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3DKL v1.0: Creating the first 3D geological model of Kuala Lumpur

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Abstract: The objective of UN Sustainable Development Goal 11 is to make cities and human settlements inclusive, safe, resilient and sustainable. Geoscience can play a significant role in achieving targets within this goal by developing a better understanding of geological properties and processes within urban environments, and by ensuring that this understanding is integrated into urban development. A key step in this process will be enhancing awareness of urban geology among non-geoscience decision-makers, so that inherent subsurface risks and benefits are understood and accounted for during all phases of development. Three-dimensional geological models are an effective tool for geologists to communicate with stakeholders in government and industry during that process. They can also provide a framework to enable geological data and information to be integrated into Building and City Information Models, and thus facilitate more effective infrastructure and utility asset management. This paper describes the modelling workflow adopted by a consortium of geoscientists from government, industry and academia to deliver the first 3D geological model of Kuala Lumpur – 3DKL v1.0. The modelling workflow involved: digitising borehole logs from site investigation reports and storing them in a dedicated geospatially-enabled SQLite borehole database; viewing and interpreting that borehole data using QGIS software; generating multiple orthogonally oriented cross-section profiles across the modelled area using Groundhog Desktop software; and integrating the information derived from the interpreted boreholes, surface data and cross-section profiles to generate a 3D geological model in Leapfrog Geo software. 3DKL v1.0 has demonstrated proof-of-concept: we have developed a workflow, based largely on freely-available software, for transforming borehole information, previously captured in paper records, into a conceptual 3D model. The modelling process has also identified areas where geological knowledge and data need to be enhanced if 3DKL is to fulfil its potential to support more sustainable and resilient urban development in Kuala Lumpur.

Keywords: UN Sustainable Development Goals, urban geology, Engineering Geology, Kuala Lumpur geology, 3D modelling, digital workflows, geoscience databases

Abstrak: Objektif bagi Matlamat Pembangunan Lestari Ke-11 oleh PBB adalah menjadikan bandar dan penempatan manusia sebagai kawasan bersifat inklusif, selamat, berdaya tahan dan lestari. Geosains dapat memainkan peranan penting dalam membantu mencapai sasaran ini dengan meningkatkan pemahaman yang lebih baik berkenaan sifat-sifat dan proses geologi dalam lingkungan perbandaran, dan memastikan pemahaman ini dapat diterapkan ke dalam pembangunan bandar. Langkah utama dalam proses ini adalah dengan meningkatkan kesedaran mengenai kepentingan geologi bandar di kalangan pembuat dasar yang bukan ahli geosains untuk memahami tentang risiko dan manfaat di bawah permukaan yang perlu diambil kira dalam semua fasa pembangunan. Dalam proses tersebut, model geologi tiga dimensi adalah medium yang berkesan bagi ahli geologi untuk berkomunikasi dengan pihak berkepentingan dalam kerajaan dan industri. Ahli geologi juga dapat menyediakan kerangka kerja bagi membolehkan data dan maklumat geologi diintegrasikan ke dalam Model Informasi Bandar dan Bangunan, seterusnya membantu dalam pengurusan infrastrusktur dan utiliti yang lebih efektif. Kertas ini menerangkan berkenaan aliran kerja permodelan yang dibangunkan oleh satu konsortium ahli geologi dari pihak kerajaan, industri dan akademik bagi menghasilkan model geologi 3D pertama kawasan Kuala Lumpur - 3DKL v1.0. Aliran kerja pemodelan yang terlibat adalah: pendigitalan log lubang gerudi dari laporan penyiasatan tapak dan penyimpanan data dalam sistem pangkalan data lubang gerudi SQLite secara geospatial; meneliti dan mentafsirkan data pengerudian menggunakan perisian QGIS; menghasilkan profil keratan rentas di seluruh kawasan model menggunakan perisian Groundhog Desktop; dan mengintegrasikan maklumat yang diperoleh dari lubang pengerudian yang ditafsirkan bersama data permukaan dan profil keratan rentas untuk menghasilkan model geologi

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3D dalam perisian Leapfrog Geo/Works. 3DKL v1.0 telah mempamerkan bukti bagi konsep iaitu: kami telah membangunkan proses aliran kerja, dengan menggunakan perisian yang tersedia secara percuma, bagi menjadikan maklumat lubang gerudi, yang sebelum ini dalam bentuk rekod cetakan kertas, ke dalam bentuk model berkonsep 3D. Proses penghasilan model ini juga telah mengenal pasti beberapa kawasan yang kurang maklumat dan pengetahuan geologinya untuk ditambah baik di masa akan datang sekiranya 3DKL berpotensi untuk menyokong pembangunan bandar yang lebih lestari dan berdaya tahan di Kuala Lumpur.

Kata kunci: Matlamat Pembangunan Mampan Pertubuhan Bangsa Bersatu, geologi bandar, Geologi Kejuruteraan, geologi Kuala Lumpur, permodelan 3 dimensi, aliran kerja digital, pangkalan data geosains

INTRODUCTION

Geoscience can have a significant role in helping to deliver the UN Sustainable Development Goals (SDGs). The objective of SDG 11 is to make cities and human settlements inclusive, safe, resilient and sustainable (United Nations, 2015). There are multiple targets within this goal, which include: safe and affordable housing; affordable and sustainable transport systems; inclusive and sustainable urbanization; reducing the adverse effects of natural disasters; reducing the environmental impact of cities; and strong national and regional development planning (Gill & Smith, 2021). Addressing these targets will require a significant investment in subsurface and surface infrastructure that considers the reciprocal interaction of the built and natural environment. A better understanding of subsurface properties (physical, mechanical and chemical) and of historic and ongoing geological processes that have created natural geological and anthropogenic materials is, therefore, critical for improving the resilience of urban environments and ensuring sustainable future development (Legett, 1982; Tan & Rau, 1986; Dearman, 1991; De Mulder *et al.*, 2001; Culshaw *et al.*, 2009; Tan, 2009; Mielby *et al.*, 2017; Lagesse *et al.*, 2021). Greater awareness of geology within the urban environment (urban geology) among non-geoscience decision-makers will also be required to ensure that inherent subsurface risks and benefits are understood and accounted for during all phases of the urban development process. A significant step forward in developing and communicating that urban geological understanding can be achieved using attributed three-dimensional (3D) geological models, which help inform the decision-making of geoscience stakeholders involved in the planning, design, construction and redevelopment of buildings and infrastructure (Culshaw, 2005; Ford *et al.,* 2008; Campbell *et al.*, 2010; Culshaw & Price, 2011; Rose *et al*., 2018; Terrington *et al.*, 2019; Smith *et al*., 2022; Petrone *et al*., 2023). 3D geological models are now frequently used across Europe, North America, Australasia and Asia as part of the urban planning and construction process (Lelliott *et al.,* 2006; Royse *et al.,* 2008; Campbell *et al.,* 2017; Mielby *et al.*, 2017; Kearsey *et al.,* 2020; Turner *et al.*, 2021; Kearsey *et al*., 2022; Zhou *et al*., 2022; Zhuang *et al*., 2023). They can also provide a framework to enable geological data and information to be integrated into Building and City Information Models, which in turn provides a mechanism for integrating urban geoscience into infrastructure and utility asset management (Price *et al.*, 2008; Kessler *et al.*, 2015; Turner *et al.*, 2021; Khan *et al*., 2021, 2023).

Kuala Lumpur is the capital city of Malaysia and has a population of *c.* 1.8 million within the 243 km² Kuala Lumpur Federal Territory, and *c.* 7.8 million within the 2,243 km² greater metropolitan area (UNESCAP, 2019). The geology of Kuala Lumpur is complex and comprises several igneous and metasedimentary rock units and a range of near-surface superficial and artificial deposits. The geology is also structurally complex, deeply weathered and host to an array of shallow geohazards, including landslides, buried karst and compressible soils (Tan & Komoo, 1990; Tan, 2009). Construction within Kuala Lumpur, is therefore, highly challenging and the cause of construction failure and significant time and cost overruns (Bergado & Selvanayagam, 1987; Tan, 2017). The construction of ever-taller buildings with deeper foundations and basements—and increasing utilisation of the subsurface for transportation and utility infrastructure—has led to deeper exploitation of the Kuala Lumpur subsurface. A more comprehensive understanding of the geology, especially at depth, has therefore become critical to the future development and prosperity of Kuala Lumpur.

To fulfil the ambition of building the first 3D geological Model of Kuala Lumpur (3DKL), a working group was formed that comprises of an international group of geoscientists from across government, industry, and academia. Key stakeholders in that working group include Jabatan Mineral dan Geosains Malaysia (JMG), the British Geological Survey (BGS), Dewan Bandaraya Kuala Lumpur (DBKL), Jabatan Kerja Raya (JKR), University of Malaya (UM), Universiti Tenaga Nasional (Uniten), Universiti Kebangsaan Malaysia (UKM) and the Mass Rapid Transit Corporation (MRT). A workshop was held in Kuala Lumpur in November 2018 as a necessary and planned first stage, shared data, software platforms, technical skills, and geological knowledge (Figure 1). A key outcome of that workshop was an agreed position on the methodology to for creating 3DKL, an agreed geological framework, and the constituent parts of the model that could be constructed. In August 2019, a second workshop generated the first iteration of the 3D geological model for Kuala Lumpur (3DKL v1.0) (see also Figure 1).

Figure 1: Geological discussions in the field (A, B, D, E and G), interwoven with workshop sessions (C and F), for working group members involved in the generation of 3DKL v1.0, the first 3D geological model of Kuala Lumpur.

Details of the methodology used to develop the 3DKL v1.0 model are presented in this paper, accompanied by statements of the objectives agreed upon, the assumptions made, and the lessons learned in taking these first steps.

MODELLING WORKFLOWS APPLIED FOR 3DKL

Step 1, developing a shared conceptual understanding of the geology of Kuala Lumpur

A critical first step in developing a workflow that could deliver 3DKL v1.0 was for all working group members to share geological knowledge and understanding and formulate a conceptual framework of Kuala Lumpur geology that would underpin the new 3D geological model (Figure 1). This step was recognised as particularly important given two key challenges faced, namely a paucity of uniformly distributed critical data in key areas and that all working group members were going to be working together, from an agreed starting position, to develop a single unified 3D geological model.

The bedrock geology of Kuala Lumpur comprises several very different rock bodies (e.g. Gobbett, 1964; Geological Survey Malaysia, 1976; Tan & Komoo, 1990; Gue & Singh, 2000; Minerals and Geoscience Department Malaysia, 2011; Hareyani & De Freitas, 2011; Leslie *et al.*, 2020). The working group members have appraised all these units and their geometrical and geological inter-relationships (Figure 1) and considered them during the construction of 3DKL v1.0. Note that the workshop(s) referred to geological units by names in common usage in order to maximise understanding across all participants. Therefore, the granitic rocks of the Main Range Granite Province (Figure 2) are designated as ‘Western Granite’ in the model/section; likewise, the Kajang Formation as the 'Kajang Schist', and the Dinding Formation as the 'Dinding Schists' etc.

The stratigraphical succession in Kuala Lumpur and the surrounding region has been informally divided (Figure 2), and includes the Lower Palaeozoic non-fossiliferous 'Dinding Schist'/Dinding Formation and the structurally overlying 'Hawthornden Schist'/Hawthornden Formation, both of which underlie the Silurian Kuala Lumpur Limestone, (Gobbett, 1964). Parts of the 'Dinding Schist' are clearly derived from an acid to intermediate volcanic origin of Ordovician (Tremadoc) age (Quek *et al.*, 2018); the 'Hawthornden Schist' is of uniformly metasedimentary character, and predominantly composed of intensely (poly)deformed pelitic and semipelitic schist.

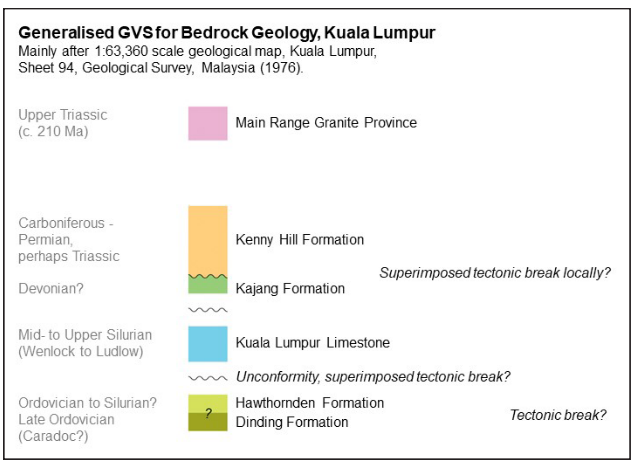

Figure 2: Simplified GVS for Kuala Lumpur and the Selangor region (after Leslie *et al.*, 2020), based on Minerals and Geoscience Department Malaysia (2011) and the authors' own observations.

The Wenlock-age Kuala Lumpur Limestone is thought to be unconformably overlain by both the 'Kajang Schist' unit (but *cf*. Yee, 1983) and the early Permian-age Kenny Hill Formation (*cf*. Hutchison & Tan, 2009). The 'Kajang Schist' strata comprise sandstone and mudstone, pyrite-rich limestone and carbonaceous shale and are generally regarded as possibly deposited in the Devonian but, alternatively may constitute a correlative and lateral facies variant of the Kuala Lumpur Limestone (Yee, 1983). All the strata underlying the dominantly sandstone units of the Kenny Hill Formation typically display intense (and demonstrably polyphase) ductile deformation (Leslie *et al.*, 2020). Many 'Kajang Schist' strata are also typically intensely palaeo-weathered and can occur as a palaeosol beneath much less paleo-weathered Kenny Hill Formation strata. The base of the Kenny Hill Formation is unconformable on all older strata (Yee, 1983), and the unit is typically much more gently folded than the underlying strata (Leslie *et al.*, 2020); less competent units (mudstones etc.) do however, always show a penetrative planar schistosity.

The higher hills that surround Kuala Lumpur on the east, north and west expose Triassic (*c*. 220–98 Ma) granite, part of the tin-bearing 'Western Belt' Main Range Granite Province suite of Peninsular Malaysia (e.g. Ghani *et al.*, 2013). These 'Western Belt Granite' plutons intruded all of the bedrock succession of Kuala Lumpur. A series of WNW-ESE striking faults cut across all the above units; these structures are locally spatially associated with thick quartz veins such as the 'Klang Gates Quartz Reef' (Gombak Selangor Quartz Ridge) in the Kuala Lumpur Fault Zone (Stauffer, 1968; Shu, 1969).

Figure 3 is a conceptual vertical cross-section constructed during the working group assessment of

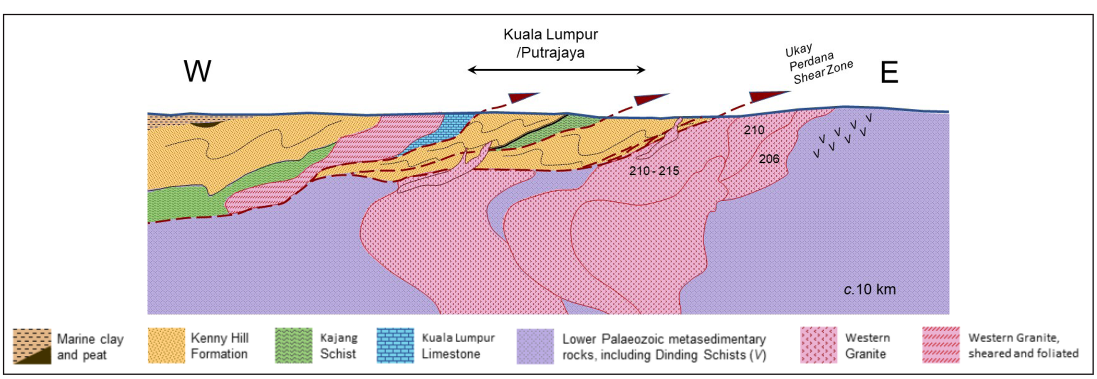

Figure 3: Conceptual vertical cross-section designed to inform the 3D model development and constructed by the workshop participants on a west to east alignment, taking general account of the likely geological relationships in the southern part of Kuala Lumpur and across Putrajaya. Figures superimposed on the granite plutons indicate age in Ma; the boundary between the Kenny Hill Formation and the Kajang Schist (Kajang Formation of Figure 2) is an unconformity, and likely marked by a significant metre-scale thickness of palaeoweathered rocks forming a discrete palaeo-regolith. Form lines superimposed on the polygons of Kenny Hill Formation strata represent the observed easterly-directed folding affecting these strata. Vertical scale is approximately equal to the horizontal. 'Western Granite' plutons are the Main Range Granite Province plutons of Figure 2.

the geology of Kuala Lumpur (at the November 2018 workshop) and following visits to some 57 field locations to examine and better understand the characteristics of the key geological units (see Figure 1), and their likely subsurface geometry and inter-relationships. The concept for this schematic cross-section follows the model of Leslie *et al.* (2020) for the Ukay Perdana Shear Zone, which is thought to be a major influence on the structural geology of Kuala Lumpur. This major shear zone may have significantly impacted the arrangement of identifiable geological units in the subsurface once the effects of later superimposed and steeply dipping strike-slip fault arrays are considered.

The conceptual section removes the effects of that faulting for clarity. It thus concentrates on the possibility that large-scale geological units beneath Kuala Lumpur may have been tectonically inter-leaved by the effects of thrusting associated with the Ukay Perdana Shear Zone.

The cross-section was constructed during debate amongst the working group members and designed to encourage robust interrogation of the data available to construct 3DKL v1.0. An overall and conceptual sense of the larger-scale geology of Kuala Lumpur is an important guide when constructing the cross-section interpretations incorporated into the 3D model. Note that this cross-section refers to geological units by the common usage terms familiar to all workshop participants.

Step 2, defining the modelling purpose and objectives

One of the key initial objectives of the August 2019 workshop was to define the purpose of the 3DKL project. Given the pilot-study nature of this project, and the availability and quality of relevant data (principally analogue data, limited data capture for superficial deposits and lithostratigraphy, and logs mainly derived from drilling undertaken by wash-boring), the working group agreed that the main purposes of the model should be:

1. *to develop a digital workflow proof-of-concept*: demonstrating that the modelling methodology and workflow proposed could be used together to build a robust 3D geological model (see Figure 4); this proof of concept was a key stage given the absence of a single ‘one-stop-shop’ application, and the necessity for the adopted workflow to incorporate several different software applications (including Microsoft Excel, SQLite, Microsoft Access, QGIS, Groundhog Desktop, and Leapfrog);

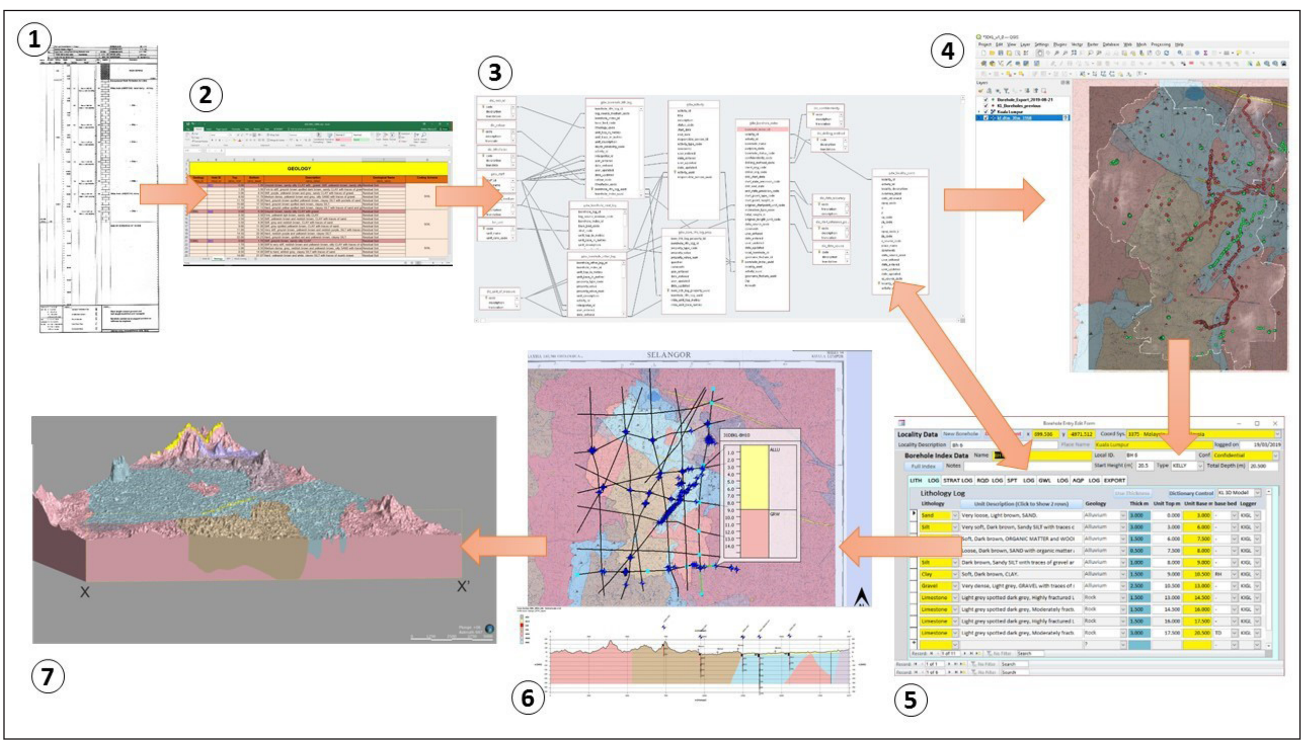

Figure 4: 3DKL v1.0 workflow. 1) Borehole logs are extracted from site investigation reports and scanned; 2) boreholes are digitised by manually coding the borehole log into excel spreadsheets laid out in an AGS format (AGS, 2020); 3) all borehole data are loaded into a dedicated geospatial SQLite borehole database; 4) QGIS software is used to view borehole, geological and topographical data, and to perform coordinate transformations to coordinate projection system GDM2000; 5) BGS Data Entry System used to assign lithology and stratigraphy to each borehole layer in the SQLite borehole database; 6) Groundhog software used to create cross-sections from interpreted borehole data, digital terrain model and geology map; 7) Leapfrog software used to combine borehole data and nodes exported from Groundhog cross-sections to create 3DKL v1.0.

2. *to identify data and knowledge gaps* in the Kuala Lumpur urban subsurface, thereby helping to target future city-scale ground investigation works and research;
3. *provide a foundation for future applied geological models*: including engineering geological, hydrogeological, and geotechnical models, and a larger-scale Greater Kuala Lumpur 3D geological model;
4. *and where possible, use freely-available open-source software applications* so that the methodology could be easily replicated by others, and at minimum cost.

To meet these four principal objectives, it was agreed that the model should encompass the whole of Kuala Lumpur and extend to a depth of 300 m whilst acknowledging that the data availability below 75 metres would, in most areas, be severely limited. It was also agreed that the units employed for the geological model construction would be stratigraphical units, accepting that these would provide an easier starting geological framework than lithological- or sedimentary facies-based units, for example. One key advantage of this approach is that the modelling units can readily be amended to provide greater detail in future iterations of 3DKL, for example, using sub-divided stratigraphical units where appropriate. The guiding framework and presentation (as provided in Figure 2) of these units should always be flexible and easily amended for the purposes of different stakeholders as required, for example presenting the modelled units as different igneous versus different sedimentary lithological groupings or associations.

Working group members agreed that a meaningful attempt to model fault structures (discontinuities) was also very important and likely to be informative. There were, however, concerns relating to whether such features could be easily incorporated into the model using the preferred Leapfrog software modelling protocols, particularly so where no significant offsets (decametre-scale, for example) could be specified in relation to individual fault features. Consequently, only larger-scale fault features, understood to be associated with greater offset displacements and previously reported on published geological maps (e.g. Minerals and Geoscience Department Malaysia, 2011), would initially be incorporated into the framework of 3DKL v1.0; these elements can be thought of as 'block-bounding' faults. Each of the steps in the modelling workflow (Figure 4) is described in more detail in the following sections.

Step 3, borehole log acquisition and digitisation

Most borehole logs used to construct 3DKL v1.0 originated from the civil engineering industry. They were supplied to JMG as part of the statutory planning and earthworks approval process. JMG is a member of the 'One Stop Centre Committee' established under the aegis of the Ministry of Housing and Local Government and is the statutory consultee responsible for evaluating all geological observations and interpretations presented by project proponents. For the last ten years, the Selangor and Wilayah Persekutuan office of the JMG has routinely requested that borehole data be delivered as part of this process to better evaluate the subsurface conditions identified at development sites as part of the planning process. Of particular value to the development and construction of 3DKL v1.0 are the numerous boreholes acquired in support of linear infrastructure developments, such as the Mass Rapid Transit, the Light Rail Transit, and the Stormwater Management and Road Tunnel (SMART); such data are particularly amenable to the construction of more consistently robust cross-sections that capture key geological relationships.

Typically, borehole information has been supplied to JMG in paper format as part of factual site investigation reports and geotechnical assessment reports. Consequently, the first operation for this pilot study was to make a digital scan of all paper borehole logs so that these data could be stored and easily retrieved during the process of building a working database. All borehole records were indexed in a master spreadsheet using the borehole number and project number; each borehole scan had a unique identity and could be related to its parent project. Borehole records were then manually digitised into Microsoft Excel spreadsheets using an AGS proforma supplied by MRT; AGS is a text file format used to electronically record, store and transfer geotechnical and geo-environmental site investigation data and is widely used in the UK, Australia, New Zealand, Hong Kong, and Singapore (AGS, 2020). AGS format was adopted as it uses standardised categories and data-dictionaries that capture nearly all data and related information typically recorded in exploratory holes undertaken for site investigation. A separate Microsoft Excel spreadsheet was compiled for each site investigation project so that multiple people could undertake the data entry and then later compile into a single 'master' spreadsheet. The 'master' spreadsheet data, containing 621 individual borehole records, were then loaded semi-automatically (using scripts supported by manual intervention) into a dedicated borehole database. It is worth noting that the data entered using spreadsheets had to be extensively corrected and quality checked due to the severe generic limitations of using spreadsheets for complex data capture. In future, it is expected that borehole data will be digitised directly into the borehole database using the dedicated data entry system described below rather than by using Microsoft Excel as an intermediary step.

Step 4, borehole database development

The BGS developed the borehole database (and data entry system) and co-designed it by integrating stakeholder feedback provided by the 3DKL Working Group during the November 2018 workshop. The database was created in SQLite v3.0, a single file-based relational database management system (RDBMS), which uses a C-language library. SQLite was chosen because it met several desirable criteria. Specifically it is free, fast, reliable, and accessible and, most importantly, is easy to use and integrate with the other software applications in the modelling workflow adopted. The SQLite free download is available at: https://www.sqlite.org/index.html.

The key features of the borehole database are that:

1. *it is geospatially enabled….*: the data are held in a series of tables that are linked to each other by unique borehole and layer IDs with the desired outcome that all data (geological description, in situ test, laboratory testing, etc.) are relationally-linked, and therefore easily queried and exported in desirable formats (see Figure 5);
2. *…. and dictionary controlled*: Many of the attributes (fields) in these tables are populated with terms that are controlled by a large number of agreed standard and specialised dictionaries. Constraining data entry employing such dictionaries eliminates typographical errors in data entry, ensures consistency and syntax of the entered field data values, limits mistaken attribution, and makes data entry more efficient overall.

The borehole database was installed on a central server in the JMG Data Centre in Ipoh (and later transferred to a staging server housed at the JMG Selangor and Wilayah Persekutuan office). Placing the database on a central server was critical to the success of 3DKL v1.0 as it allowed all participants of the August 2019 workshop to simultaneously view, add, and edit one centrally stored and managed master database. This ensured that working group members were not amending multiple copies of Excel spreadsheets stored locally on each workstation, thus avoiding the problems of duplication, aggregation, and version control.

The data entry system

A dedicated data entry system was developed by BGS using Microsoft Access to make entering and amending data in the database straightforward and more systematic: the Kuala Lumpur Bore Hole Entry System (KL-BHES). This 'gateway' was installed on the workstations used by members of the 3DKL Working Group and linked to the borehole database stored on the central server. All participants in the data entry effort were then given individual read-and-write access to the borehole database folder. This allowed data within the borehole database to be viewed and amended simultaneously by all working group members.

An important proviso to that general protocol is that the data entry system manages version control by locking out borehole records being edited to a single user but maintains global access to all other records not being edited at that time by that user, thus avoiding duplication and maintaining the integrity of the database. The constituent forms of the data entry system are laid out in a spreadsheet-style format, with field options for data entry ranging from free text to dictionary-controlled drop-down menus. Data entry is also constrained using logical rules embedded in both the database (using appropriate database Triggers and Functions code) and the data entry system (using appropriate Functions and Event-driven code). In addition to allowing borehole data to be added and amended, the data entry system can also be used to amend existing dictionaries (see Figure 6).

The data entry system was created using Microsoft Access v16. Two functionally identical versions were created for Windows workstations, one for those with the Microsoft Access application already installed and a runtime version for those workstations lacking Microsoft Access installation. The Microsoft runtime licence version for Access is free to use and distribute.

Step 5, working with QGIS

QGIS software was installed on all workstations used by the working group to validate the spatial relationships of all borehole records added to the database. QGIS is preferred as it is a free and open-source Geographical Information System (GIS) software package that delivers integration and analysis of geospatial and georeferenced data in a single map-based environment. As with other GIS platforms, QGIS accommodates both vector and raster data and has a large user community, which it relies upon to drive forward software development. The QGIS free download is available at: https://qgis.org/en/site/forusers/download.html).

The working group members used QGIS to view the locations of boreholes over:

- a georectified raster image of the published geological map (Selangor Sheet 94: Geological Survey Malaysia, 1976);
- a 30-metre resolution digital terrain model (DTM), in this case, Shuttle Radar Topography Mission DTM (SRTM), freely available under NASA's open government licence (Farr *et al.*, 2007);
- a topographic map, in this case sourced from a free online web map service (WMS) (OpenStreetMap contributors, 2019);

- and to verify borehole location and assist with stratigraphic interpretation (see Figure 7).

QGIS was also used after the borehole coding had been carried out (see below) to spatially visualise all such data and ensure that they were spatially located using the same coordinate projection system (in this case, GDM2000 – EPSG:3375). Borehole data initially entered into Excel spreadsheets in the Kertau (EPSG 3167) co-ordinate system were imported into QGIS and re-projected into the GDM2000 projection system. The GDM2000 borehole coordinates were then all exported from QGIS in .csv file format, ready to be input into the Groundhog Desktop and Leapfrog stages of the modelling workflow.

Step 6, interpreting and assigning lithology and stratigraphy and borehole quality checking

Boreholes loaded into the borehole database were then assigned to working group members for 'coding' and quality checking (QC). Coding was prioritised based on borehole depth and location to maximise data distribution horizontally and vertically within the final model. Within each priority

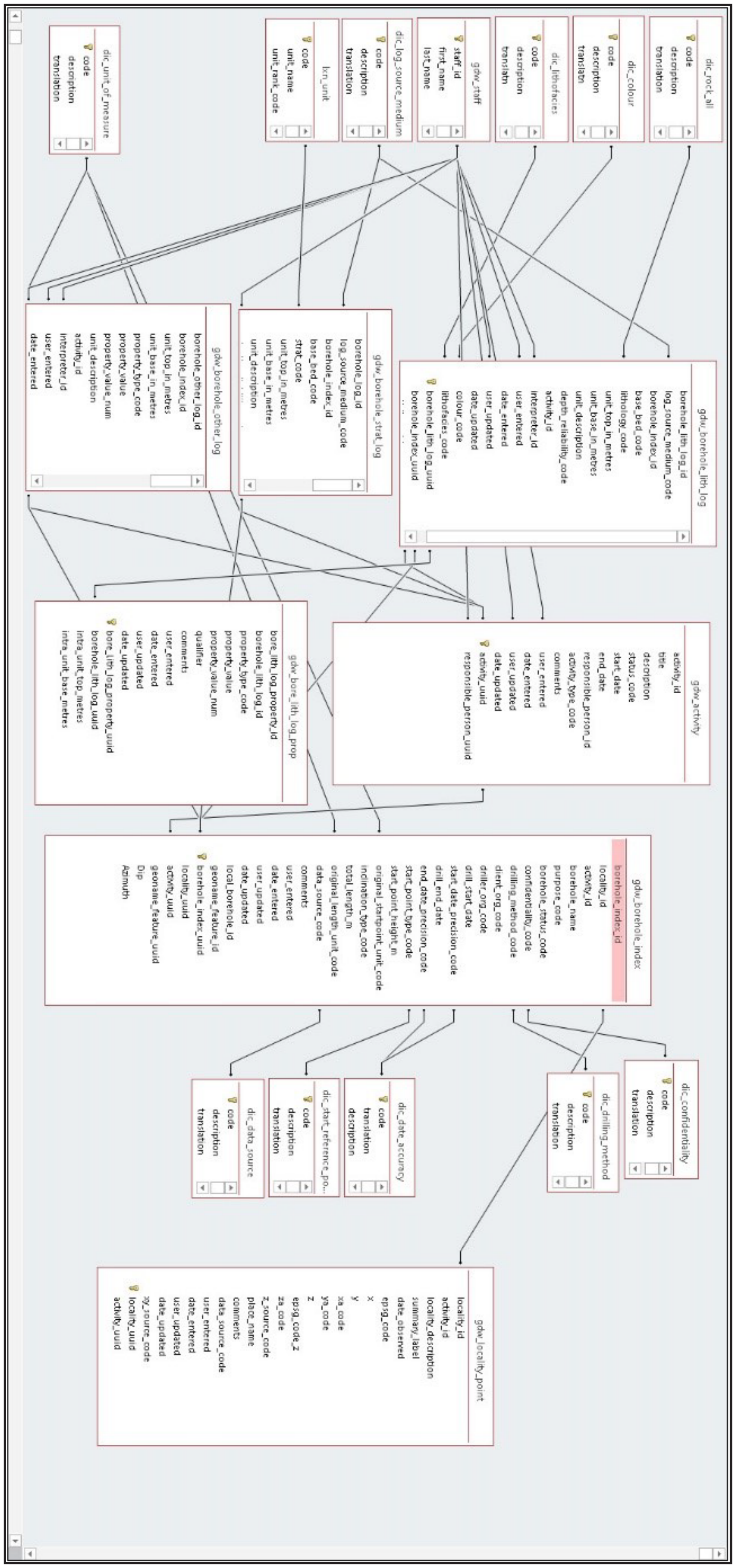

Figure 5: Borehole database schema showing all the different tables and how they are linked.

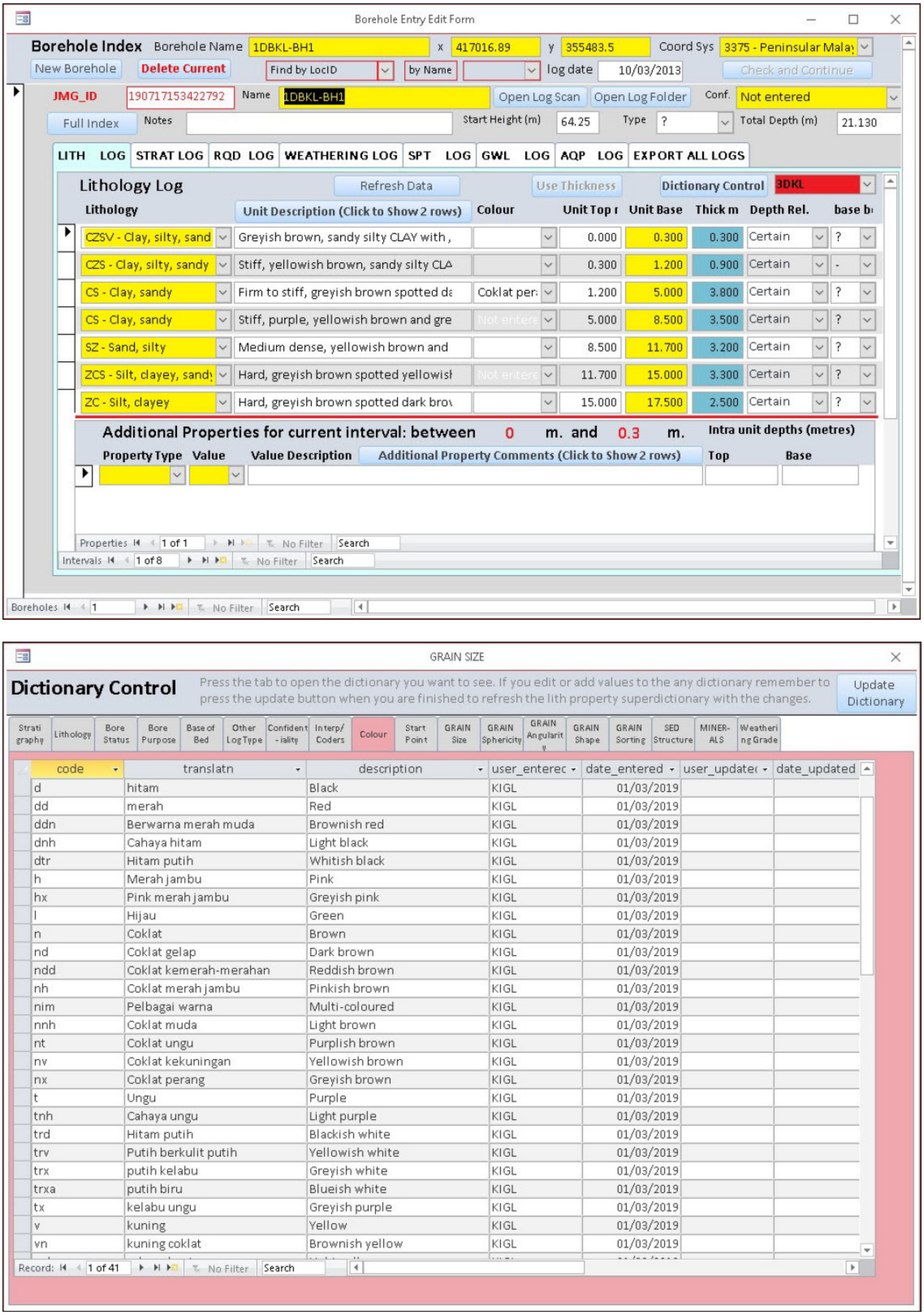

Figure 6: Examples of forms used as part of Data Entry System for entering lithology data (top) and for amending dictionaries (bottom).

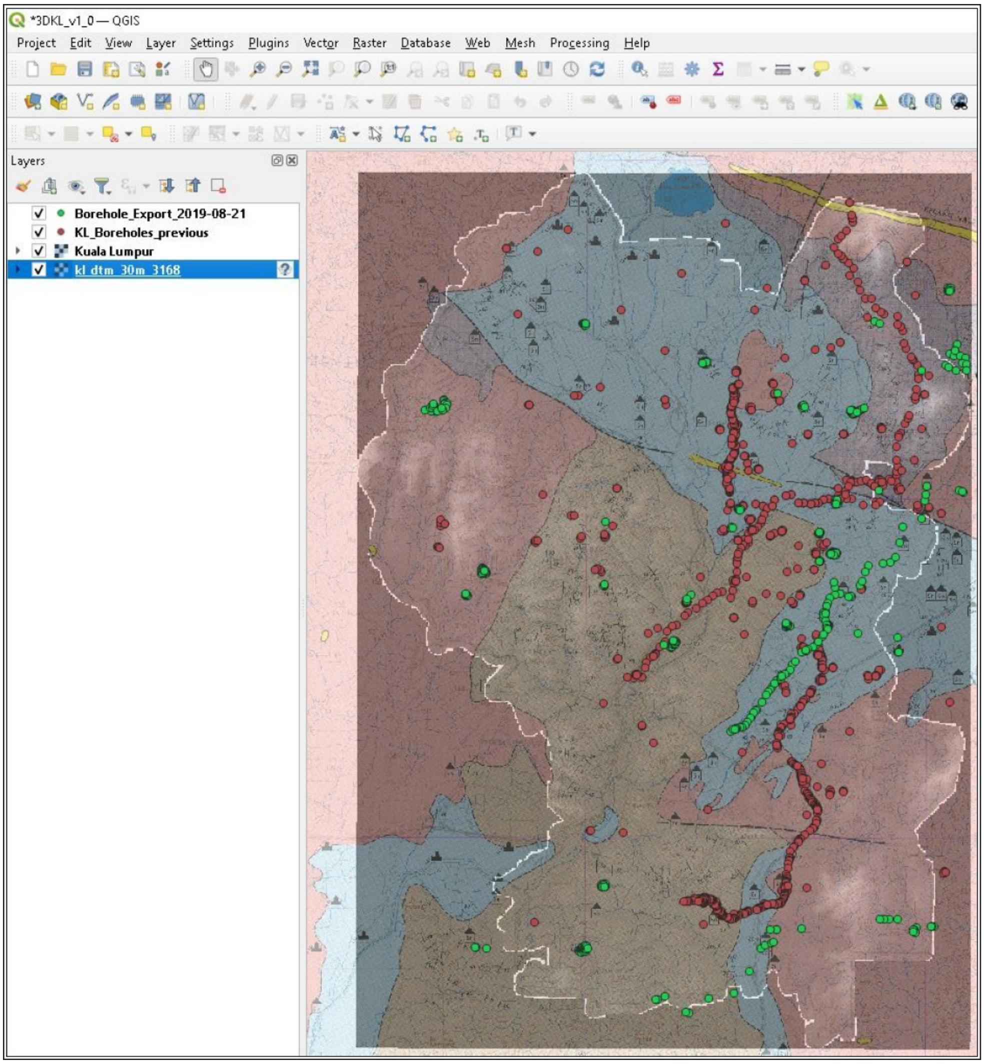

Figure 7: QGIS interface with map window displaying borehole locations (vector data) over a geological map image and digital terrain model (raster data).

borehole, a lithology code and stratigraphy code were assigned to each recorded layer and a QC process undertaken.

Data entry, attribution, and QC are involved in ensuring that:

- each borehole had an Easting, Northing and start height (metres above sea level), and the given location was acceptable when checked against the topographic map, DTM, and the project development title (using QGIS and the pdf scan of the borehole);
- there were no gaps or overlaps between individual layers (intervals) within each borehole record;
- data for SPT, RQD, and groundwater level had been entered into their respective database logs, where these existed in the original borehole log scan;
- if weathering were recorded in the source data as a weathering grade or as a description consistent with weathering grade, it would be entered in the weathering log;
- if the description of weathering was not consistent with weathering grade then it was not entered;
- terminal Depth (base of the borehole) and Rockhead Depth (defined as a transition to rotary coring from wash-boring) were recorded in the layer with the corresponding base depth;
- lithology was entered for each layer using the lithology dictionary;
- stratigraphy was interpreted and entered for each layer using the stratigraphy dictionary;
- confidence was assigned to the stratigraphical interpretation using the confidence field. This allowed users to enter a value for the perceived status of the geological interpretation: remote – unlikely – even chance – probable – likely – almost certain – certain;
- the basis for stratigraphical interpretation was recorded. This ensured that the rationale for interpretation was available for consideration during any subsequent re-interpretation;
- and finally, the status of the borehole was recorded as: '*Ready*' (if all points above had been checked and entered), '*Needs Z*' if a borehole start height was not

present and, as '*Needs XY*' if grid co-ordinates were not present for the borehole data entered.

During the August 2019 workshop, 278 boreholes were coded for lithology and stratigraphy and Quality Checked in the above manner; that data subset was then used in the subsequent Groundhog and Leapfrog stages of the modelling workflow.

Step 7, Groundhog cross-section modelling

Boreholes, coded for lithology and stratigraphy, were imported into the cross-section modelling software Groundhog Desktop (v1.10), along with the geological map, topographical map, and DTM of Kuala Lumpur. Groundhog was chosen as the preferred software for this step as BGS has expertise with this software, the software is freely available, and it would enable all working group members to contribute to the construction of the cross sections (there was only a single user license available for Leapfrog).

Groundhog Desktop is a geoscience information system software developed by BGS that integrates borehole data with geological maps, other images (such as geophysical profiles), and topographical surfaces. It includes a drawing tool that enables users to create deterministic representations of the geology as cross-section profiles (see Figure 8; Kessler *et al.,* 2009); these interpretive sections integrate the user's own geological knowledge with available geoscience and topographic data (DTM, boreholes, geological maps, and other images). This deterministic approach is beneficial when subsurface data are sparse or clustered, and/or the geology is particularly complex and beyond the capability of computer algorithms to generate geologically realistic predictions.

Groundhog Desktop v2.8 (https://www.bgs.ac.uk/technologies/software/groundhog/) is free to use and the cross-section profile construction approach designed to be intuitive for geological users. The paucity of data, and particularly deep borehole data in Kuala Lumpur, was one of the main reasons for including Groundhog (and cross-section development) as an intermediate step in the modelling process, before proceeding to create 3D model volumes in Leapfrog. Many data import and export functions are built into the Groundhog Desktop application, meaning that it is versatile enough to work alongside most commercial 3D modelling software. 3D modelling capability has also recently been added to v2.8 of the software.

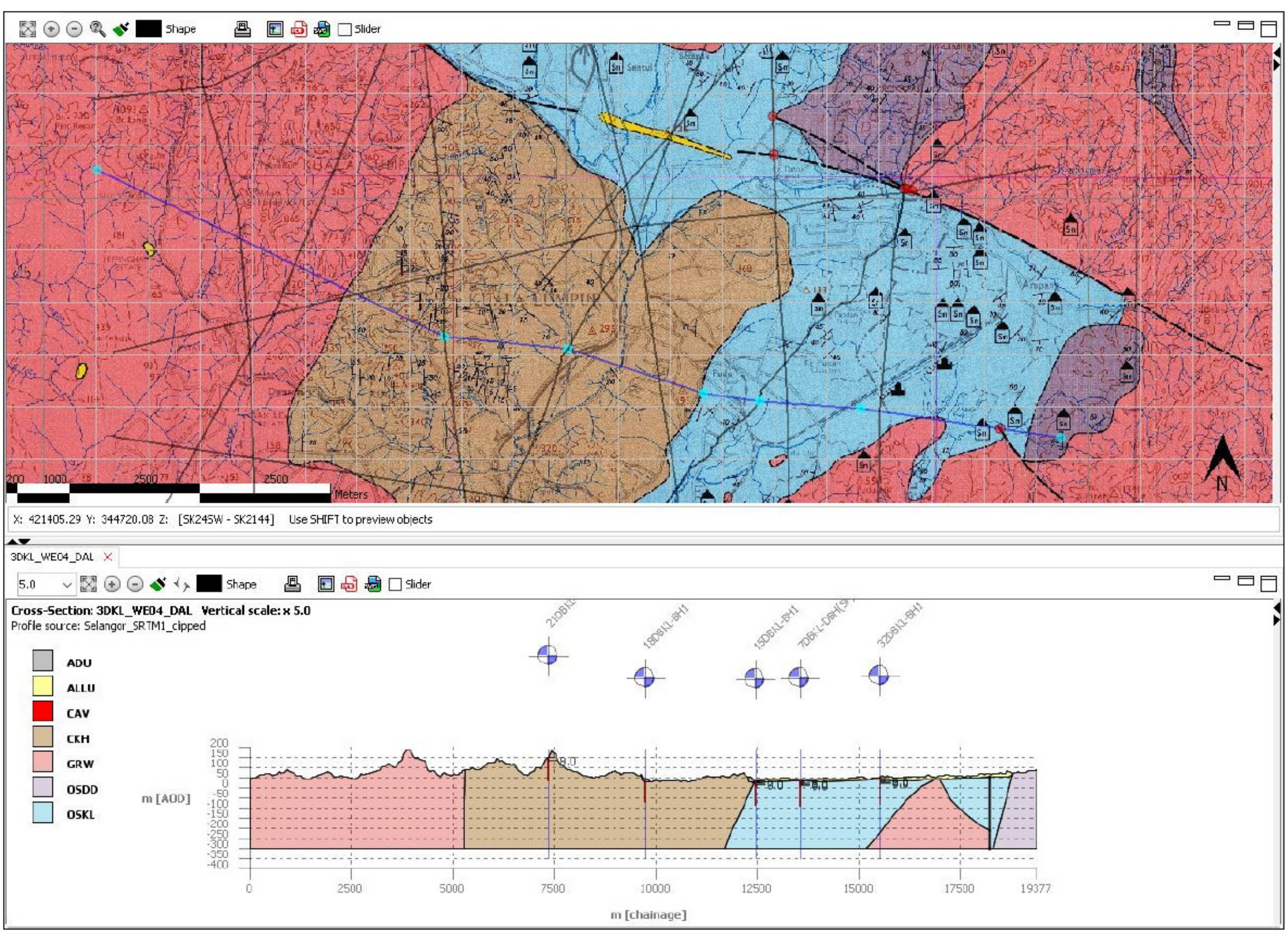

Figure 8: Example cross-section from 3DKL (top) with location shown in plan-view (below).

Fence diagram design

After importing the coded boreholes, geology map and DTM, the first step was to create a fence diagram (cross-section profile network) for 3DKL (see Figure 9). The fence diagram was designed to:

- be evenly spaced to produce consistent coverage across the whole model area;
- have one axis of the fence diagram perpendicular to the strike of major boundaries (stratigraphic and tectonic);
- pass through as many available boreholes as possible;
- and avoid crossing boundaries, or indeed other cross-sections, at acute angles.

Cross-section profiles were then allocated to individuals within the working group for construction and profile modelling in Groundhog.

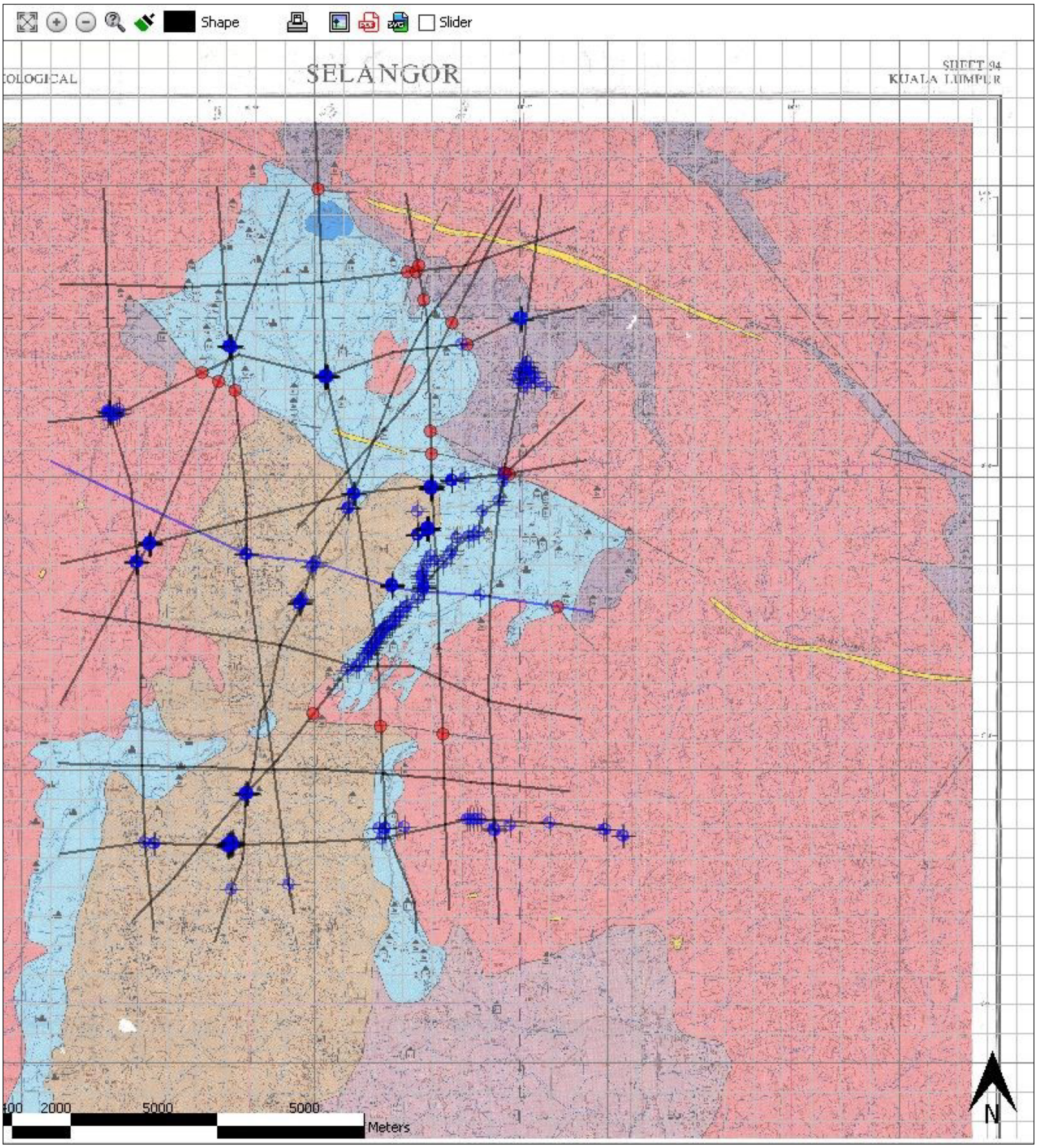

Figure 9: Groundhog Map Window showing boreholes overlying geology map with fence diagram showing location of cross-sections and borehole log for one selected borehole.

Cross-section drawing assumptions

As part of the cross-section construction process, it soon became apparent that there were several data and knowledge gaps. In many cases, these could only be addressed by making simplistic assumptions about the geological setting. The key considerations in this respect are in relation to the artificial deposits, alluvium, the ‘Western Belt Granite’ (of the Main Range Granite Province (Ghani *et al.,* 2013, Figure 2), the Kenny Hill Formation and the Kuala Lumpur Limestone, and the likely nature of the contact between these latter two units.

Artificial deposits

With a legacy of mining and rapid urban development, extensive spreads and thicknesses of artificial deposits are likely to be encountered across Kuala Lumpur. However, these deposits’ depth, distribution, and nature are largely unknown. As such, artificial deposits were only modelled locally where they were observed and recorded in the captured borehole data (see Figure 10).

Alluvium

The paucity of data for alluvium meant that it was difficult to model in any meaningful or robust way. An attempt was made to resolve this by using a georectified image of the JMG engineering geology map of Kuala Lumpur (Jabatan Mineral dan Geosains Malaysia Negeri Selangor dan Wilayah Persekutuan, 2015). However, it quickly became clear that this also only provided partial coverage of the presence, or absence, of alluvium. Research by Universiti Malaya, and commissioned by JMG (Jabatan Mineral dan Geosains Malaysia Negeri Selangor dan Wilayah Persekutuan, 2003), suggests the average thickness of alluvium across Kuala Lumpur is 14 metres, with a maximum recorded thickness of 66 metres: the greater thicknesses are presumed to be related to localised occurrences within karst solution features occurring within the extent of Kuala Lumpur Limestone. Accordingly, cross-section profile construction for 3DKL v1.0 has incorporated an assumed blanket 14 metres thickness of alluvium, except where contrary evidence was accepted from any available quality checked borehole data (see Figure 10).

‘Western Belt Granite’

These ‘Western Belt Granite’ intrusions are a major feature of the bedrock geology in Kuala Lumpur and numerous isolated and small occurrences of granite enclosed within strata assigned to the Kuala Lumpur Limestone are shown on the published geological map (Geological Survey Malaysia, 1976). The borehole logs likewise record thicknesses of granite within limestone rocks in several places across Kuala Lumpur. The working group decided to assume that all such records are likely to be indicative of localised, but still significant, granite occurrences at a shallow depth beneath the Kuala Lumpur Limestone, which locally penetrates the limestone host rocks as veins or other sheet-like bodies. This arrangement may well be indicative of a more general occurrence of granitic rocks beneath other strata at a range of depth intervals. The constructed cross-sections therefore incorporated granite occurrences locally where there was evidence of these on either the geological map or within boreholes (see Figure 11). Though it is likely that granite rock occurs more widely at shallow depth than is constrained by the currently available data, it was considered too speculative, without direct evidence, to include a ubiquitous layer of ‘shallow granite’ across adjacent cross-section profiles.

Kenny Hill Formation–Kuala Lumpur Limestone contact

The boundary between Kenny Hill Formation strata and those assigned to the Kuala Lumpur Limestone will likely be a faulted contact at many locations within the modelled volume. The strike of bedding in one or other unit is often broadly orthogonal to the mappable boundary between the units; in some cases, the stratigraphically younger beds of sandstone are dipping beneath stratigraphically older limestone beds. Even where no significant fault structures have been included on the published geological maps at such locations, discordant faulted boundaries have been modelled

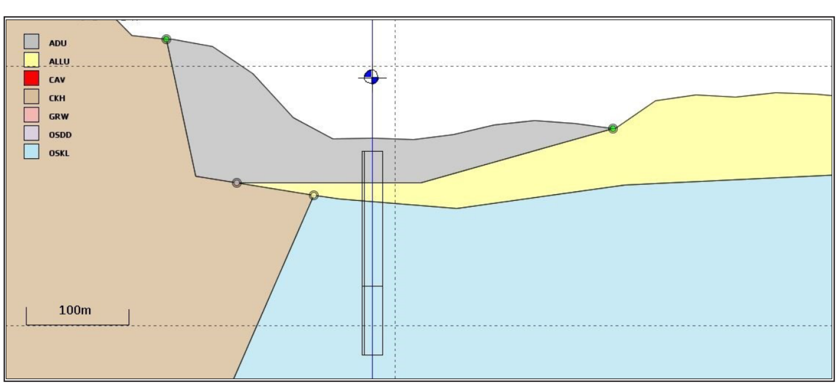

Figure 10: Example of cross-section showing both localised artificial deposits interpreted adjacent to a borehole, and more ubiquitous alluvium over Kuala Lumpur Limestone.

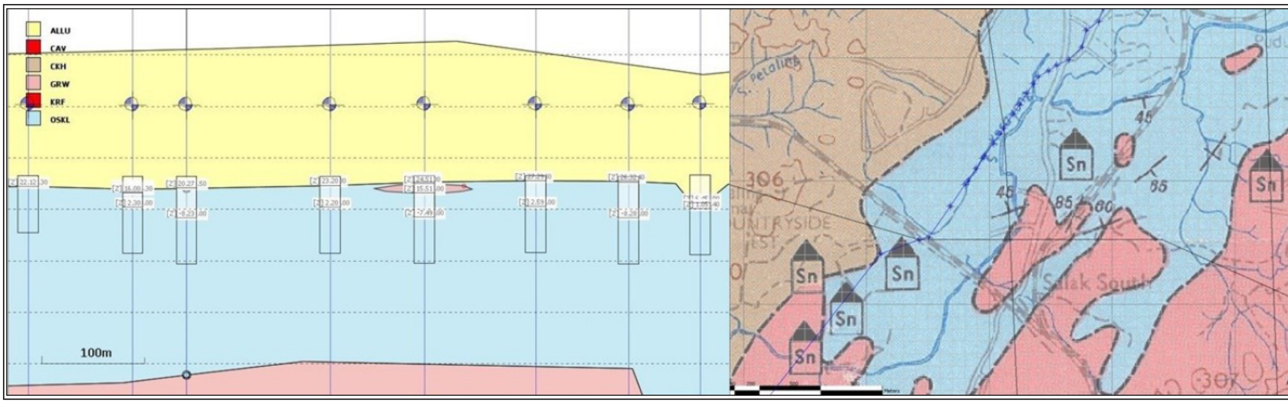

Figure 11: Example of cross-section showing 'Western Belt Granite' interpreted below boreholes based upon localised occurrences of granite rock within in the Kuala Lumpur Limestone (as seen in boreholes in image on left), and in erosional outliers of granite surrounded by the Kuala Lumpur Limestone nearby (as seen in plan-view on the map on right).

in 3DKL v1.0, and thus appear to truncate individual rock volumes. Metadata records have been created noting that these features are 'probable' faults requiring further investigation. Non-faulted and less obviously discordant boundaries between these two formations are likely to be unconformable, with the Kenny Hill Formation strata deposited over an eroded (and, locally at least, probably karstic) upper boundary of Kuala Lumpur Limestone strata. Though the exact nature and geometry of this depositional boundary are unknown, it is thought to be generally shallowly-dipping and, as such, has been modelled this way in the cross-sections.

Kuala Lumpur Limestone at depth

While it may be assumed that units of the Kuala Lumpur Limestone lie below outcrops of Kenny Hill Formation strata in the central area of Kuala Lumpur, there are no deep boreholes to constrain the depth or true nature of this contact. Therefore, it was decided not to incorporate this boundary in cross-section profiles that transected central Kuala Lumpur; Kenny Hill Formation strata were interpreted to the base of section in such cases. The most significant thickness of Kenny Hill Formation strata encountered in boreholes was around 100 metres and thus provides a minimum thickness for this unit.

Cross-section construction and iteration, metadata, and QC

A total of 16 cross-sections were constructed by the working group, generally approximating an orthogonal grid (see Figure 9). A section tracker tool (*Cross-section Tracker Metadata Recording Database*) was used as part of the section drawing workflow to document who, amongst the working group members, had constructed (or collaborated on) each section, as well as to record any assumptions (metadata) made during the cross-section construction.

Cross-section profiles, which were produced in orthogonal arrays by multiple different individuals, resulted in several conflicts. Crossing sections and adjacent sections frequently presented geological mismatches and alternative interpretations. Consequently, multiple iterations of cross-sections were required to constructively resolve these conflicts and ensure consistency.

The first stage of conflict resolution was for the working group to reach a consensus on the assumptions to be employed during cross-section drawing (see previous section).The second stage involved cross-section construction iteration using two specific Groundhog Desktop tools:

- *the crossing-section node snapping tool* shows the location of unit boundaries on crossing sections and was used to ensure geological boundary intersections were snapped together at the same depth (see Figure 12);
- *and the active drawing code tool* shows the distribution of a selected unit within cross-section profiles in plan-view and was used to ensure consistency in the interpretation of geological units at subcrop in adjacent sections (see also Figure 12).

Changes to cross-sections were also recorded in the *Cross-section Tracker Metadata Recording Database* so that future amendments could be informed by the previous assumptions and decision taken. Once the cross-sections were considered finalised, the sections were clipped to remove the 'base of section' so that only geological contacts above that base were preserved. The lines within the clipped cross-sections were then exported as nodes and compiled in a text file ready for importing into the Leapfrog software programme.

Step 8, Leapfrog 3D geological modelling

3D modelling was undertaken using Leapfrog software due to a combination of cost and usability. Only a single user license was required to construct the model as this element of the workflow could not be undertaken in parallel in the way that that the previous components were. The 3DKL v1.0 geological model was created from the following key components:

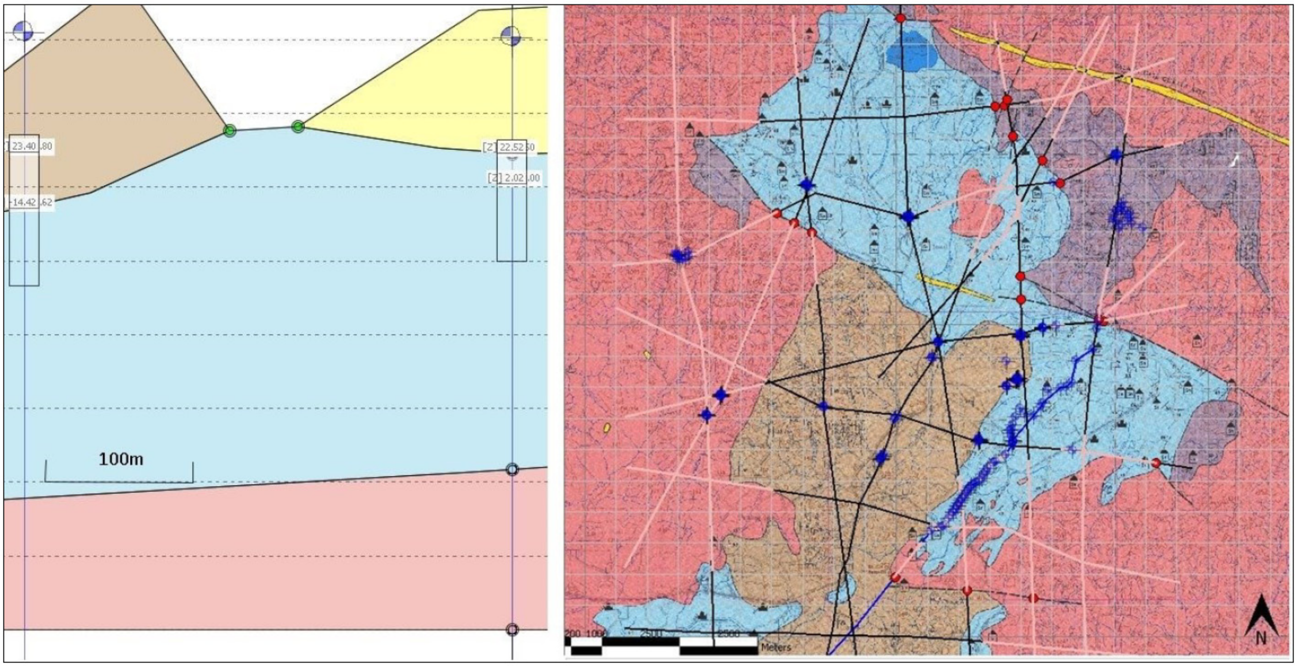

Figure 12: Example of how the crossing-section node snapping tool is used to ensure the geological boundary intersections of crossing sections are correctly aligned: symbolised by nodes with two circles (left image); example of how the active drawing code tool is used show the distribution of a specific geological unit within cross-sections: the presence of 'Western Belt Granite' in any cross section is symbolised here as pink lines in plan-view (right image).

- borehole records attributed with stratigraphy;
- cross-sections exported from Groundhog Desktop as attributed XYZ points;
- georectified raster image of the geological map (Selangor Sheet 94: Geological Survey Malaysia, 1976);
- and Shuttle Radar Topography Mission DTM (SRTM) (Farr *et al.*, 2007).

Leapfrog is an implicit modelling software programme that uses a semi-automated workflow to generate 3D geological models constrained by a range of input data. The workflow used to create 3DKL v1.0 in Leapfrog involved:

1) defining the model top, base and boundary (set as +500 metres and -500 metres respectively; the model boundary was set to a rectangle fitted to the maximum extent of the administrative boundary of Kuala Lumpur);
2) setting the topographical surface (model capping surface) as the input DTM;
3) defining the geological units and their mutual relationships (each sedimentary unit is identified within a stratigraphical order; likewise, intrusive units and their cross-cutting relationships);
4) major block-bounding faults were digitised in plan-view, based on the published geological map; the faults are modelled as vertical surfaces and divide the model volume into individual fault-blocks within which the stratigraphic surfaces are subsequently modelled (see Figure 13); note that the large faults are extended beyond the mapped extent to the model boundary and that intra-block faults were regarded as subsidiary at this stage and not separately modelled;
5) surface outcrop boundary lines were manually digitised using the published geological map, draped over the DTM;
6) bedding dip and strike were manually digitised using the published geological map;
7) geological boundary surfaces were then calculated from an integration of the borehole data, XYZ cross-section data, and the surface outcrop boundary lines;
8) and 3D geological volumes were generated for each individual fault-block unit.

3D model iteration

A 'first-pass' model was created using only the borehole data, the DTM, and the published geological map boundaries. These results were very poor as the implicit modelling technique, as expected, failed to construct plausible geological volume geometries in regions with few constraining data. Calculating a limiting surface for alluvium deposits was quickly identified as a challenge at this stage. No published map of the superficial geology of Kuala Lumpur was available to constrain the surface exposure of this unit; as a result, alluvium was shown to be everywhere at surface in this model version.

A 'second-pass' model was then created using the node text file (XYZ points) extracted from the Groundhog cross-sections, in addition to the inputs from the 'first-pass' model. The superficial geology components were also removed by constraining the modelling algorithms to

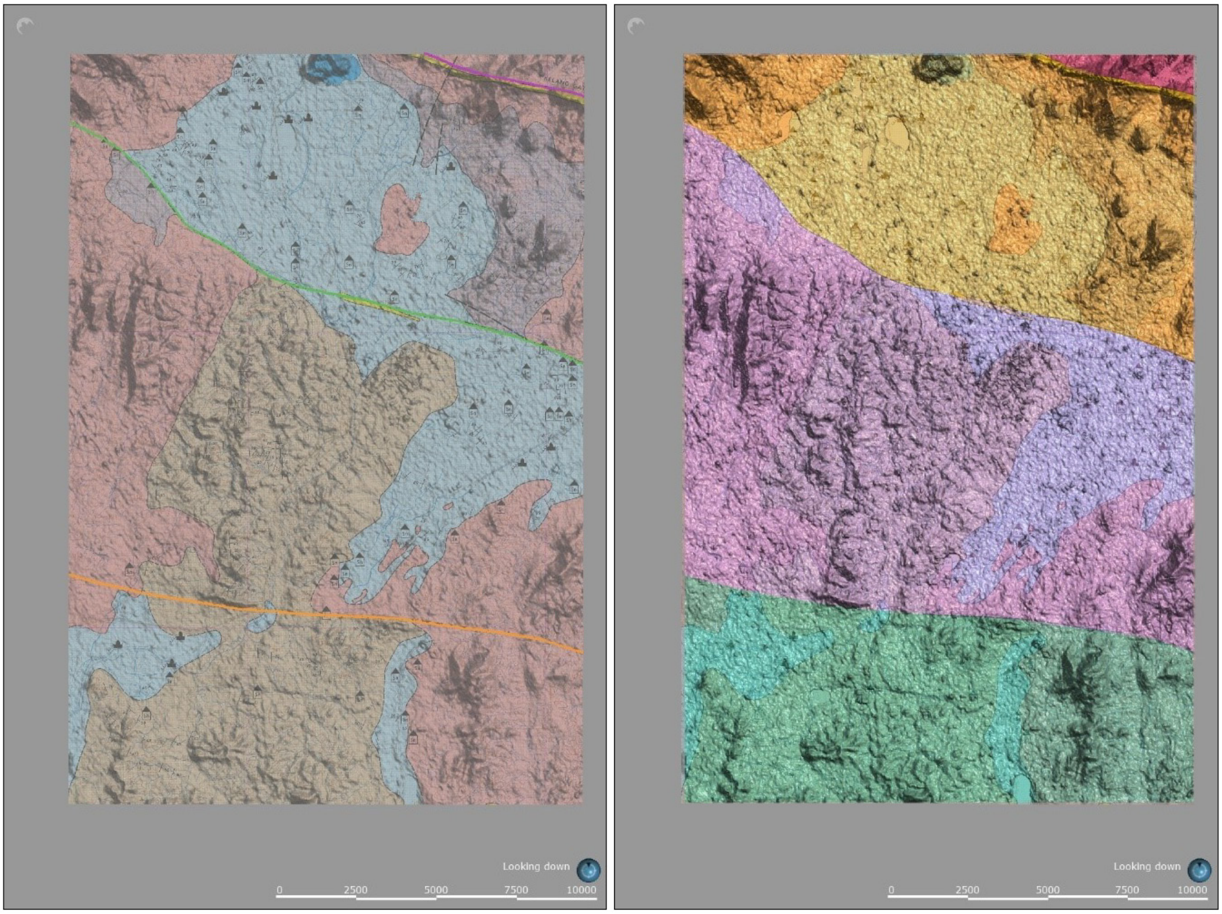

Figure 13: Major block-bounding faults (shown in the left image as orange, green and purple lines) were manually digitised onto the DTM using a georectified raster image of the geology map. These block-bounding faults separate the model into four distinct volumes for calculation (right image).

ignore the presence of these units in input data. The resulting 'second=pass' model was a substantial improvement on the 'first pass' model as it produced volume geometries that were more consistent with the working group's conceptual understanding of the 3D geology of Kuala Lumpur.

Where model boundaries were identified as having unexpected or unrealistic geometries, the constructed cross-sections informing those 'mis-fit' elements of the model were revisited and adjusted within the limits of the working group's current understanding of the geology. The model was then re-calculated in Leapfrog for a third time using a revised XYZ export of the Groundhog cross-section dataset. Returning to the input cross-sections, and amending those in Groundhog, generally produced a geometrically and geologically realistic set of model surfaces and unit limits within the overall model volume. This 'third-pass' model provided the first calculation of 3DKL v1.0 (see Figure 14).

3DKL V1.0

The 3DKL v1.0 model shows the distribution of the principal mappable bedrock units at surface in Kuala Lumpur and their likely projection into the subsurface (Figure 14).

3DKL v1.0 captures the principal elements of the bedrock geology of Kuala Lumpur and already begins to pose questions in relation to the current level of understanding of that geology. Volumes of 'Western Belt Granite' dominate the model volume in the north-east, north-west and west, and south-east. Kuala Lumpur Limestone and Kenny Hill Formation dominate much of the remainder of the bedrock geological model. The model also includes discrete volumes of Dinding Formation ('Dinding Schist') and Hawthornden Formation ('Hawthornden Schist') strata (cf. Figures 2 & 3), with the latter occurring structurally above the former.

The WNW–SSE-trending boundary separating the larger northern outcrop of Kuala Lumpur Limestone from the Kenny Hill Formation (and 'Western Belt Granite') outcrop is modelled as a faulted relationship, with this fault zone exploited locally by a vertically extended sheet (vein) of quartz mineralisation. Another such vein, the Klang Gates Quartz Reef (Stauffer, 1968; Shu, 1969), is a prominent feature in the north-east corner of the model. A second WNW–SSE-trending fault is the most likely geological explanation for the relationships between the central portion

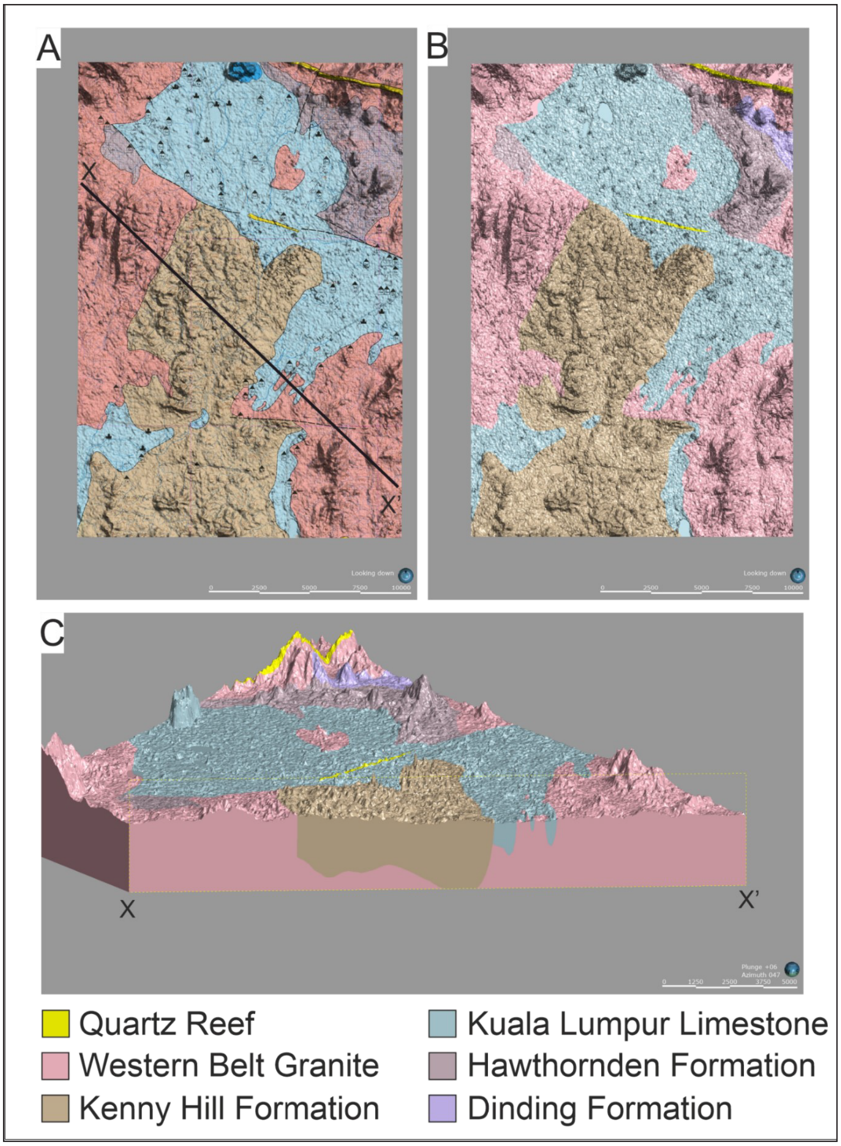

Figure 14: Final iteration of 3DKL v1.0. (A) The geological map of the modelled area overlain on the DTM and showing the location of the cross-section in C. (B) Map view of 3DKL v1.0, which reflects the original geological map. Note the addition of the Dinding Formation in the northeast which was not previously mapped. (C) Synthetic cross-section slice through 3DKL v1.0.

of the model—dominated by Kenny Hill Formation and a single unit of Kuala Lumpur Limestone—and the abrupt southwards change to a region where the Kuala Lumpur Limestone occurs both to the west and the east of Kenny Hill Formation strata. The NNE–SSW-trending boundary between Kuala Lumpur Limestone and Kenny Hill Formation in the central-eastern part of the model is likewise portrayed, in the model as a fault, though it is not shown as such on the draped geological map.

Where not faulted—and therefore portrayed in 3DKL v1.0 as a vertical boundary—the other geological unit boundaries are typically portrayed as steeply dipping but have been 'shaped' where data are available from structural measurements on the geological map (Geological Survey Malaysia, 1976). The model volume can be sliced along any chosen transect: Figure 14C illustrates such a slice through the Kuala Lumpur subsurface, which highlights the possibility that an undisturbed (i.e. un-faulted) intrusive contact between the 'Western Belt Granite' and the Kuala Lumpur Limestone can be very irregular in both the horizontal and vertical frame (i.e. in 3D). The contact between the 'Western Belt Granite' and the Kenny Hill Formation strata in the same transect is apparently much more regular and planar, and steeply-dipping, in this case. The linear (almost straight) surface trace of this boundary reflects its steep dip, perhaps indicating that this contact might best be considered and interpreted as a faulted boundary, although it is not shown as such on published geological maps (Geological Survey Malaysia, 1976; Minerals and Geoscience Department Malaysia, 2011). Indeed, it is possible that such a fault could continue further to the south-southwest, defining the western boundary between Kenny Hill Formation and Kuala Lumpur Limestone strata in that region.

DISCUSSION

3DKL v1.0 has demonstrated proof-of-concept: we have developed a workflow, based largely on freely-available open-source software, for transforming borehole information previously captured in paper records into a 3D model using a SQLite borehole database, QGIS, Groundhog Desktop and Leapfrog.

At the time of modelling, no freely-available 3D modelling software was available to the project team and so Leapfrog was chosen due to a combination of cost and usability. Today, however, that component of the workflow could be replaced with a range of open-source or freely available alternatives such as Groundhog Desktop v2.8, GemPy (de la Varga, 2019; Schaaf *et al*., 2021), Loop (Ailleres *et al*., 2019; Jessell *et al*., 2021) and Visual Karsys (Malard *et al*., 2019; Kelsey & Valentina, 2022). A wide range of commercially available software could also be utilised, such as GeoModeller, GeoScene3D, GoCAD, Maptek Vulcan, MOVE, Petrel, etc.

Other software within the workflow can also easily be replaced with existing commercial or freely-available software. For example, the:

- borehole database software by SQL Server, MySQL, PostgresQL, or even a dedicated borehole data management software such as gINT;
- GIS software by ArcGIS, Hexagon Geomedia, MapInfo, etc;
- and cross-section modelling software by Geopropy (Hassanzadeh *et al*., 2022) as well as many of the commercial 3D modelling software identified above.

The workflow developed here lends itself to iteration, whether this be through the addition of new borehole data to revise existing cross-sections or to generate new ones in Groundhog, or the addition of new borehole data and cross-sections to Leapfrog to generate new 3D geological unit volumes. The capacity for iteration within the workflow will help ensure that geological models of Kuala Lumpur can continue to evolve as the quality and quantity of baseline geological data and geological knowledge grows.

The development of the modelling workflow and creation 3DKL v1.0 has also proved a valuable exercise for identifying existing geological data and knowledge gaps, which provides a direction for future research into the subsurface geology of Kuala Lumpur.

Lessons learned

While 3DKL v1.0 has successfully captured the principal features of the bedrock geology Kuala Lumpur, it incorporates a significant number of assumptions about the nature and thickness of these units and their relative spatial and temporal relationships. It also entirely omits the superficial and artificial deposits, which are a key feature in the subsurface and of importance for urban development. The lack of refinement within the final model can be almost exclusively attributed to a paucity of input data and existing geological knowledge gaps.

Data gaps

Due to the limited time available to complete the model during the second workshop, only 278 of the 621 boreholes available were coded for lithology and stratigraphy and used to derive 3DKL v1.0. However, even if all the remaining 343 boreholes were to be included, this would still only provide coverage of approximately 2.5 boreholes per square kilometre. This is typically half to a tenth of the desirable density for a ‘systematic model’ and two orders of magnitude less than desirable for a ‘detailed model’ (*cf.* Culshaw, 2005). Of additional significance is the nature of the site investigations, which produce a non-uniform city scale borehole distribution; boreholes tend to be focussed along linear corridors for infrastructure development, or are densely clustered in small and isolated areas to support the development of buildings. Furthermore, the depth of site investigation boreholes is significantly less than the 300 metres that 3DKL v1.0 extends to: 90% of the boreholes used in this study were less than 60 metres deep and the maximum borehole depth was only 131.5 metres. Significantly more boreholes, and importantly much deeper boreholes, are therefore required if 3DKL is to graduate from an ‘overview model’ (suitable for education or general catchment assessments) to a ‘systematic model’ or ‘detailed model’ that can support groundwater resource evaluation, urban development and project planning.

Other significant geological data gaps relate to the availability of detailed surface geological data, specifically:

- superficial deposit mapping to help constrain the extent of alluvium at surface;
- historical land use maps to help constrain the nature and extent of artificial deposits;
- a greater number and more extensive distribution of structural measurements to better constrain bedding geometries within units and non-faulted unit boundaries;
- and detailed structural geology mapping to better constrain the geometry of faulted unit boundaries and the overall distribution of discontinues within the subsurface.

Knowledge gaps

A much more rigorous geological knowledge-base is required to answer the many geological unknowns identified by this pilot study. Among the most important of these are:

- Can the depth to the ‘Western Belt Granite’ below the surface extents of the Kuala Lumpur Limestone and Kenny Hill Formation strata be better determined?
- Can the nature of geological boundaries between the Kenny Hill Formation and Kuala Lumpur Limestone be better determined over a wider extent in the subsurface?
- Likewise the relationships between the Dinding, Hawthornden, and Kuala Lumpur Limestone strata?
- As the model is extended laterally, how should the units assigned to the Kajang Formation/’Kajang Schist’ be portrayed in relation to the other strata?

- Can the lateral variation in thickness and lithology be better determined for the Kenny Hill Formation?
- What is the kinematic model that best explains the observed patterns of faulting and how can that model be used to better predict the occurrence of other significant faults and fracture systems (damage zones) affecting the bedrock geology of Kuala Lumpur
- How is the regional-scale (Indosinian) orogenic-scale deformation reflected in the evolution of the bedrock geology of Kuala Lumpur, its inherent fracture systems and tectonic fabrics, and critically in the physical and mechanical properties of the subsurface rock mass?
- How can the extent, thickness, and nature of superficial and artificial deposits be better constrained and more accurately modelled?

Future work

To address the borehole data gaps identified by this study, JMG propose that, in addition to boreholes received as part of the current planning process in Kuala Lumpur, they will also use the Geological Survey Act 1974 (Azizi, 2019) to obtain copies of all site-investigation-related excavations (including boreholes, trial pits and probing) and enter these into a central borehole database. Data sharing agreements are also proposed with other national and local government departments with subsurface interests to further enrich the geoscience data and information held by all parties. This includes the Ministry of Federal Territories (Kementerian Wilayah Persekutuan, KWP), the Public Sector Data Centre (PDSA) of Malaysian Administrative Modernisation and Management Planning Unit (MAMPU), Kuala Lumpur City Hall (Dewan Bandaraya Kuala Lumpur, DBKL), the Public Work Department (Jabatan Kerja Raya, JKR), the Department of Irrigation and Drainage (Jabatan Pengairan Dan Saliran, JPS), the National Water Research Institute of Malaysia (NAHRIM), the Department of Environment (Jabatan Alam Sekitar, JAS), Sewerage Services Department (Jabatan Perkhidmatan Pembetungan, JPP) and other national and states agencies. The development of a national-scale borehole database would not only support future iterations of 3DKL, but could also be used to:

- support expansion of 3DKL to the whole of Greater Kuala Lumpur;
- the development of 3D geological models in other urban centres in Malaysia;
- and broader research into the engineering and hydrogeological properties of geological units throughout Malaysia.

The acquisition of additional site investigation boreholes alone will not be enough to address all the data and knowledge gaps identified by 3DKL v1.0. Consequently, we also consider that a coordinated city-scale ground investigation programme is also required. It would be preferable for this to be undertaken by a consortium of geoscientists from government, industry and academia to make best use of the different resources available within each sector. Projects and tasks to be undertaken could include:

- acquisition of targeted and deeper (300 m+) exploratory boreholes designed to allow the bedrock geology to be modelled with greater confidence at depth in future iterations of 3DKL. These boreholes would also allow the range of unit thicknesses to be quantified with greater certainty;
- acquisition of inclined boreholes orientated to intersect significant faults and unconformity surfaces, therefore allowing the nature and geometry of such boundaries to be determined with greater certainty;
- a programme of geological mapping designed to enhance knowledge of the geometry, inter-relationships, and distribution of bedrock, superficial, and artificial units at surface and in in the subsurface;
- a comprehensive in situ and laboratory testing programme designed to enhance the understanding and characterisation of the geotechnical and hydrogeological properties of the superficial and bedrock units of Kuala Lumpur;
- application of remote sensing technologies to compliment field mapping of surficial units, and to identify ground motion associated with shallow geohazards such as landslides, karst and compressible deposits;
- and geophysical surveys to compliment borehole investigation, particularly the identification of subsurface karst features, major geological boundaries and fault zones.

A similar urban geoscience investigation programme has recently been completed by the Building and Construction Authority in Singapore (Gillespie *et al.*, 2019; Leslie *et al.*, 2019; Dodd *et al.*, 2019, 2020; and Chua *et al.*, 2020) and another is proposed by the General Department of Geology and Minerals of Vietnam (GDGMV) for the city of Hanoi (McKenzie *et al.*, 2018).

Future development of 3DKL

This paper describes the development and generation of the first iteration of a 3D geological model for Kuala Lumpur. Many further iterations, and variations that support applied geology, will be required if 3DKL is to truly fulfil its potential to support more sustainable and resilient urban development in Kuala Lumpur. Future steps that should be taken to improve the model, modelling workflow, and application of the model include:

- routinely updating the model with additional geological data (such as boreholes records, surface mapping datasets, and tunnelling records) to enhance the model and keep it up to date;
- expanding the model to include the whole of Greater Kuala Lumpur to support city-catchment and regional-scale planning and resource evaluation;
- developing a more high-resolution version of the model

within the top 50 m, and particularly the addition of superficial and articial deposits to support the integration of geological and geotechnical data within Building and City Information Models.
- exploring model parameterisation and the development of applied geological models using parameters readily-found in borehole data (such as groundwater levels, weathering grade, SPT, and RQD) to broaden the application of the model;
- creating model variations that recast stratigraphical units as lithological, engineering geological, or hydrogeological units, so that 3DKL can be made more readily applicable and meaningful to those outside the geoscience community;
- and exploring the application of alternative low-cost or freely-available open-source 3D modelling software to reduce the cost of 3D modelling and ensure the modelling workflow is more accessible to others (e.g. Groundhog Desktop v2.8, GemPy or Loop).

CONCLUSIONS

3DKL v1.0 has demonstrated proof-of-concept: we have developed a workflow, based largely on freely-available open-source software, for transforming borehole information, previously captured in paper records, into a digital 3D geological model. Importantly, the modelling methodology developed appears to be well-suited to the creation of 3D geological models where only sparse borehole data are available. The combined semi-deterministic approach—which uses deterministic cross-section interpretations produced in Groundhog with implicit modelling in Leapfrog— allows borehole data gaps to be filled using expert geological knowledge and understanding. For many cities, particularly those in the Global South where access to subsurface urban geological datasets may be limited, this approach offers a cost-effective and robust solution for the construction of informative 3D geological models.

While 3DKL v1.0 is only a first draft, it successfully captures the principal features of the bedrock geology and provides an 'overview' model for Kuala Lumpur (*cf.* Culshaw, 2005). In addition to providing a starting point for future iterations of 3D geological models in Kuala Lumpur, 3DKL v1.0 can also easily be expanded, using the same modelling workflow, to produce a regional-scale 3D geological model of Greater Kuala Lumpur. Finally, 3DKL v1.0 also has the potential to provide a foundation for future applied 3D geological models by reattributing the stratigraphical unit volumes with engineering and hydrogeological units derived from in situ and laboratory test data. Developing a more high-resolution version of the model within the top 50 m would also facilitate integration of geological and geotechnical data within the Building and City Information Models, which will become more established in the civil engineering and planning communities in future.

The development of 3DKL has effectively highlighted areas where local geological knowledge can be enhanced and where more data are required to develop a more robust understanding of the subsurface geology of Kuala Lumpur. Significant further work is required to develop 3DKL v1.0 from an 'overview' model, capable of communicating conceptual geology at a regional-scale, to a 'systematic' or 'detailed' model that is capable of integration with Building and City Information Models, and truly usable for urban planning and management (*cf.* Culshaw, 2005). We consider the best way of addressing existing knowledge and data gaps in Kuala Lumpur is to:
- significantly expand the borehole database by acquiring copies of all recent, and any future, site-investigation records in Kuala Lumpur;
- and undertake a coordinated city-scale ground investigation programme involving geoscientists from government, industry and academia.

Ultimately it is our ambition that 3DKL enables more effective interaction between planners, developers, civil engineers and geoscientists in Kuala Lumpur, which in turn supports attainment of UN Sustainable Development Goal 11: to make cities and human settlements inclusive, safe, resilient and sustainable. A shared 'bigger picture' view of the subsurface is required by all those working within the urban development sector if we are to transition from responding to disasters and construction failures to predicting, pre-empting, and preventing them.

DATA AVAILABILITY

The 3DKL v1.0 model is included as a supplementary dataset with this article/available to download from.

Open-source software used as part of the digital workflow can be accessed as follows:
SQLite: https://www.sqlite.org/index.html
QGIS: https://qgis.org/en/site/forusers/download.html
Groundhog: https://www.bgs.ac.uk/technologies/software/groundhog/

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AUTHORS CONTRIBUTION

MRD, QAR, RBH, KL, AGL and ST contributed to the writing of the manuscript and preparation of the figures. All authors contributed to the development of the 3DKL workflow and participated in the development sprint to create 3DKL v1.0.

CONFLICT OF INTEREST

None.

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