6	Halliburton
	D047	Schlumberger
	Antifoamer*	
	Defoamer*	
Anti-gas migration agent	Anti-gas migration	
Dispersant	FR 100	Aubin Italmatch Chemicals
	CFR	Halliburton
	CFR-3	Halliburton
	Halad 322	Halliburton
	D065	Schlumberger
	D202	Schlumberger
	Dispersant*	
Expansion agent	Microbond	Halliburton
	Expansion	
Extender	Bentonite	Generic
	Fly ash	Generic
	FP-9	BJ Services Australia
	Econolite	Halliburton
	POZMIX A	Halliburton
	Spherelite	Halliburton
	D020	Schlumberger
	D079	Schlumberger
	Extender*	
Fluid loss agent	FL-66L	BJ Services Australia
	FL-67L	BJ Services Australia
	FDP-C1273-16	Halliburton
	Halad 344	Halliburton
	LAP-1	Halliburton
	D167	Schlumberger
	D255	Schlumberger
	FLAC	Schlumberger
	Fluid loss*	
Lost circulation agent	Graphite	BJ Services Australia
	Diamond Seal	Halliburton
	Flocele	Halliburton
	Phenoseal	Halliburton
	Pol-E-Flake	Halliburton
	CemNET	Schlumberger
	D029	Schlumberger
	LCM (Lost Circulation Material)*	
Retarder	R-21LS	BJ Services Australia
	Halad 413	Halliburton
	HR-5	Halliburton
	HR-7	Halliburton
	D013	Schlumberger
	Retarder*	
Thixotropic agent	Versaset	Halliburton
	T.A.C 13.5	TRICAN
	Thixotropic*	
Unknown	A7L	BJ Services Australia
	PDF-C1331-18	Halliburton

* Name of the specific additive not provided in some WCRs; its presence only indicated by its functionality.

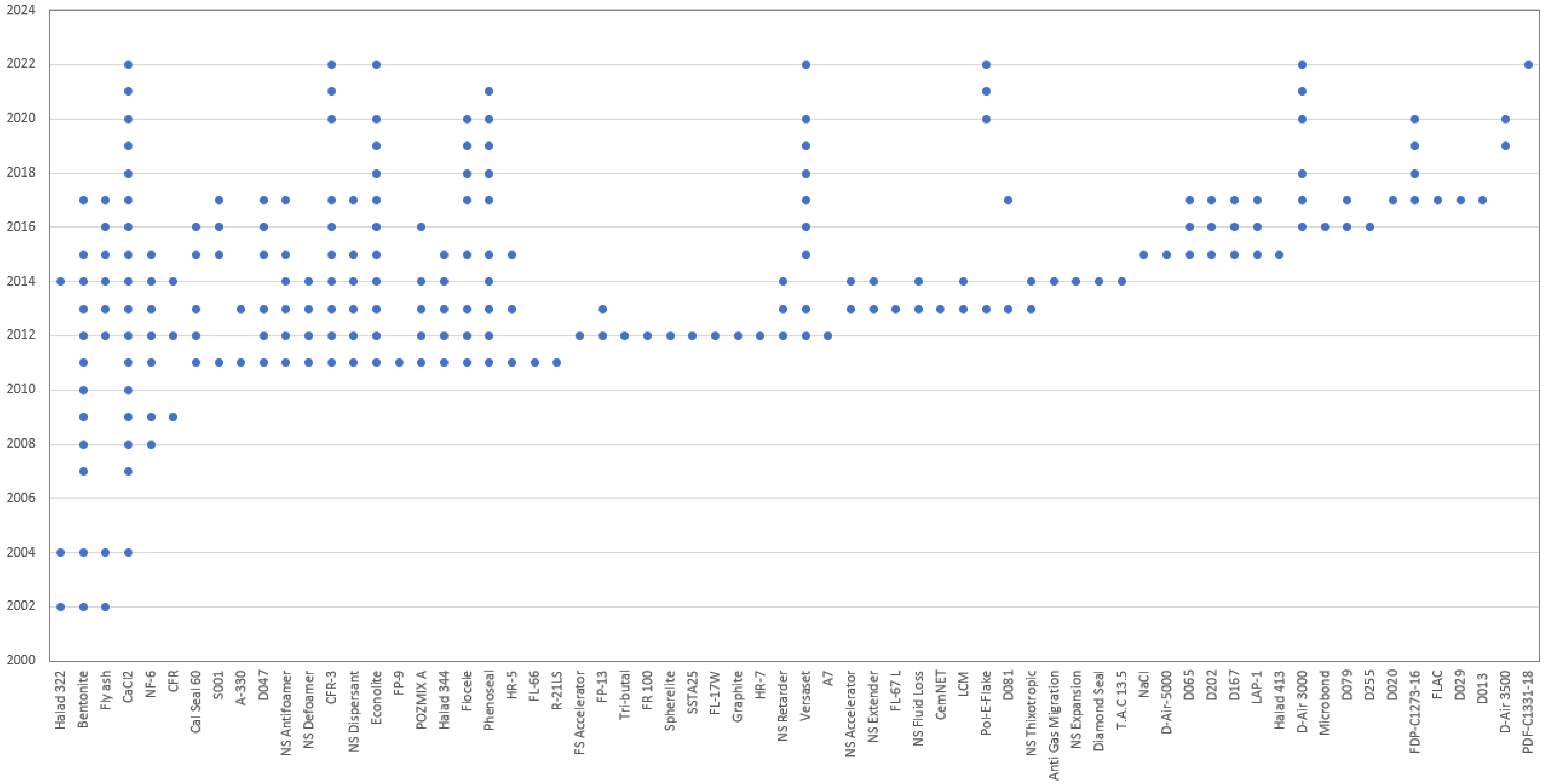


Figure 20: Additives used in cement slurry formulation of the selected CSG wells between 2002 and 2022

6 Summary

This study sought to provide information to community members on materials used in CSG well completions. To do this, the project examined a random sample of 131 WCRs for CSG wells drilled in Queensland between 2002 and 2023. Most of these WCRs were in the public domain, though a few newer reports were obtained from industry. Data on casings, cements and cement additives were extracted from these reports.

Drilling and completing a CSG well is a complex engineering undertaking. The process involves drilling a cylindrical hole into the rocks of the subsurface to a desired depth and lining this hole with various casings and cementing these into place to prevent leakage. Steel is generally the material of choice for casings, while cement, which is used to seal and support the casings, varies considerably in its composition.

Data on material used in CSG well casings are available in Section 4 of this report. The casings used by industry are mostly carbon steel which has been manufactured to meet the specifications of the American Petroleum Institute (API). From the dataset examined, K55 steel was the most used steel for casings (around 60% of the casings reported in the WCRs note the use of K55). K55 steel has the necessary mechanical strength requirements for use at the depths, temperatures and pressures encountered across CSG fields in Queensland. Six other steel grades were also reported (e.g. C350, X42, J55, N80, L80 and P110), though these were used at lower frequency. Only a very small number of non-metal casings (fibreglass and polyethylene) were reported to have been used. This use was related to situations where the CSG fields overlap with coal mining tenure in lateral wells drilled in the Bowen Basin. Some WCRs did not specify the details of casing materials. The lack of detail reported was more common for shallow (< 20 m from surface) conductor casings, but also occurred for other casing types. WCRs where casing type was not specified included wells drilled both before and after the Code was introduced in 2011.

Data on cement slurries and their compositions are available in Section 5 of this report. Cements reported in the sample of WCRs were Class A, Type GP, Type GB, Type SL, Type SR, Class G and gas-tight cement. Other cements were also reported but details of their composition were not available as they are proprietary products. In addition to proprietary products, some generic cements made by other cement manufacturers were also reported in WCRs. Around three-quarters of all the cements reported in the WCR dataset were general purpose cements, while a smaller number of specialised cements (gas-tight and sulphate-resistant cements) were reported in four WCRs. In addition to general purpose and specialised cements, some lightweight cements were also reported in the WCRs. These lightweight cements have various materials added that affect their density, which is useful under a range of operational situations during cementing.

Unlike steels used in casing, cement formulation is complex and variable, with a range of potential additives that affect the behaviour and performance of the cement. Some of the key cement properties that can be adjusted using additives include viscosity, density, pumpability, bonding characteristics, strength and setting time. This study demonstrates marked changes in the reporting of additives in CSG wells drilled in Queensland since the early 2000s. Prior to 2005, dispersants, extenders and accelerators were the main categories of additives reported in the

WCRs. These additives are typically added to the cement slurry to regulate its density, setting time and pumpability and to prevent fluid loss to various porous or fractured rock formations intersected in the well. Since 2008, numerous other additives have also been added to cements to improve their performance in securing casing and maintaining well integrity. These new additives include antifoamers/defoamers and anti-gas migration agents, which are added to prevent the formation of foam and generation of channels within the cement slurry prior to its curing, respectively.

Reporting of cementing varied, particularly by casing. In the WCRs analysed, only about 41% of conductor casings were reported as cemented, whereas about 95% of surface, intermediate and production casings were reported as cemented.

WCRs are written or compiled by specialist geoscientists and engineers to document information related to drilling and construction of the well. They are not written for a non-technical audience and extracting information from the reports is not straightforward for those not familiar with these documents. This is further complicated by the formatting and layout of the reports, which differ according to the organisations and individuals involved in their production. Moreover, the type of information on casings and cements included in the reports, nomenclature used for cement types and additives, and the measurement units (i.e. imperial or metric) used are also inconsistent between WCRs.

In conclusion, this study provides a comprehensive listing of the materials used in a randomly selected subsection of WCRs. Most of the information sought was present in the reports, though some exceptions and challenges are noted. The study demonstrates that K55 grade steel is the principal material used for casing CSG wells drilled in Queensland. In addition, the study highlights the complexity of cement formulations used and that increased reporting of cement additives has occurred over time.

Appendices

A.1 Coal seam gas well casing

A key aspect of designing a CSG well is to select casings suitable for downhole conditions, to ensure long-term well integrity. Casings are essentially a series of pipes, primarily composed of steel, inserted into the wellbore to provide structural support and protect the wellbore from collapsing. Typically, multiple layers of casings are used during construction of a well. The type and size of casings used in a well depend on factors such as depth of the drilled well, pressure within the subsurface geological formations and the mechanical properties of the rock formations being drilled. It is critical to ensure that casings are designed to maintain the structural integrity of the well and to provide a pressure barrier between the well and subsurface rock formations. Casings are also designed to prevent cross-flow of fluids (i.e. gas and water) from a high-pressure to low-pressure layer. In addition to selecting appropriate casing materials and dimensions, the casing also should be effectively installed in the well to maintain well integrity.

A.1.1 Casing types

Designing casings typically involves determining the depths at which the casings will be placed in the well, the size of the casings and the material (e.g. steel, fibreglass, PVC) that will allow safe drilling and completion of the well, with the optimal configuration for producing gas from the target reservoir. The process involves sequentially installing a series of casing strings of different diameters in the wellbore (Figure 1). In CSG wells, three types of casings are typically used: conductor casings, surface casings and production casing. Each type of casing serves a specific purpose in the well construction process (Huddlestone-Holmes & Elaheh, 2018):

- The conductor casing is the outermost casing and is designed to provide structural support and stability to the well during drilling operations. It is typically a large-diameter casing, for example 0.5 m (or 20 inches) in diameter and is cemented in place at a depth of about 10 - 20 m from the ground surface. The conductor casing prevents the wellbore from collapsing during initial drilling and provides a stable foundation for subsequent casing strings. It protects the environment by preventing drilling mud and other fluids from leaking into the shallow rock formations. It also protects shallow water aquifers.
- The surface casing is installed through the conductor casing and is designed to provide additional structural support to the wellbore. The surface casing is smaller in diameter than the conductor casing, for example 0.24 m (approximately 9 5/8 inches) in diameter, and it is installed at a depth where the rock formations are more consolidated and there is high fluid pressure. The surface casing is typically placed at depths between 100 and 300 m.
- The production casing is the innermost casing in the wellbore, and it is designed to extract gas from the targeted reservoirs (i.e. coal seams) intersected by the wellbore. The production casing is typically the smallest in diameter of the three casing types, for example 0.18 m (or 7 inches) in diameter, and it is installed after the surface casing. The

length of a production casing varies depending on depth of the target reservoirs. The production casing is often perforated or slotted at specific depth intervals to allow gas to flow from the target reservoirs into the well. It is cemented in place to prevent gas leakage. On occasion, the production casing is placed over the production zone and subsequently drilled to expose the reservoir to the wellbore. The production casing is also designed to withstand the pressures and temperatures that are typically present in the gas production zone of the well.

- In some CSG wells, there may also be another internal conduit referred to as ‘tubing’, which is mainly made from steel. This tubing is typically not cemented and serves as a distinct component within the well (Figure 1). In CSG wells, the tubing is usually used to extract water from coal seams, while the space (i.e., annulus) between tubing and casing is utilised to produce gas (Figure 1).

A.1.2 Casing grades

Casings are manufactured using several steel grades and classified according to strength and metallurgical properties. Manufacturing is standardised by the API. The steel grades classified by the API have different mechanical properties, chemical compositions and manufacturing processes, including heat treatment (Table A 1 and Table A 2). The API standards for casing manufacturing are crucial for producing materials capable of maintaining their integrity throughout the well’s operational life. API standards stipulate specific chemical compositions for steel grades used in casing and tubing (Table A 2). These standards ensure consistent material properties and performance, enabling casing and tubing to withstand extreme pressures, temperatures and corrosive conditions.

Steel grades are standardised according to the API 5CT standard and denoted by a combination of a letter and a number (e.g., H40, J55; Table A 1). The number indicates the minimum yield strength of the steel used, which is a measure of the material’s ability to withstand deformation under load. The letter serves to distinguish the chemical requirements specific to each grade as shown in Table A 2.

Table A 1: API casing grades, tensile strengths (API Spec 5CT)

Grade	Yield strength (kpsi)		Minimum tensile strength (kpsi)
	Min	Max.	
H40	40	80	60
X42	42	–	60
J55	55	80	75
K55	55	80	95
N80	80	110	100
M65	65	85	85
L80	80	95	95
C90	90	105	100
C95	95	110	105
T95	95	110	105
P110	110	140	125
Q125	125	150	135

Table A 2: Chemical composition of standard API casing grades for casing and tubing (mass fraction, %)

Group	Grade	Type	C		Mn		Mo		Cr		Ni	Cu	P	S	Si
			min.	max.	min.	max.	min.	max.	min.	max.	max.	max.	max.	max.	max.
1	H40												0.03	0.03	
	X42			0.28	1.3								0.03	0.03	
	J55												0.03	0.03	
	K55												0.03	0.03	
	N80	1											0.03	0.03	
	N80	Q											0.03	0.03	
2	M65												0.03	0.03	
	L80	1		0.43		1.90					0.25	0.35	0.03	0.03	0.45
	L80	9Cr		0.15	0.30	0.60	0.90	1.10	8.00	10.0	0.5	0.25	0.02	0.01	1.00
	L80	13Cr	0.15	0.22	0.25	1.00			12.0	14.0	0.5	0.25	0.02	0.01	1.00
	C90	1		0.35		1.20	0.25	0.85		1.50	0.99		0.02	0.01	
	C90	2		0.50		1.90		NL		NL	0.99		0.03	0.01	
	C95			0.45		1.90							0.03	0.03	0.45
	T95	1		0.35		1.20	0.25	0.85	0.40	1.50	0.99		0.02	0.01	
	T95	2		0.50		1.90					0.99		0.03	0.01	
3	P110												0.03	0.03	
	Q125	1		0.35		1.35		0.85		1.50	0.99		0.02	0.01	
	Q125	2		0.35		1.00		NL		NL	0.99		0.02	0.02	
	Q125	3		0.50		1.90		NL		NL	0.99		0.03	0.01	
	Q125	4		0.50		1.90		NL		NL	0.99		0.03	0.02	

C: Carbon
Mn: Manganese
Mo: Molybdenum
Cr: Chromium
Ni: Nickel
Cu: Copper
P: Phosphorus
S: Sulfur
Si: Silicon

API casings are predominantly made of carbon steel. Carbon steel is a type of steel consisting primarily of iron and carbon, with trace amounts of other elements. It is a common material used for casing pipes in the oil and gas industry due to its favourable combination of strength, durability and cost-effectiveness. The carbon content in these steels can vary, and alloying elements may also be added to achieve specific mechanical and chemical properties. Different API casing grades, such as H40, J55, K55, N80, L80 and P110 have varying carbon contents and may include additional elements to enhance their performance in specific subsurface conditions. Elements such as chromium, nickel and molybdenum are also used to improve corrosion resistance, strength and other properties of the steel used for various API casing grades. API casing steel grades are divided into three groups called product specification levels:

- Group 1: H40, J55, K55, N80, R95
- Group 2: M65, L80, C90, C95, T95, C110
- Group 3: P110, Q125.

Group 1: Common casing grades

Casing grades H40, J55, K55 and N80 are commonly used in wells due to their lower cost and versatility compared to other grades. However, this group of casings generally has lower corrosion resistance and mechanical strength than those in groups 2 and 3. In group 1, K55 casing has the same yield strength as J55; however, its tensile strength is higher.

Group 2: Corrosion-resistant casing grades

Casing grades L80, C90, T95 and C110 are designed for corrosion-prone environments and exhibit increased resistance to the presence of hydrogen sulphide (H_2S).

Group 3: Deep well casing grades

Casing grades P100 and Q125 have superior yield strengths compared to other casing grades and are specifically suited to withstand high-pressure environments such as over-pressured gas reservoirs. These two grades are commonly employed in the deeper sections of wellbores, where stress and pressure are generally elevated.

A.1.3 Casing corrosion

Corrosion occurs because of the tendency of metal to revert to its original and more stable forms, such as oxides, sulphates or carbonates. The corrosion rate can be quantified by the loss of weight and the rate of penetration. Corrosion and wear can lead to strength degradation and casing deformation. Corrosion in wells can lead to a range of detrimental effects such as compromised structural integrity, leakage of fluids, and increased maintenance costs. The corrosion process is accelerated by the presence of hydrogen sulphide (H_2S) and carbon dioxide (CO_2) encountered in some gas reservoirs.

Chromium is an element in steel that improves the corrosion resistance and overall performance of a casing. Its concentration within the steel determines the ability to withstand corrosive environments. High levels of chromium in the casing promote the formation of a passive oxide layer on the steel surface, serving as a robust barrier against corrosive agents prevalent in downhole environments. This layer effectively mitigates corrosion-induced material degradation and contributes to the extended service life of casing and tubing.

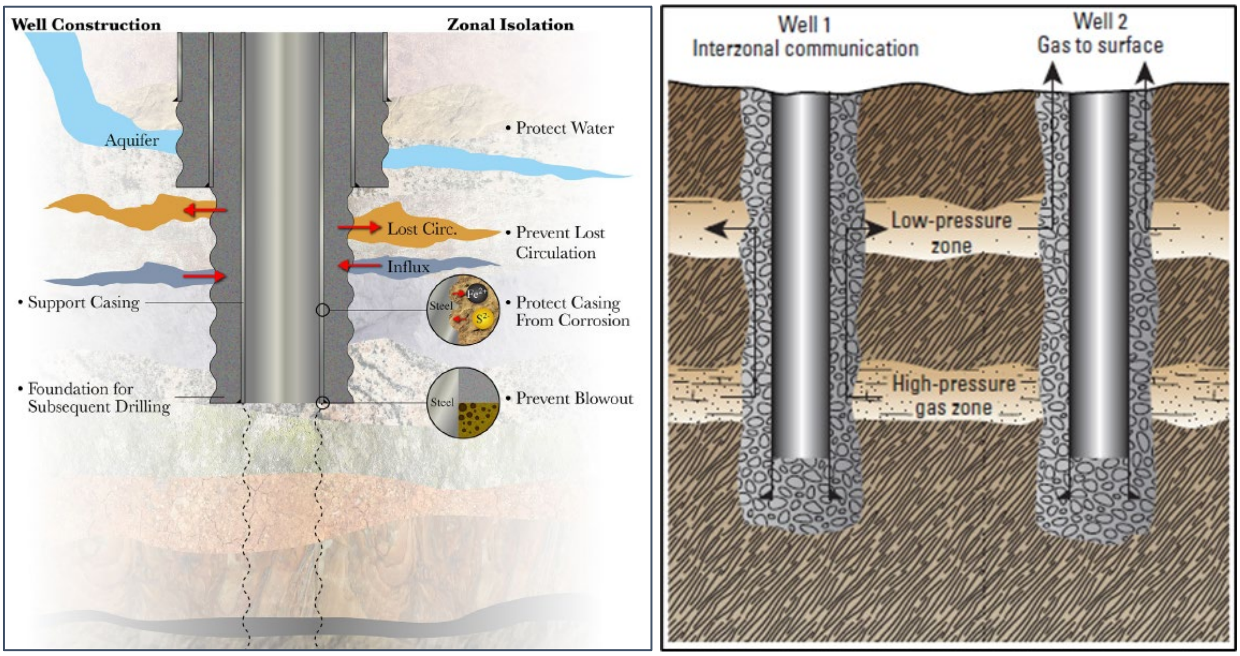
A.2 Cementing of wells

Cementing is a critical process of drilling and completing a well, which serves to maintain its integrity throughout its lifecycle. During the cementing process, specific types of cement are pumped to fill any space between casing and the wall of a borehole, casing or tubing, or between different casing types (e.g. conductor, surface and production casings). One of the most important functions of cement is to prevent flow of fluids (i.e. gases and liquids) between a coal seam and other rock layers (e.g. sandstone, siltstone and shale layers) or to prevent escape of the fluids from the well (Figure A 1). In a CSG well, cement is specifically designed to:

- isolate the coal seam from other rock formations (such as sandstone, siltstone and shale) to prevent fluid migration between the formations (i.e. zonal isolation) or to prevent fluid reaching the surface
- protect groundwater resources (aquifers) from contamination
- maintain pressure of aquifers and water quality
- obtain and maintain well integrity
- protect casings from corrosion
- reduce possibilities of casing buckling and collapse.

In order for cementing to be effective, the cement sheath has to:

- form a strong bond with both casing and the rock formations
- have very low permeability to fluids in the formations
- withstand the downhole environment, such as high pressure and temperature
- protect against detrimental effects of formation fluids chemistry such as dissolved CO_2, H_2S and sulphates (SO_4^{2-}), and the activity of microorganisms.



(a)

(b)

Figure A 1: (a) Schematic showing various roles of cement in a well (Liu, 2021); (b) potential gas migration paths from different pressure zones (Nelson & Guillot, 2006)

Cementing of a gas well involves two stages:

- Primary cementing – initial job of placing cement slurry behind and between casings during construction of the well. An effective primary cementing job is important to successfully completing drilling operations and establishing well stability.
- Secondary cementing – also known as 'squeeze cementing' is performed after the well has been constructed to remedy any deficiencies associated with primary cementing and to place cement plugs.

A.2.1 Well drilling and cementing

During the process of drilling, a drilling fluid (i.e. drilling mud) is pumped through the nozzles of the drilling bit and flowed back to the surface carrying rock cuttings (produced during drilling) along the annular space between the drill string and the rock formations (Figure A 2). After drilling is terminated at the desired depth, the drill string is removed and a casing pipe is lowered into the wellbore. Mud circulation is continued through the casing and flowed back to the surface in the annular space between the casing and the rock formation. The circulating mud deposits a thin mud-cake along the borehole wall. As drilling mud and the cement slurry (mixture of cement, chemical additives and water) are not chemically compatible, the mud must be completely removed from the wellbore to prevent contamination of cement slurry. Therefore, the remaining mud is removed through injecting chemical washes containing surfactants and spacers; washes help to thin the mud and wet the formation, while the spacers separate the mud and any washes from the cement slurry.

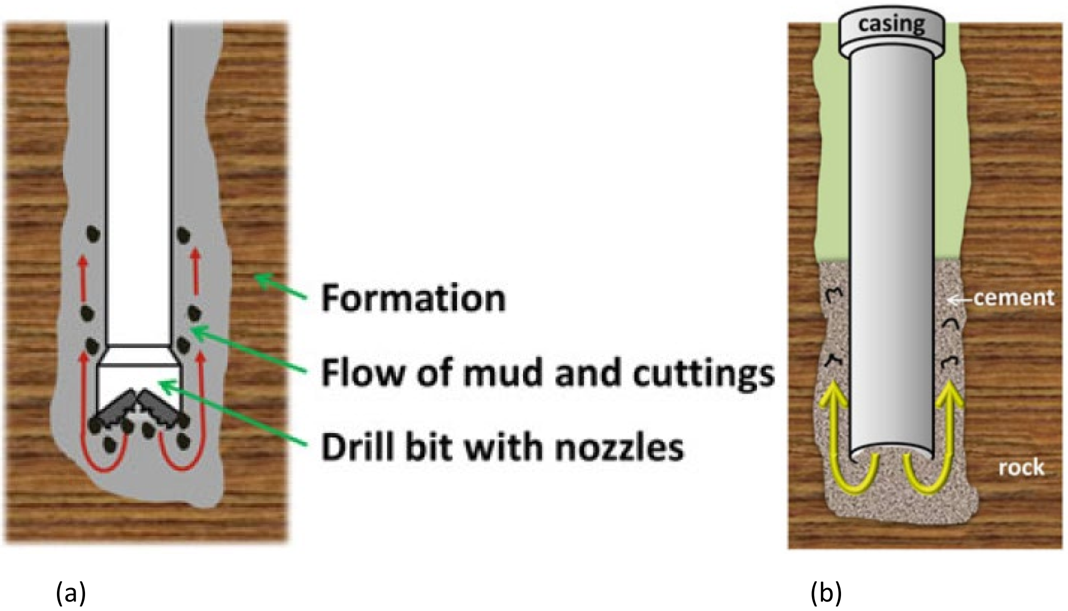


Figure A 2: (a) Schematic of a drilling a wellbore using a drilling bit, where the rock cuttings are removed by the drilling mud; (b) injection of drilling mud and cement slurry through the casing and flowed back into the annulus between casing and rock formation (Lavrov & Torsæter, 2016)

In the next step, the cement slurry is pumped through the casing and flowed back between the casing and rock formations. One or two cement slurries for each casing string are pumped based on the characteristics of the well and downhole environment (DeBruijn & Whitton, 2021). In general, shallow wells require a single cement slurry, which is commonly referred to as 'tail' slurry. Two consecutive cement slurries are referred to as 'lead' and 'tail' slurries. The lead slurry is pumped first and is placed in the upper part of the casing. The tail slurry is pumped after the lead slurry and is placed in the lower part of the casing. The tail slurry has greater density (is heavier than the same volume of lead slurry) and different rheological properties (i.e. flow, pumpability) than the lead slurry. The cement slurry is pushed out of the casing into the annulus by a displacement fluid (DeBruijn & Whitton, 2021). The pumped cement is transformed from a liquid slurry to a solid material after placement. The strength of the cement sheath begins to develop during initial setting stage, taking several hours to reach significant strength. Afterwards, the hardening process of the cement sheath starts (it develops compressive strength). During this process, the strength of the cement sheath increases quickly in the first couple of days, and then it continues to increase at a slower rate over several years (Jennings et al., 2002).

Some of the important properties of the slurry to consider through specific stages of cementing include (Hossain & Al-Majed, 2015; Lavrov & Torsæter, 2016):

- **Slurry state** – density (controls the pressure applied by slurry on the rock formations), rheological properties (pumpability of slurry, settling/sedimentation of cement particles and gas migration after cement placement), thickening time (time that slurry remains pumpable) and filtration rate (how fast the slurry loses water into rock formations).

- **Transition from slurry to solid state during the setting stage** – volumetric change (cement shrinkage or expansion), rate of strength build-up, and degree of accessibility of formation fluids to the semi-hardened cement. Cement particles react with water, transforming the cement slurry into a gel-type material. The gelled cement does not act as either liquid or solid and has no ability to counteract the gas pressure in the coal seam. Formation gases could percolate the gelled cement, forming bubbles or flowing through the pores of the gelled cement. At the end of the setting stage, the cement gel becomes strong enough to prevent gas flow.
- **Properties of the hardened cement** – stability (cement performance under well conditions), permeability (gas migration through cement), the quality of bonding of the cement to casing and rock formation, and sensitivity to fracturing.

A.2.2 Cements

The conditions to which cement is exposed in wellbores are different to those experienced in construction applications and, therefore, the quality requirements of cement for gas wells have been specified by the API (API SPEC 10A) (American Petroleum Institute, 2019b). The main component of well cements is Portland cement, which consists of Portland cement clinker ground with up to 5% calcium sulphates such as gypsum ($CaSO_4 \cdot 2H_2O$) or bassanite ($CaSO_4 \cdot 0.5H_2O$) (Jennings et al., 2002). The clinker is composed of tricalcium silicate ($3CaO \cdot SiO_2$), dicalcium silicate ($2CaO \cdot SiO_2$), tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$) and tricalcium aluminate ($3CaO \cdot Al_2O_3$) (Table A 3). The clinker is produced in rotary kilns at 1300–1500°C from raw materials such as limestone, clay, shales, sand, bauxite and iron ore mixed in specific ratios.

Table A 3: Mineral composition of Portland cement clinker

Common name	Composition	Abbreviation	Concentration (weight %)
Alite	$3CaO \cdot SiO_2$ (C_3SiO_5)	C_3S	50–70
Belite	$2CaO \cdot SiO_2$ (C_2SiO_4)	C_2S	15–30
Aluminate	$3CaO \cdot Al_2O_3$ ($Ca_3Al_2O_6$)	C_3A	5–10
Ferrite phase	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ (Ca_2AlFeO_5)	C_4AF	5–15

(Lavrov & Torsæter, 2016)

There are eight API classes of cements, with varying degrees of resistance to sulphate, including ordinary (O) grade, moderate sulphate-resistant (MSR) grade and high sulphate-resistant (HSR) grade (Table A 4).

Classes A, B and C cements are intended for use in relatively shallow wells (shallower than 1830 m or 6000 ft) (Michaux et al., 1990). Class A cement, in particular, is used when special properties are not required for the downhole conditions; it is available only in O grade (Table A 4). Class B cement is used in wells where moderate or high resistance to sulphate is required. Class C cement is used where the wellbore requires high early strength.

Classes D, E and F cements are known as ‘retarded cements’ and include additives to prevent rapid stiffening/setting of the slurry, which is a property required for deep wells (Michaux et al., 1990). They are available in both MSR and HSR grades. Class D cement is used under moderately high temperatures and pressures and is generally intended for depths between 1830 and 3050 m (6000 and 10000 ft). Class E cement is used for high temperature and pressures conditions and is generally intended for depths between 3050 and 4270 m (10000 and 14000 ft). Class F cement is used for the extremely high temperatures and pressures generally encountered in very deep wells. Class G and H cements are intended for use as basic well cements in wells less than 2440 m (8000 ft) in depth (Michaux et al., 1990).

Table A 4: Chemical properties of well cements (API SPEC 10A)

	Cement class					
	A	B	C	D, E, F	G	H
Ordinary grade (O)						
Magnesium oxide (MgO), maximum (%)	6.0	NA	6.0	NA	NA	NA
Sulphur trioxide (SO_3), maximum (%)	3.5[a]	NA	4.5	NA	NA	NA
Loss on ignition, maximum (%)	3.0	NA	3.0	NA	NA	NA
Insoluble residue, maximum (%)	0.75	NA	0.75	NA	NA	NA
Tricalcium aluminate (C_3A), maximum (%)	NR	NA	15	NA	NA	NA
Moderate sulphate-resistant grade (MSR)						
Magnesium oxide (MgO), maximum (%)	NA	6.0	6.0	6.0	6.0	6.0
Sulphur trioxide (SO_3), maximum (%)	NA	3.0	3.5	3.0	3.0	3.0
Loss on ignition, maximum (%)	NA	3.0	3.0	3.0	3.0	3.0
Insoluble residue, maximum (%)	NA	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C_3S), maximum (%)	NA	NR	NR	NR	58[b]	58[b]
Tricalcium silicate (C_3S), minimum (%)	NA	NR	NR	NR	48[b]	48[b]
Tricalcium aluminate (C_3A), maximum (%)	NA	8	8	8	8	8
Total alkali content, expressed as sodium oxide (Na_2O) equivalent, maximum (%)	NA	NR	NR	NR	0.75[c]	0.75[c]
High sulphate-resistant grade (HSR)						
Magnesium oxide (MgO), maximum (%)	NA	6.0	6.0	6.0	6.0	6.0
Sulphur trioxide (SO_3), maximum (%)	NA	3.0	3.5	3.0	3.0	3.0
Loss on ignition, maximum (%)	NA	3.0	3.0	3.0	3.0	3.0
Insoluble residue, maximum (%)	NA	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C_3S), maximum (%)	NA	NR	NR	NR	65[b]	65[b]
Tricalcium silicate (C_3S), minimum (%)	NA	NR	NR	NR	48[b]	48[b]
Tricalcium aluminate (C_3A), maximum (%)	NA	3[b]	3[b]	3[b]	3[b]	3[b]
Tetracalcium aluminoferrite (C_4AF) plus twice the tricalcium aluminate (C_3A), maximum (%)	NA	24[b]	24[b]	24[b]	24[b]	24[b]
Total alkali content expressed as sodium oxide (Na_2O) equivalent, maximum (%)	NA	NR	NR	NR	0.75[c]	0.75[c]
C_3S – $3CaO{\cdot}SiO_2$; C_3A – $3CaO{\cdot}Al_2O_3$; C_4AF – $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$						

NR – no requirement; NA – not applicable

[a] When the tricalcium aluminate content (expressed as C_3A) of the cement is 8% or less, the maximum SO_3 content shall be 3%.

[b] The expression of chemical limitations by means of calculated assumed compounds does not necessarily mean that the oxides are actually or entirely present as such compounds. When the ratio of the percentages of Al_2O_3 to Fe_2O_3 is 0.64 or less, the C_3A content is zero. When the Al_2O_3 to Fe_2O_3 ratio is greater than 0.64, the compounds shall be calculated as follows:

C_3A = (2.65 ´ % Al_2O_3) — (1.69 ´ % Fe_2O_3)

C_4AF = 3.04 ´ % Fe_2O_3

C_3S = (4.07 ´ % CaO) – (7.60 ´ % SiO_2) – (6.72 ´ % Al_2O_3) – (1.43 ´ % Fe_2O_3) – (2.85 ´ % SO_3)

When the ratio of Al_2O_3 to Fe_2O_3 is less than 0.64, the C_3S shall be calculated as follows:

C_3S = (4.07 ´ % CaO) – (7.60 ´ % SiO_2) – (4.48 ´ % Al_2O_3) – (2.86 ´ % Fe_2O_3) – (2.85 ´ % SO_3).

[c] The sodium oxide equivalent (expressed as Na_2O equivalent) shall be calculated by the formula: Na_2O equivalent = (0.658 ´ % K_2O) + (% Na_2O).

A.2.3 Cement hydration

Cement hydration occurs spontaneously when water is added to dry Portland cement. Hydration of Portland cement is a complex process, involving a series of chemical reactions between mineral components (phases) of the cement and water, which leads to the development of cement structure. The hydration of calcium silicates ($3CaO{\cdot}SiO_2$ and $2CaO{\cdot}SiO_2$) in the cement results in the formation of an amorphous calcium silicate hydrate (C-S-H) phase ($nCaO{\cdot}SiO_2{\cdot}mH_2O$), referred to as a ‘gel’, and crystalline calcium hydroxide ($Ca(OH)_2$). The ratio of CaO/SiO_2 (n) in C-S-H can range from 1.4 to 2.0, with an average value of 1.7. $Ca(OH)_2$ precipitates as crystals, up to several tens of micrometres in diameter, evenly distributed throughout the hardened cement (Beaudoin & Odler, 2019).

The composition and structure of hydrated cement changes significantly during cement setting (generally up to 48 hours) and hardening (up to two years) stages. The reactions continue over many years, constantly altering the porosity of hardened cement and increasing its overall strength (Jennings et al., 2002). Hydration of cement also leads to bulk volume shrinkage. The reduction in volume of the hardened cement depends on the degree of hydration of each component of the cement and its concentration. Further details of the chemistry of cement hydration and products are provided in a number of references (Beaudoin & Odler, 2019; Beaudoin & Ramachandran, 1992; Cadix & James, 2022).

A.2.4 Cement slurry formulation

The cement slurry must be designed to remain fluid and readily pumpable under the downhole environment for the time necessary to complete the cementing operation; it must also be designed to develop high strength and minimal porosity (to prevent gas flow through or along the cement sheath). In addition, the slurry should not lose water into porous rock formations and be lost in fractured rock formations.

The formulation of cement slurries has to take into consideration the composition of the fluids in the well, pore pressure in the rock formations, maximum temperature encountered in the well, porosity of the rock formations and degree of consolidation of rock formations. Therefore, the ratios of cement, additives and water in slurries are tailored for conditions encountered in each well. There is not one well cement slurry formulation that can overcome all the issues associated with primary cementing. The properties of the cement slurry can be adjusted using chemical and mineral additives:

- Slurry density: extenders and weighing agents
- Slurry thickening/setting time: accelerators and retarders
- Slurry rheological properties: dispersants and anti-settling agents
- Slurry pumpability and cement gel strength (set cement): thixotropic agents
- Slurry de-aeration: defoamers/antifoamers
- Cement gel tightness (set cement): anti–gas migration agents
- Shrinkage of hardened cement: expansion additives.

Furthermore, to address issues associated with porous and unconsolidated rock formations, fluid loss and lost circulation additives are also used. Some additives can have multiple roles, for example, lignosulphonate can act as retarder, dispersant, fluid loss additive and water reducer (Liska et al., 2019).

Slurry density

The density of the slurry determines the pressure that is applied by the cement slurry column on the rock formations exposed in the wellbore. A wellbore with mechanically weak rock formations requires low density cements to lower the pressure applied by the slurry on the rock formation to prevent formation fracturing and partially or totally losing the slurry into the rock formation (i.e lost circulation). A cement slurry column that applies less pressure than that of the formation would result in an uncontrolled release of gas (known as a blowout). Extenders and weighing agents are additives used to reduce or increase slurry density.

The density of neat cement slurry (mixture of water and cement) varies from 1773 kg/m^3 to 1965 kg/m^3, depending on the type of cement and the water/cement ratio (Hossain & Al-Majed, 2015). The density of the slurry can be increased by reducing the water/cement ratio, which leads to an increase in slurry viscosity and affects its pumpability. Slurry density can be decreased by increasing the water/cement ratio; however, this will reduce compressive strength and increase porosity of set cement. Hence, including additives with greater or lower density than that of cement in slurry formulation prevents the undesired effects generated by modifying the amount of water added to the slurry.

Extenders (Lightweight additives)

Extenders such as bentonite, pozzolans, sodium silicate and lightweight particles are added to the cement slurry to reduce its weight per unit volume.

- Bentonite is a clay that decreases slurry density through absorbing water and expanding its volume. Bentonite is added to cement as dry powder or pre-hydrated with fresh water. Prehydrated bentonite can decrease slurry density to as low as 1380 kg/m^3.
- Pozzolans are silica and silica-rich materials that can be of natural (e.g. diatomaceous earth and volcanic ashes) or synthetic (e.g. fly ashes and amorphous silica products – silica fumes) origin. They react with portlandite ($Ca(OH)_2$), a reaction product of cement hydration, to form C-S-H. The formation of C-S-H improves the compressive strength and decreases porosity of hardened cement (Cadix & James, 2022). Pozzolans can lower the density of the slurry to 1320 kg/m^3.
- Sodium silicate (Na_2SiO_3) reacts with calcium ions in the slurry ($CaCl_2$) or those released during cement hydration to form a calcium silicate gel (Cadix & James, 2022). The silicate is used as a solid or liquid in slurry preparation. The lowest density that can be achieved by adding silicates to the slurry is 1320 kg/m^3.
- Lower density particles (lightweight particles) include hollow glass microspheres, cenospheres (hollow fly ash particles), expanded perlite, powdered coal, gilsonite and ceramic microspheres (Cadix & James, 2022; Nelson & Guillot, 2006). Hollow glass microspheres are glass beads (2-200 µm) of low density (600-700 kg/m^3), where the

spheres are filled with water, which is released during cement setting to lower cement shrinkage (Fink, 2015b).

Commercial lightweight cements

Pre-mixed commercial lightweight cements are also available. These are Portland cements mixed with specific ratios of extenders by the cement supplier (Cadix & James, 2022).

Weighting agents

Weighting agents are used to increase the density of the slurry for cementing deep wells and zones with high formation pressure. Commonly used weighting agents include hematite (Fe_2O_3), barite ($BaSO_4$), ilmenite ($FeTiO_3$) and hausmannite (Mn_3O_4).

Thickening time

Thickening time is the time required for stiffened cement slurry to develop compressive strength (setting time). Accelerators and retarders are used to modify the setting time of cement slurry.

Accelerators

Accelerators not only reduce the setting time but can also increase the rate of compressive strength development (Cadix & James, 2022). The most common accelerators are inorganic calcium salts ($CaCl_2$, NaCl). Calcium ions released by $CaCl_2$ in the slurry increase the hydration rate of calcium silicates (C_3S) at the initial stages (Cadix & James, 2022).

Sodium silicate is not only an extender, but also an accelerator. It promotes the formation of C-S-H by reacting with $Ca(OH)_2$ generated by cement hydration (Cadix & James, 2022).

Colloidal silica acts as an accelerator in a similar manner to that of sodium silicate (Cadix & James, 2022).

Retarders

Retarders delay cement setting at high temperatures, allowing sufficient time to complete cement slurry placement (Hossain & Al-Majed, 2015). They slow the interaction between cement and water and delay the formation of C-S-H compounds. Retarders added to the cement are adsorbed onto the surface of the partially hydrated cement compounds or the hydration products, forming a film around the particles that prevents further hydration of the cement compounds or growth of hydration products (Cadix & James, 2022). The most common retarders used are organic compounds, including sugars, lignosulphonates, hydroxycarboxylic acids and synthetic polymers:

- Sugars - sucrose and raffinose
- Lignosulphonates - sodium and calcium sulphonates (derived from wood pulp)
- Hydroxycarboxylic acids - tartaric acid and the sodium salts of gluconic and glucoheptonic acids
- Synthetic polymers (low molecular weight polymers) – copolymers of acrylamide tertiary butyl sulphonic acid (ATBS) and acrylic acid (AA), copolymers of ATBS and itaconic acid (IA) or maleic acid (MA)
- Silicates - alkali metal silicates or nanosilica.

Rheological properties

Rheological properties of cement slurry control its flow and behaviour during both pumping (shear stress) and setting (yield stress) stages. Optimal rheological properties under shear stress (i.e. apparent viscosity) are important for appropriate placement of the slurry, and those under yield stress (at static conditions) are important to prevent sedimentation and formation of free fluid, as well as to control gas migration (Cadix & James, 2022). Rheology behaviour of cement slurries is complex and influenced by a combination of factors, including the volume of solids, the shape and particle size distribution of solids, viscosity (consistency or thickness of the fluid) of the interstitial fluid and interactions between particles within the slurry.

The pumpability of the slurry is determined by its viscosity, which needs to be sufficiently low during cement placement. The apparent viscosity of the slurry can be adjusted through admixing various additives, including:

- density-adjusting particles to change the volume of solids
- fluid loss control additives and viscosifiers (anti-settling agents) to modify the viscosity of the interstitial fluid
- particles of different sizes to that of cement to modify particle size distribution
- dispersants to reduce the attractive interactions between solid particles.

Rheological properties at rest (after slurry placement) are influenced by the interactions between particles. At rest, the cement slurry develops a yield stress, which is determined by the attractive forces between particles, concentration of particles, and their shape and size. The yield stress increases with increasing attraction forces between particles. Typical yield stress of a cement slurry ranges between 1 and 10 Pa (Cadix & James, 2022). Cement slurries with yield stress outside this range produce gels of poor performance during the setting stage. The cement particle requires an optimum amount of dispersion to produce high-quality hardened cements.

The particles of a neat cement slurry are poorly dispersed due to the high attractive forces between them, leading to agglomeration and increased slurry viscosity during pumping; while at rest, the gel formed collapses (Cadix & James, 2022). The attractive forces between particles can be adjusted by mixing the slurry with additives such as dispersants and fluid loss control polymers. Retarders also influence the attraction forces between particles. An optimum amount of additive reduces the viscosity of the slurry and produces a stable and homogeneous gel structure at rest. In a slurry where the attraction forces are very low, the particles will be over dispersed. The slurry has low viscosity under shear, but the particles settle at rest and free fluid is generated. In such cases, anti-settling agents are used to prevent cement particles from settling.

Additives such as dispersants and anti-settling agents are used to control the rheological properties of slurries.

Dispersants

Dispersants (or friction reducers) are added to the slurry to decrease viscosity and maintain slurry pumpability within the recommended limits. Appropriate dispersion of the slurry improves early compressive strength, and controls both fluid-loss and free-water formation (Hossain & Al-Majed, 2015). Dispersants are adsorbed on the surface of cement grains reducing the attractive forces between them and generate particles that repel each other (Cadix & James, 2022; Liska et al., 2019). At low temperatures dispersants may also act as retarders slowing setting time of the slurry. Types of dispersants used in well cements include sodium sulphate, sodium polynaphthalene sulphonate, sulphonic acid salt and cellulose derivative.

Anti-settling agents

Diutan and Welan gums are the most common polymeric anti-settling agents (Cadix & James, 2022). These polymers increase the viscosity of the fluid in the slurry.

Thixotrophic agents

Thixotropy is the property of the cement slurry that allows it to be fluid during pumping and rapidly develop a gel structure (strength), or to stiffen, when at rest. The gel structure breaks when reagitated and the slurry becomes pumpable again.

Thixotropic cement slurries are used to overcome problems with lost circulation and weak zones in the formation, due to their ability to rapidly develop gel strength and apply less pressure on the formation. This way, cement slurry is not lost into fractured formations and damage to weak rock formations is prevented.

Thixotropic agents are used to enable the thixotropic properties of cement slurries. Bentonite, bassanite ($CaSO_4{\cdot}0.5H_2O$) and mixtures of iron and aluminium sulphates ($FeSO_4$ and $Al_2(SO_4)_3$) are some examples of thixotropic agents (Nelson & Drecq, 1990).

Antifoamers and Defoamers

Antifoamers are used to prevent the formation of foam during cement mixing and the entrainment of gas in the slurry, whereas defoamers break down previously formed foam. The formation of foam can lead to the loss of pump priming and hinder the uniform mixing of the slurry.

Antifoam agents commonly used in the industry are polypropylene glycol and silicones.

Common defoamer agents used are alkenes, olefinic hydrocarbons, oxylated alcohols and crystalline silica.

Anti-gas migration agents

Formation fluids, in particular gas, can generate channels within the cement slurry during setting. The tightness of set cement to gas migration can be improved by adding anti-gas migration additives. Synthetic rubber powder, carbon black, polymer latex and silica fumes are some examples of anti-gas migration additives used in the industry (Fink, 2015b).

Expansion additives

Cements shrink during setting and expansion additives can be added to reduce the degree of such shrinkage. These additives improve the bonding between set cement and both casings and rock formations. The set cement expands slightly when extra calcium sulphate (i.e. gypsum) or magnesium oxide are added to cement slurry (Cadix & James, 2022).

Fluid loss

If the rock formation has high porosity, the aqueous phase of the cement slurry can migrate (permeate) into rock formations, which is known as ‘fluid loss’. If the volume of water in the slurry, which is required for cement hydration, is dramatically reduced, this leads to cement placing failure due to partial hydration of cement particles (Cadix & James, 2022). Therefore, it is critical to minimise water loss from the slurry in porous formations to ensure optimal cement hydration and maintain desired slurry properties such as rheology, density and thickening time. The pumpability of the slurry is also influenced by the extent of the fluid loss, and the slurry can become unpumpable if a significant volume of fluid is lost.

Fluid loss additives are included in the cement slurry formulation to prevent the loss of fluid. There are two categories of fluid loss additives: particulate materials (bentonite, microgels and latexes) and water-soluble polymers.

Lost circulation

The cement slurry can be partially or totally lost into unconsolidated rock formations, highly porous formations, and naturally or artificially fractured formations (Nelson & Guillot, 2006). In case of total loss, the slurry does not return back to the surface. This is commonly known in the industry as ‘lost circulation’.

Lost circulation agents, such as Lost Circulation Materials (LCM), are mixed with the slurry to reduce cement slurry loses. Different types of materials are used in controlling lost circulation (Fink, 2015a; Halliburton, 1996; Lavrov & Torsæter, 2016), including:

- fibrous materials – fibres flow into fractures to form bridges of plugs
- granular materials – coarse particles form bridges or plugs in fracture, channels or vugs
- lamellar/laminated – chemically inert flake materials (fibres), which are injected into very narrow fractures. These can also be used to prevent fluid loss.

A.3 Qualitative aspects of WCRs

A.3.1 Observations during the data collection process

The documents that form part of a WCR are a record of communications between specialists during the completion of the well. Even though they become publicly available documents, their original purpose is not to inform the general public but to communicate a large volume of complex information effectively. The following points, from a non-specialist's point of view, were noted when searching for and collecting data from the WCRs and should be considered as potentially having a bearing on the data collected. Additional notes are also referred to in Table A 5.

- While the contents of the reports are regulated, the formatting of the reports are similar and the units used in the reports are reasonably consistent, *the level of detail entered in each section of the report can differ greatly between reports*. In some cases, this can mean that the quantity of cement and additives are listed with full commercial names/identifying numbers and concentrations and volumes used, and in other cases the information may be missing, or only partially quoted, such as only cement volumes or generic additive descriptions, such as 'defoamer'.
- Information about cement and casings is sometimes scattered through text summaries, tabulated in the well card section or in the cementing reports in the appendix. It is possible to miss information if the reader assumes that one of these sections contains a comprehensive summary and there is no further information to be found in other sections of the report.
- Different terms for the same cement or cement additive are sometimes used within the same WCR and attached cementing report. In some cases, the front part of the report has more general terms such as 'gel' or 'defoamer' to describe an additive, but the cementing report in the appendix lists the commercial name of the additive.
- In some cases, the cement volumes used or the additive concentrations are included within the additive name, such as 'Gladstone GB Cement at 94lb/sk', or 'Antifoam – 4.5 gals', which may be initially mistaken by a general audience as part of the additive name, rather than a quantity or proportion.
- Cemented interval for a given section of the well, such as production or surface sections, is not always clearly listed, and often the depth of cement and interval is taken from the well schematic. At times, it was mentioned that the cement was 'tagged' at a certain depth, which was taken to mean the maximum depth of the interval, where this information was not found elsewhere in the report.
- Sometimes cement additive information is partially listed, or not available at all, particularly for the initial conductor cement job, typically covering the first 10 metres of the well (though the depth of the conductor section varies).
- Information in different sections is sometimes contradictory, potentially due to transcription errors. An example is a report where the text description of the cement job lists a full return, whereas the tabulated version states there are no returns.

- Cementing reports in the appendix of WCRs sometimes contain the record of the cementing job only or contain information on a ‘cement program’ describing the design-intended additives.
- Specific information on cement additives, such as the identifying name, main component or concentrations of each additive are often only listed in the cementing reports in the appendix.

Table A 5: Some examples of notes made during the data collection process

Comment
Report contradictory – text says full return, table says no return.
Report for lateral and vertical well. Only vertical well has been tabulated. Could not find cement reports on website. Only ‘consumables used during drilling’ are listed. Unsure of these are drilling ingredients or cement additives.
Much of the information is text-based, not tabulated. No separate cementing reports. Could find no mention of additives other than the basic description of cement.
Text mentions remedial production cement job, but this doesn’t appear to be listed with any further information.
Complex Lateral Well – cannot find much information in report, information scattered between tables and text.
Report refers to appendix 1; however, the ‘casing and cementing summary’ is in appendix 3. ‘Final well report’ and the ‘casing and cementing summary’ are blank, except for casing information.
Summarised in both cement report and first few pages of WCR, but descriptions are not identical.
Cement report in appendix hard to read, only appears to contain ‘production casing’ info. Note that information about the additives in the cement report are described differently. Concentrations are listed in the cement report, but not in the WCR.
No information for production casing other than water/cement ratio used. Possibly more information in daily drilling reports, not checked.
Cement report and WCR don’t use the same terminology for same stages of the well – assuming that the 7-inch intermediate casing in the cement report is the 7-inch production casing in the WCR.
Cement volumes in the cement report seem to differ from the summary in the WCR.
Unclear if conductor was cemented or not.
No cement reports, all cementing done by the drilling contractor, plug and abandon well.

A.3.2 Recommendations to improve accessibility

- The well schematic is an extremely effective way to communicate the main points about the well to the non-specialist.
- If there is depth or section-related information, such as additives used or cement type, it would be useful to also show these on the well schematic, or potentially an abbreviated form of the schematic, which does not show other information to avoid crowding.
- Further to the above, a simple three-bar chart showing the depths and section name, with the additives and their concentrations and amounts listed beside them would greatly increase the accessibility of this information to the general audience.

- It is more accessible to include trade names, or identifying numbers/terms for each additive, in the front of the WCR, rather than in the cementing report in the appendix, which contains specialised information.

A.4 Further information on the well selection process

A.4.1 Project objectives

The overall objective of the project (as per the project proposal approved by GISERA) was to analyse between 100 and 200 WCRs for randomly selected wells drilled in Queensland; the final number of wells analysed was to be determined by the complexity of retrieving casing and cement information from the WCRs within the time constraints of the project. Reports for 116 wells drilled prior to 2019 were open-file and were downloaded from the Geological Survey of Queensland's Open Data Portal. Information on an additional 15 wells was supplied by operators. Data from these two sources comprised the 131 wells reviewed during this study.

A.4.2 Statistical correlation of the final 131 well dataset by year

The age range of the randomly selected 131 well dataset used in this study was compared with the age range of the total dataset of all wells drilled in Queensland (normalised to 131). The dataset ('final sample' in Figure A 3) is a good representation of the spread of well ages, with a Pearson's correlation coefficient of 0.88 and a p-value of 4.22e-13.

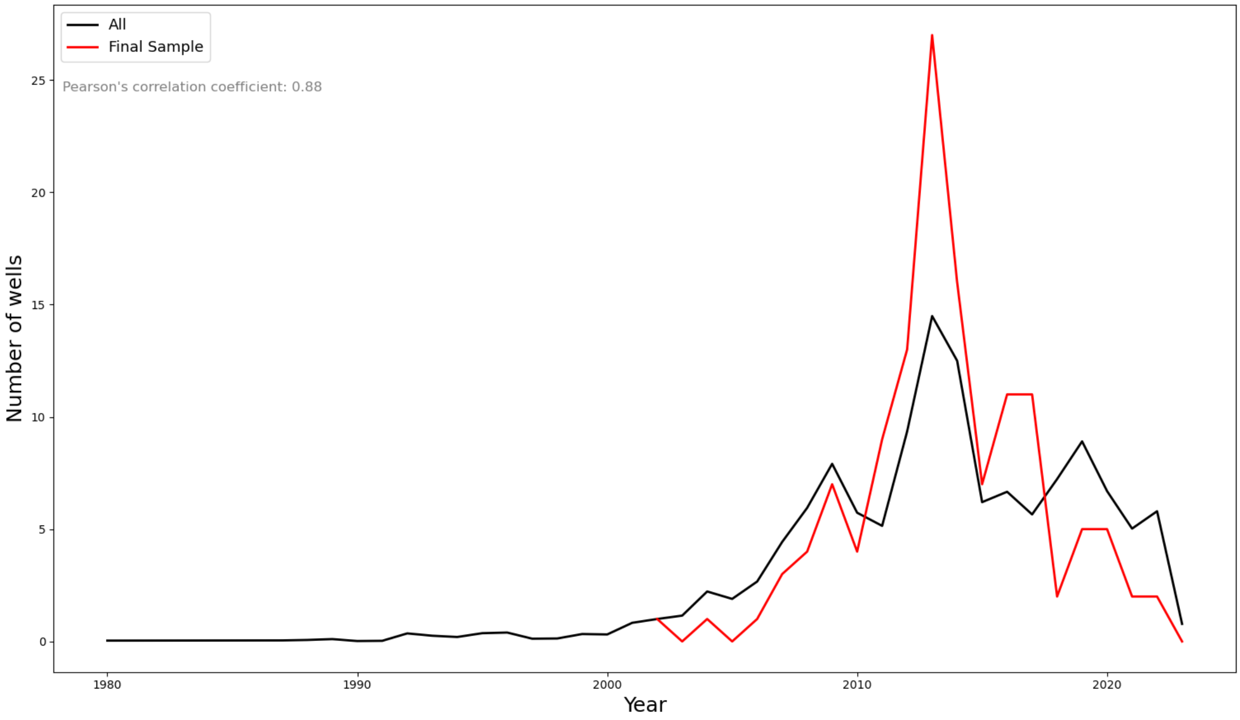


Figure A 3: Number of wells drilled by year in the final sample of 131 wells, compared with all wells drilled

A.4.3 Correlation of the final 131 well dataset by depth

The depth distribution of the randomly selected 131 well dataset used in this study was compared with the depth distribution of all CSG wells drilled in Queensland. The dataset ('final sample' in Figure A 4) has a similar distribution of well depths to the total dataset of wells drilled. Most wells in this study have total drilled depths between 250 and 1,500 m, reflecting the general trend in Queensland CSG wells.

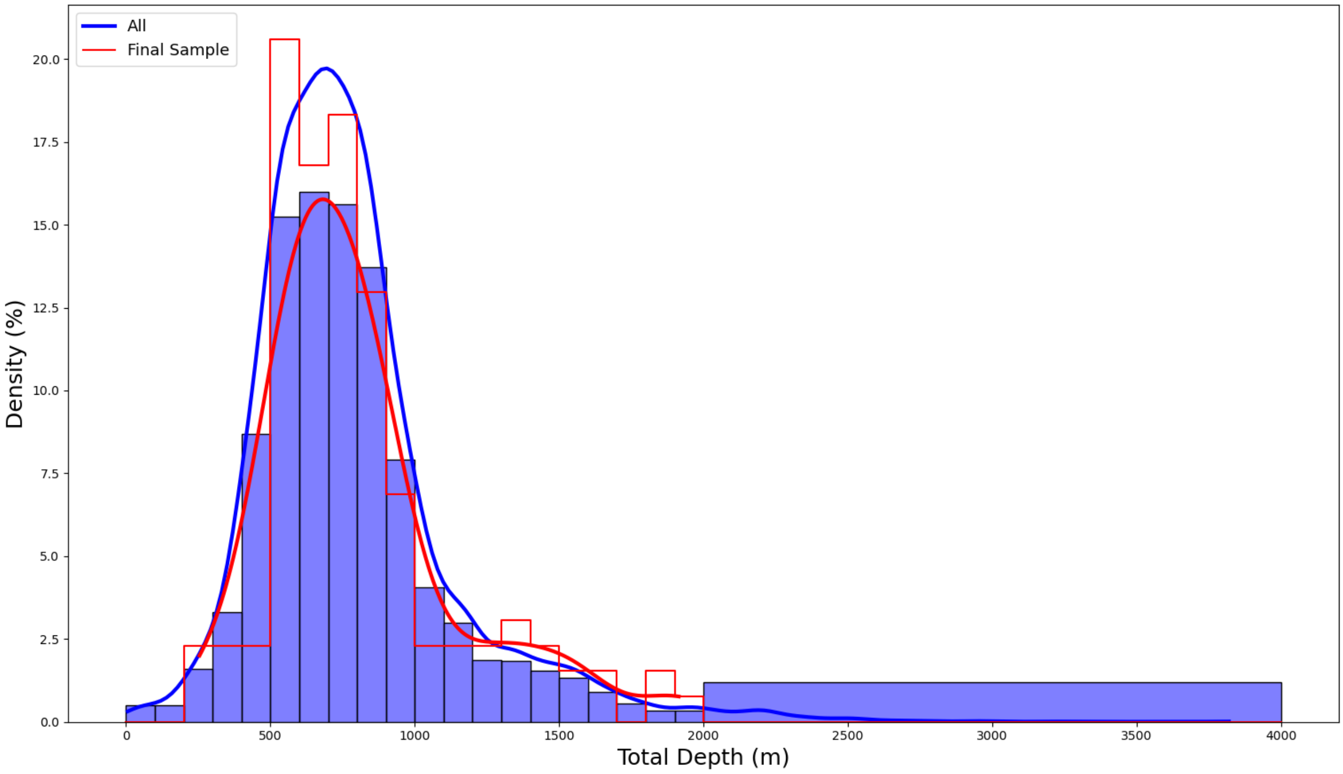


Figure A 4: Depth distribution of wells (expressed as percentages) in the final sample of 131 wells, compared with depth distribution of all CSG wells drilled in Queensland

A.4.4 Data source

Location information and other technical data for the wells are lodged with the Geological Survey of Queensland, and these can be accessed through the Open Data Portal.[9] For this study, data for 13,912 wells drilled by 91 operators were downloaded and the classification of the wells as described in the dataset include:

- 1300 exploration
- 1922 appraisal
- 10,662 production or development
- 28 injection (18 water, 10 gas)

The 91 operators listed in the well dataset include subsidiaries of larger operators. These subsidiaries were grouped for each of the large operators. Junior operators (small independent companies that have drilled a small number of wells) were grouped together.

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[9] https://geoscience.data.qld.gov.au/

A.4.5 Random sampling method testing

Initially, a sample of 200 wells was randomly selected using the Pandas dataframe sampling method,[10] which is well established and built on the Python programming language.[11] This 200-well sample was compared with the total dataset and five other random 200-well samples selected with the same method, to determine:

- if the wells in the sample set had a similar spread of operators to the wells in the complete dataset (section A.4.6)
- if the wells in the sample set had a similar spread of ages to the wells in the complete dataset (section A.4.7).

The final 200-well random sample and the Pandas sampling method were considered adequate to capture general trends and representation.

A.4.6 Comparison of operator distribution – 200 well sample

Table A 5 shows a comparison of the five 200 well selections, the final 200 well sample and the total dataset of all wells in Queensland by operator and subsidiary companies (denoted 'sub.') and percentage of the total dataset. Most operators are represented in proportion to the number of their wells in the total sample, except when wells from those operators represented less than 0.5% of total wells (for instance, AGL and Anglo are not represented in the final sample; however, their total number of wells represent only 0.1% and 0.2% of all wells in Queensland).

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[10] https://pandas.pydata.org/pandas-docs/stable/reference/api/pandas.DataFrame.sample.html

[11] https://pandas.pydata.org

Table A 5: Comparison of operators for randomly selected wells using Pandas dataframe sampling method (Sample 1 to Final sample), with the total Queensland dataset (All wells)

Operator	All wells		Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Final sample	
	#	%	#	%	#	%	#	%	#	%	#	%	#	%
AGL	16	0.1	–	0.0	–	0.0	2	1.0	1	0.5	–	0.0	–	0.0
Anglo	23	0.2	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0
Arrow	1570	11.3	23	11.5	25	12.5	17	8.5	15	7.5	33	16.5	22	11.0
Arrow sub.	668	4.8	11	5.5	4	2.0	14	7.0	12	6.0	9	4.5	11	5.5
Junior	471	3.4	7	3.5	9	4.5	4	2.0	8	4.0	5	2.5	6	3.0
Origin	3300	23.7	35	17.5	47	23.5	62	31.0	45	22.5	42	21.0	49	24.5
Origin sub.	133	1	2	1.0	3	1.5	3	1.5	1	0.5	4	2.0	1	0.5
QGC	4225	30.4	72	36.0	57	28.5	61	30.5	68	34.0	60	30.0	57	28.5
QGC sub.	51	0.4	–	0.0	2	1.0	–	0.0	2	1.0	1	0.5	1	0.5
Santos	2380	17.1	36	18.0	35	17.5	25	12.5	39	19.5	33	16.5	34	17.0
Santos sub.	593	4.3	7	3.5	10	5.0	7	3.5	6	3.0	6	3.0	13	6.5
Senex	212	1.5	3	1.5	5	2.5	2	1.0	1	0.5	1	0.5	2	1.0
Tristar	64	0.5	–	0.0	1	0.5	–	0.0	2	1.0	2	1.0	–	0.0
Westside	206	1.5	4	2.0	2	1.0	3	1.5	–	0.0	4	2.0	4	2.0

sub. – subsidiary company; # – number of wells

A.4.7 Comparison of well age – 200 well sample

The drilling years of all wells in Queensland is compared to the final 200-well sample in Figure A 5. The grey line shows the distribution of drilling year for all Queensland wells, normalised to 200 for comparison. The 200-well sample (red) reflects the general trends of the overall dataset, with the other randomly selected samples also reflecting these trends, as shown in Figure A 6.

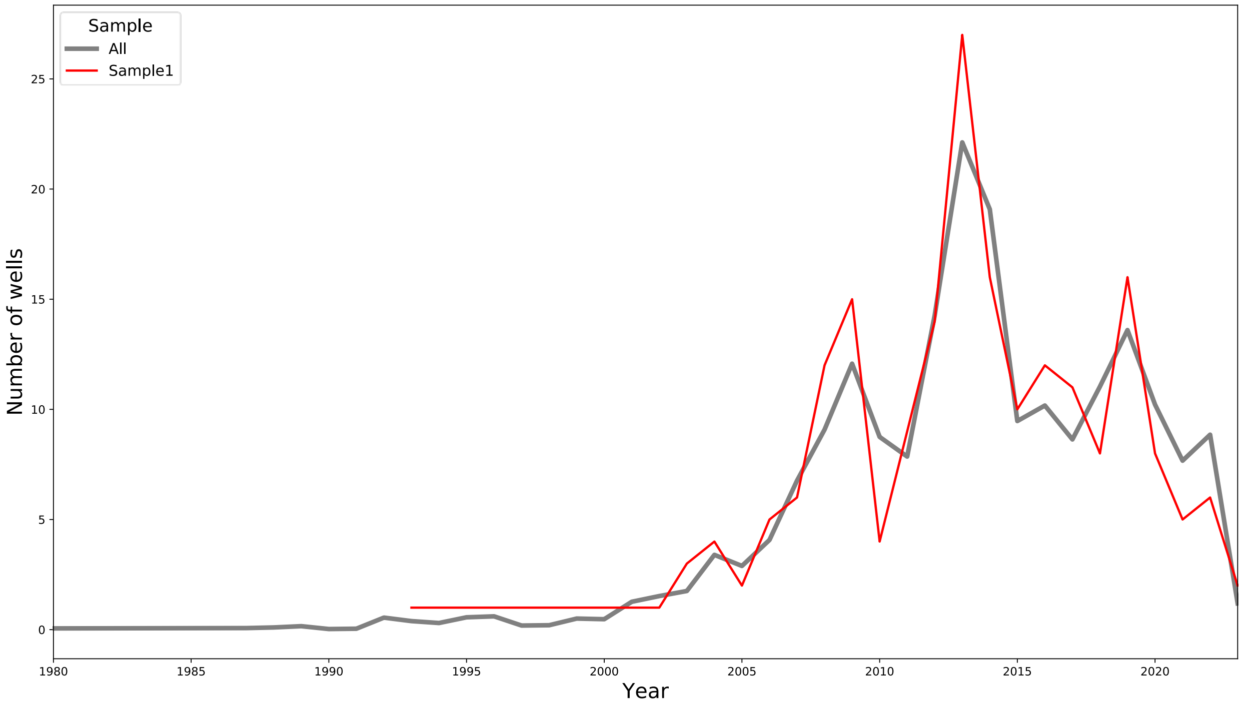

Figure A 5: Comparison of the number of wells drilled over time for the final sample, with the total well dataset (normalised to 200)

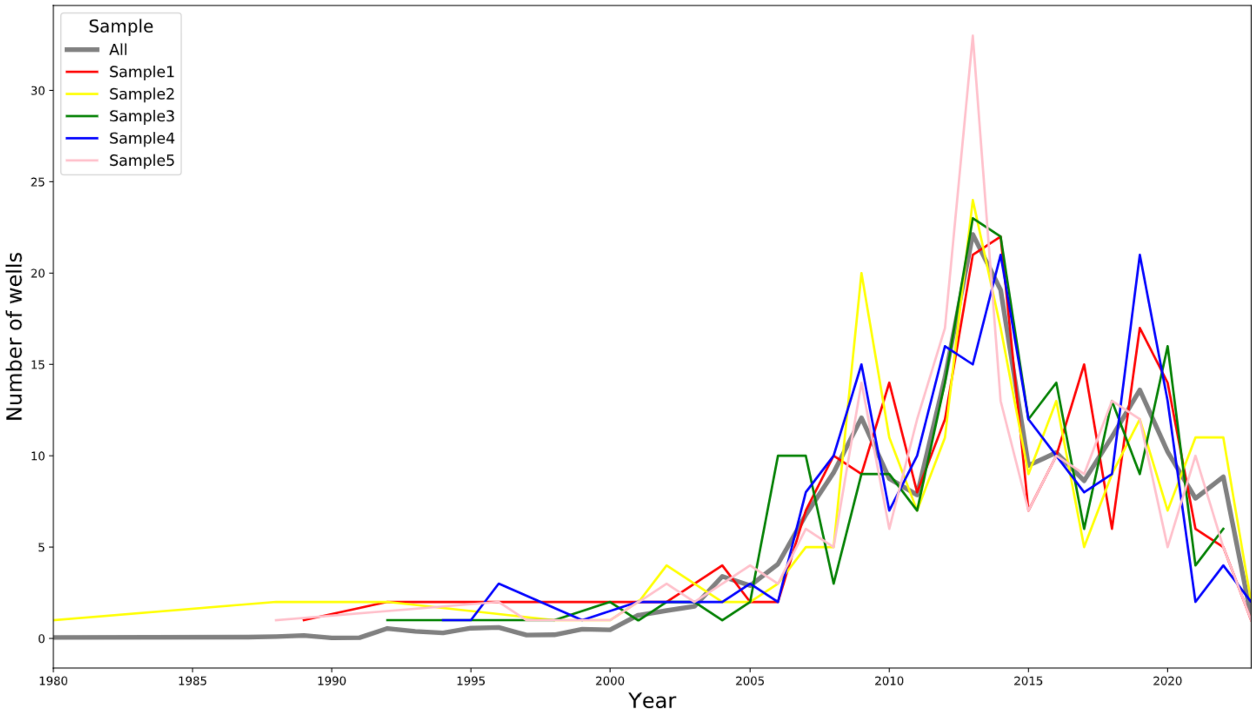

Figure A 6: Comparison of the number of wells drilled over time with each randomly selected sample, with the total well dataset (normalised to 200)

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