International boundaries on a dynamic planet: issues relating to plate tectonics and reference frame changes

Don GRANT, Australia, William ROBERTSON, New Zealand and Vincent BELGRAVE, New Zealand

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SUMMARY

International boundaries, agreed directly between the nation states or through an international commission, are defined and demarcated in a number of ways on land or in marine areas. These include: coordinates expressed in terms of a local or global geodetic reference frame, lines depicted on maps or charts, physical monuments (either on the boundary or with the boundary defined in relation to nearby monuments) or by natural features. Such boundaries, once agreed, accepted and demarcated, can generally be expected to be in place for a very long time - at least decades and potentially centuries. As our ability to define positions (including boundaries) accurately in a global frame improves, we also become increasingly aware that no point on the surface of the Earth can be truly considered to be "fixed" in place - due to pervasive tectonic plate motion. Furthermore, in response to this tectonic motion, the global and local reference frames used for positioning, mapping and coordination change much more frequently than international boundaries are renegotiated. This paper looks at the geodetic and geophysical issues that earth dynamics may impose on the reliable and enduring definition of international boundaries. A case study of the Iraq Kuwait boundary is used to illustrate these issues. The role that earth dynamics plays in modern geodetic positioning should be considered at an early stage of international boundary determination.

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1. INTRODUCTION

In this paper, we explore issues relating to the impact of plate tectonics on international boundaries that have been defined in terms of a geodetic reference frame. While these issues are usually insignificant in the short term (a few years) there are a number of issues that can potentially cause ambiguity and conflict in the long term if not well managed at the time of negotiation.

Whether or not these issues and ambiguities will become serious over time depends on a number of factors such as the hierarchy of definitive evidence of boundary location; the nature of tectonic motion in the vicinity of the boundary and the form of geodetic reference frame used to gather information and document the boundary location.

2. INTERNATIONAL BOUNDARIES

2.1 Process and Timeframe of Definition

Many international land boundaries have their origins in historic occupation and agreements stretching back a century and more. The authority for establishing international boundaries rests with the territorial parties themselves and bilateral agreement on international boundaries is the norm. The delimitation descriptions can define the boundary in relation to geographical features such as mountains, dividing ranges, hills or valleys, lakes, river and inlets of the sea.

Over time international boundary agreements are refined by demarcation and confirmed by occupation and administrative control. The delimitation and demarcation process is lengthy and demanding even for seemingly small issues. Once the boundaries are finally demarcated and accepted the influence of international boundaries on occupation, settlement and administration will the last for centuries.

2.2 Forms of Survey Definition

The practice of accurately surveying and mapping international boundaries has only become common in the nineteenth century. The Canada/USA boundary in the first half of the 1800s and boundaries of the old British and Spanish Empire colonies are some examples. These boundary determinations include the identification of natural features and demarcation with boundary monuments defining the boundaries. More recently geodetic datum have been used to tie survey positioning to a unique geodetic reference frame. A new boundary datum provides a neutral and up-to-date reference system.

The Iraq Kuwait Boundary Datum (IKBD), Eritrea Ethiopia Boundary Datum (EEBD) and Cameroon Nigeria Boundary Datum (CNBD) are all examples of the establishment of an independent geodetic boundary datum separate from the datum of each party. The legal boundary along the Iraq/Kuwait border is defined by the coordinates submitted to the Secretary General of the United Nations. This boundary is also marked with substantial monuments but the coordinates held by the UN are definitive. Similarly, the Eritrea Ethiopia Boundary is defined by the coordinates provided by the Eritrea Ethiopia Boundary Commission on the completion of its work.

The pre-eminence of monuments as the definition of boundary positions is now being brought into question by superior coordinates and measurements and changing needs. For maritime boundaries, coordinates are the norm and these can vary greatly in reliability and in the ease of reinstatement.

This wide range of descriptive, surveying and mapping definitions of international boundaries have served the practical purposes of their times. However, in a world of globalization and efficient national development, every nation needs to ensure and maintain the integrity of its borders. This need is particularly evident where international boundaries divide significant resources such as oil fields, water resources, fertile lands etc.

2.3 Positioning Challenges Ahead

The role of clearly defined territorial boundaries in enabling positive international relations and effective governance and resource management are well established. However, the demands for security and integrity on international boundaries are escalating through the application of new technology and increased scientific knowledge of the dynamics of global tectonic movement. These advances present a number of challenges that need to be addressed in the demarcation and maintenance of international boundaries.

The assumptions of the past, that international boundaries were established on a stable earth, are well superseded by increasing knowledge of the tectonic plate movement and deformation. This tectonic movement can impact on the international boundaries, particularly where coordinates provide the legal definition of a boundary. The annual rate of tectonic plate movement is of positioning significance and over decades or centuries it accrues to a readily observable amount.

3. PLATE TECTONICS

3.1 Developing Theory of Plate Tectonics

The idea of “Continental Drift” – later Plate Tectonics - developed through the 20th Century. It began as a controversial and speculative theory (Wegener, 1929) with no obvious mechanism for causing the proposed movements. Now it is a fully formed model of earth dynamics confirmed by geodetic, seismic and geological evidence (Oreskes, 2008).

The impacts on cadastral boundaries within a country are increasingly recognised and can managed by the government. For example, in New Zealand, the legal response to movements of property boundaries resulting from the Canterbury earthquake sequence is encapsulated in the Canterbury Boundaries and Related Matters Act 2016.

The broad acceptance of plate tectonics as a working model of solid Earth dynamics, overwhelmingly supported by both geodetic and geological evidence, means that it is clearly recognised that movement not only occurs episodically on fault lines at the time of major earthquakes but also continuously, slowly and imperceptibly to most observers.

3.2 Magnitude of movements

The movements of tectonic plates are typically several centimetres per year. This may seem to be an insignificant problem for international boundary determination. However, expressed as several metres per century – then the potential problem can more easily be seen. At the time a modern international boundary is defined, especially on land, the negotiating parties will usually seek to have the boundary surveyed and defined. An accuracy of several centimetres may be sought in which case it may take only a few years of tectonic plate movement to exceed the survey threshold.

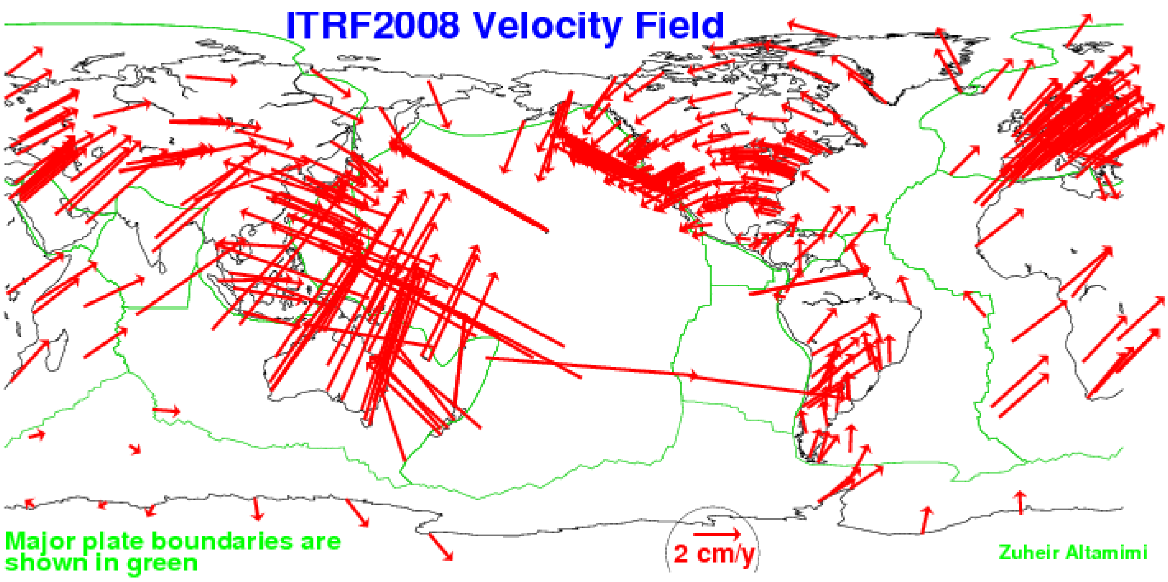

Figure 1: Velocities of geodetic observations stations in terms of ITRF2008
(retrieved from http://itrf.ensg.ign.fr/ITRF_solutions/2008/ITRF2008.php)

Depending on how the definition of the boundary has been expressed in the agreement, it would be possible for tectonic plate movement to have the effect of causing the agreed boundary line to appear to inexorably creep across the land as a steady encroachment, small but increasing year by year. One party to the agreement may become aggrieved by this apparent encroachment while the other party may be in no rush to resolve a situation that slowly works to their advantage.

As an example of potential value associated with boundary location, statistics on the Rumaila oilfield (http://www.rumaila.iq/english/the-oilfield.php), which crosses an east-west section of the Iraq Kuwait boundary indicate reserves of 17 billion barrels of oil in a field that extends 80km north south. Assuming a value of US$50 per barrel gives a rule of thumb value of over US$10M for every metre of boundary movement in the north-south direction.

The only mechanism to resolve this situation would be to renegotiate a boundary that had been thought to be resolved. A better approach would be to consider this scenario at the outset and define the boundary in such a way that future disputes are avoided.

3.3 International boundaries potentially affected by plate tectonics

3.3.1 Marine boundaries

It can be seen in Figure 1 that the great majority of tectonic plate boundaries are in deep ocean areas where accurate positioning and physical occupation is problematic. However even in these cases, international maritime boundaries can be affected. For example, ocean boundaries may account for extensive oil reserves in basins with a resource sharing agreement based on the area allocated to each country. An example of this is the 1989 treaty between Australia and Indonesia. (http://www.austlii.edu.au/au/other/dfat/treaties/1991/9.html)

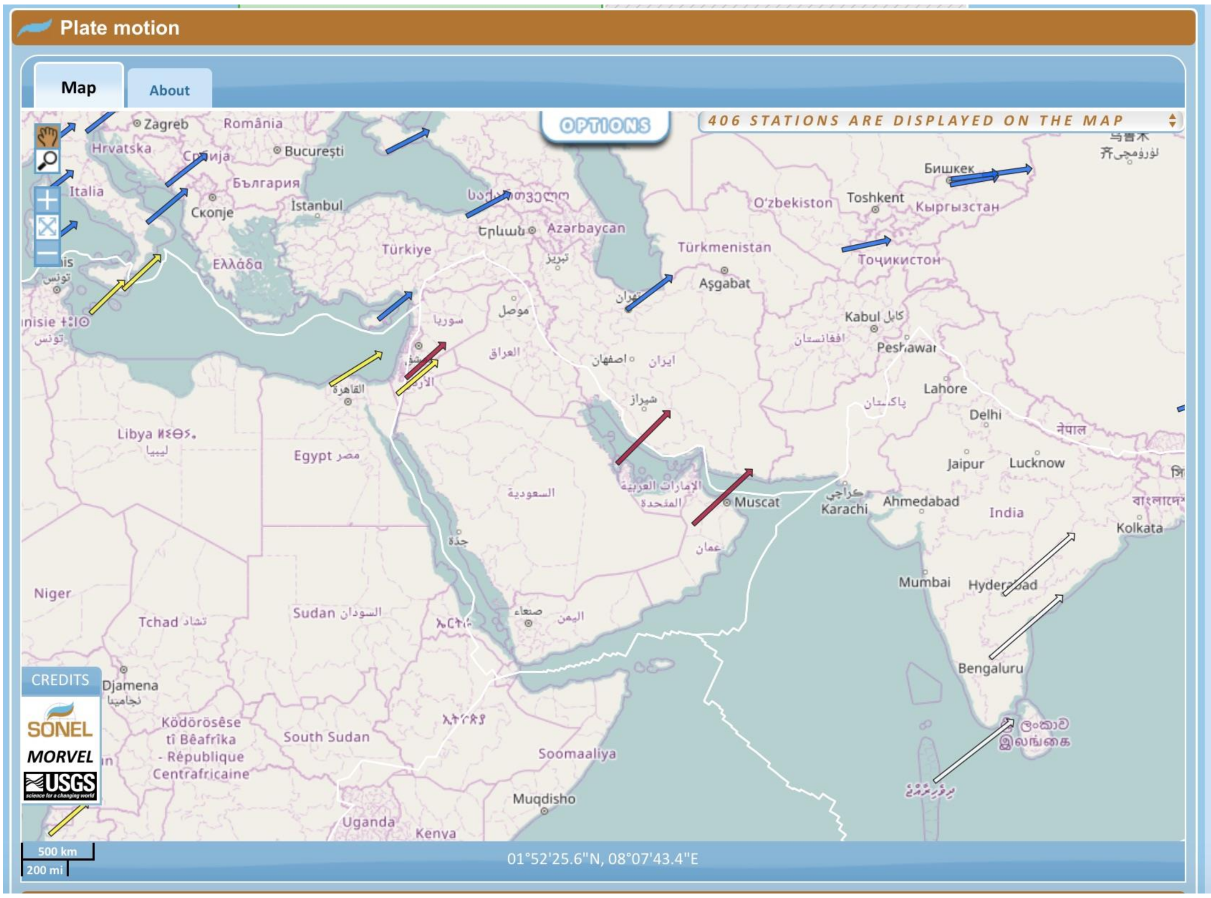

Figure 2: Complex relationships between the boundaries of the Arabian tectonic plate (plate boundaries shown in white) and international boundaries in the region (shown in purple). (Retrieved from http://www.sonel.org/-Horizontal-land-movements-.html)

3.3.2 Land boundaries

Some international boundaries on land also cross tectonic plate boundaries (Figure 2). Over time, straight lines could have a slowly developing offset or step in the formerly straight boundary line. This may occur either slowly as a result of gradual tectonic movement of a few centimetres per year, or suddenly as a result of a major earthquake.

We see in Figure 2 that he tectonic plate boundary between the Arabian plate and the Eurasian plate crosses the international land boundaries of Iran-Iraq, Iraq-Turkey and Turkey-Syria while the Arabian and African tectonic boundary crosses the land boundaries of Syria-Lebanon, Lebanon-Israel, Israel-Egypt, Eritrea-Ethiopia and Ethiopia-Djibouti.

4. REFERENCE FRAMES

4.1 International Terrestrial Reference Frames

The International Terrestrial Reference System (ITRS) is managed by the International Earth Rotation Service (https://www.iers.org/IERS/EN/DataProducts/ITRS/itrs.html). This idealized reference system is periodically realized by International Terrestrial Reference Frames. The two most recent frames are ITRF2008 (Altamimi et al, 2011) and ITRF2014 (Altamimi et al, 2016).

These reference frames incorporate a model of tectonic plate motion. The motions of tectonic plates are defined as rotations about a pole of rotation. In the models used to define the ITRFs, no point on earth is considered to be "fixed". No plate is considered to be motionless while all other plates move around it. The ITRF uses a constraint that all plate rotations are averaged to zero, known as the No-Net-Rotation (NNR) model (DeMets et al 1994).

The ITRS and its sequence of ITRFs, starting with ITRF1989, are increasingly relied on for national and international positioning. The importance of the ITRFs was recognised by the United Nations (United Nations, 2016) with a General Assembly Resolution 69/266 on the Global Geodetic Reference Frame (GGRF).

Increasingly, national, regional and global geospatial datasets will be defined in terms of an ITRF. Global Navigation Satellite Systems (GNSS) such as GPS provide positions on Earth in terms of reference frames (such as WGS84) which are kept in close alignment with the latest ITRF. Many historical international boundaries have been specified in terms of national or regional geodetic datums and reference frames. However, in the future, the mapping and geospatial data that underpins international boundaries, and the positioning systems that allow people to locate themselves in relation to international boundaries will see an increasing move towards the use of ITRFs under the umbrella of a United Nations supported Global Geodetic Reference Frame (GGRF).

4.2 National / Regional Reference Frames

4.2.1 Plate Fixed Frames

The ITRF frames are known as dynamic because all points fixed to the surface of the Earth have not only defined positions (coordinates) but also velocities. The velocity at a point generally reflects the tectonic plate motion in relation to the coordinate reference frame.

Several modern national or regional geodetic datums are based on ITRF but are "plate fixed" datums. These are generated by generating coordinates in terms of an ITRF at a specified point in time – known as the reference epoch. From that time on the coordinates (unlike those of the defining ITRF) remain unchanging.

What this means for a plate fixed datum is that the datum effectively moves as the plate moves. The coordinates of all points in that datum can remain unchanging because those points move along with the tectonic plate.

This has an advantage that there will be no visible movement of an international boundary defined by coordinates over the surface of the Earth.

It has a disadvantage that a plate fixed national datum is subject to periodic review and replacement when it becomes too far removed from the latest ITRF used for positioning and geospatial datasets. This review means that the boundary will continue to be defined in terms of a reference frame that is no longer in general usage for survey or geospatial data.

4.2.2 Definition of Plate Fixed Frames

Plate fixed frames were traditionally defined, in practice, by the fixed coordinates of a number of primary geodetic control stations. Prior to the use of Global Navigation Satellite Systems (GNSS) these coordinates were typically based on one or more origin stations derived from astronomical observations of the stars. Examples of classical astro-geodetic datums or reference frames are New Zealand Geodetic Datum 1949 (NZGD49) and Australian Geodetic Datum 1966 (AGD66).

The advent of the Transit doppler system for satellite positioning provided an alternative to geodetic astronomy. This allowed geocentric coordinates with a few metres accuracy to be determined for primary geodetic control stations to define the datum or reference frame origin. Examples of reference frames that made use of Transit doppler observations are Australian Geodetic Datum 1984 (AGD84) and – in an international boundaries context – the Iraq-Kuwait Boundary Datum 1992.

More recently geodetic datums and reference frames are often based on one of the International Terrestrial Reference Frame (ITRF) realizations of the International Terrestrial Reference System (ITRS). Coordinates of a plate fixed reference frame are observed using GNSS and calculated to be in terms if a specified ITRF at a specified date (epoch). Examples of ITRF plate fixed reference frames are:

- Geocentric Datum of Australia 1994 (GDA94) which is based on ITRF1992 at 1 January 1994 (epoch 1994.0)
- New Zealand Geodetic Datum 2000 (NZGD2000) which is based on ITRF1996 at 1 January 2000 (epoch 2000.0).
- Geocentric Datum of Australia 2020 (GDA2020) which will be based on ITRF2014 at 1 January 2020 (epoch 2020.0)

4.3 Impact on Boundary Positions

The historic option for managing long term boundary positions has been to assume the stability of boundaries over time. This approach works until earth movements are of such magnitude that ad hoc local solutions no longer suffice. The serious disadvantage of accepting historic positioning is that the coordinated positions become increasingly at variance with the modern measuring capability of users. In addition, differential tectonic movement across the boundary line can cause ambiguity and dispute.

If the boundary is defined by the positions of monuments or physical features, then the boundary will, in effect, move with the tectonic plate. This will cause the least disruption to management of the boundary because there will be no apparent movement.

However natural features can move in relation to the local environment and boundary monuments can be damaged or destroyed. In this case, a boundary maintenance program is likely to recommend reinstatement. If this reinstatement relies on historical survey measurements or coordinates, combined with modern global positioning technology, then ambiguities in interpretation and survey conflicts may result.

An alternative is to establish a plate fixed geodetic datum to define the boundary coordinates. This means that the boundary will not appear to move in relation to the local landscape while allowing unambiguous reinstatement of damaged or destroyed boundary monuments using the geodetic datum.

This option however places great reliance on the geodetic datum itself, which must be maintained to ensure that it remains accessible and useable.

As noted above, there are 2 options for establishing a plate fixed geodetic datum:

1. Establish a geodetic mark based network in general alignment with the ITRF and rely on the defined coordinates of one or more primary control stations to define the datum
2. Specify an ITRF and a reference epoch. For example, ITRF2014 at 1 January 2014.

The utility of option 1 depends on continued protection and maintenance of the geodetic control stations that define the network. Any loss of those stations imperils the whole boundary definition.

Option 2 provides more long term security because the international community protects the definition of International Terrestrial Reference Frames, including precise transformations from each ITRF to the next one. This option requires an accurate connection, ideally at the few centimetre level at least, between the geodetic network used to measure and monitor the boundary, and the ITRF used to define it.

It should be noted that each of these plate-fixed options will, over time, result in the boundary coordinates becoming increasingly out-of-terms with local surveying and mapping systems including geospatial datasets and personal positioning devices. However, provided that accurate transformations are available between the reference frame of the definitive boundary coordinates, and the more commonly used coordinate systems, this issue is manageable.

5. CASE STUDY: IRAQ-KUWAIT BOUNDARY

5.1 Original Geodetic & Boundary Survey

The survey definition of the Iraq Kuwait boundary is described in Belgrave, 1995, Grant & Olsen, 1994 Grant 1995, and Pinther, 2013.

During the period 1991-1994 a total of 105 boundary pillars (plus one existing) and 28 intermediate boundary pillars were constructed and surveyed along the boundary by surveyors from the Department of Survey and Land Information (NZ) and Swedesurvey (Sweden) along with engineering contractors. The original 1992 specification for boundary pillars was that the true position must be within 200mm of the specified coordinate.

As noted earlier, the coordinates submitted to the Secretary General of the United Nations –define the legal boundary along the Iraq/Kuwait border – not the pillars that were placed with those coordinates. Therefore, the geodetic datum is crucial to the boundary definition.

The geodetic datum Iraq Kuwait Boundary Datum 1992 was an independent datum that established marks on both sides of the boundary. Transit Doppler observations were made at 4 datum stations – 2 in each country. These provided a connection to WGS84 in an average sense with a coordinate accuracy (1σ) estimated at 0.75m in each axis (Grant, 1995). WGS84 is close to, although not identical to, the sequence of ITRFs.

GPS observations then accurately connected the datum stations to each other and to a network of primary and secondary control stations around the boundary. In relative terms, these stations were all accurate to the centimetre level. The boundary pillars were then precisely connected to or set out to be in terms of the primary stations and thus the datum.

At the time of the IKBDC survey, neither the state of surveying technology or the advances in the knowledge of tectonic movement were sufficiently advanced for a precise datum shift between IKDD92 and ITRF (such as could be determined today) to be identified in the boundary definition.

5.2 Maintenance of Boundary Marks

The Commission made recommendations to the Secretary-General of the United Nations to allow for ongoing maintenance of the pillars and markers of the international boundary including the ability to emplace additional markers if required. It was not within the scope of this project to provide an updated reference system for the survey. Nor was it within the scope to assess the global accuracy of the original datum. A project to undertake the maintenance work in 2013 is described in Belgrave, 2015.

All 106 main pillars were visited and inspected for damage. Of these, 72 had missing or damaged centre plaques that required replacing. In addition, 3 main pillars were considered too badly damaged to be repaired and were noted for replacement.

Selected stations in the primary and secondary networks were resurveyed by GPS. The boundary pillars were then connected by GPS survey directly or indirectly to the primary and secondary control networks.

One of the four original datum stations (D12) was located in an abandoned UN camp in the south of the border area and was in surprisingly good condition. A second datum Station (NGN-43) near Kuwait City was not searched but may be still available.

5.3 Implications for the Boundary Datum & Coordinates

The integrity of the Iraq Kuwait boundary depends on the ability to re-establish the location of the original definitive coordinates. This in turn depends on the ability to reliably re-establish the IKBD92 in terms of which those coordinates are defined.

While re-establishment of the datum was not within the scope of the 2013 maintenance project, nevertheless some conclusions can be drawn:

- Only one of the original 4 datum stations was recovered. A second one may be available. Nevertheless, the location of the datum is at risk of being lost.
- The original 1992 survey specified accuracy at the 200mm level for boundary pillars but the connection between IKBD92 and say ITRF2014 is not known to that level of accuracy. The uncertainty at 95% confidence is approximately 2 metres.
- The 2013 maintenance project has, in effect, used the primary network to re-establish the datum that the primary control mark coordinates were derived from. This was made necessary due to the loss of at least 2 datum stations. This reverse engineering to locate the datum is effective although a further loss of accuracy can be expected.

6. CONCLUSIONS

It is increasingly common for geodetic survey to form part of the definition of modern international boundaries. The form of definition can vary but nevertheless the negotiations for delimitation, demarcation and maintenance should take into account the long-term characteristics of the geodetic datum used to support or define the boundary. This will include consideration of:

- The global rather than local nature of modern geodetic datums
- The ability to define coordinate reference frames with an accuracy of a few centimetres or better
- The impact of tectonic plate motion and other forms of earth deformation on geodetic systems
- The increasing use and security of a Global Geodetic Reference Frame (GGRF).
- The need for program of boundary and geodetic datum maintenance in terms of the GGRF.
- Mechanisms for maintaining alignment between boundary coordinates and other survey and geospatial datasets in use in each jurisdiction.

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BIOGRAPHICAL NOTES

Don Grant was the New Zealand Surveyor-General from 2004 to February 2014. He holds a BSc Honours in Physics from Canterbury University, a Diploma in Surveying from Otago University and a PhD in Surveying from the University of New South Wales. He registered as a surveyor in New Zealand in 1979 and is currently registered as a Licensed Surveyor in Victoria. From 1991-93 he was Chief Geodesist for the UN Iraq Kuwait Boundary Demarcation Commission. Don was elected as a Fellow of the NZ Institute of Surveyors in 2007, is New Zealand's delegate to FIG Commission 7 and Chair of Commission 1 Working Group 1.3 International Boundary Settlement and Demarcation. In 2014 he took up the position of Associate Professor at RMIT University.

William (Bill) Robertson was New Zealand Director-General and Surveyor-General from 1987 to 1996. He has been Chairman of NZ Aerial Mapping, 1999 -2001, Aspect North, Lismore, NSW2001-2003, and Terralink International 2002 -2014. He is a Registered Surveyor, and holds a Diploma in Town Planning from Auckland University, Master of Public Policy from Victoria University, Wellington and has an Honorary Doctorate in Surveying from Melbourne University. He was a Commissioner on the UN Iraq/Kuwait Boundary Demarcation Commission, a Special Consultant to the Eritrea/Ethiopia Boundary Commission, a Senior Consultant to the Cameroon/Nigeria Mixed Boundary Commission, Senior Consultant to the Permanent Court of Arbitration Sudan Tribunal and Consultant on the Kuwait/Saudi Arabia International Boundary Project. Bill is a Fellow of the NZ Institute of Surveyors and a Fellow of the NZ Planning Institute. He was appointed an Officer of the NZ Order of Merit (ONZOM) in 2008 for services to surveying.

Vincent Belgrave has a Diploma in Surveying from Otago University and registered as a surveyor in New Zealand in 1979. From 1991-94 he was the Chief Surveyor for the UN Iraq Kuwait Boundary Demarcation Commission. From 2001-2005 he was Chief Surveyor for the Eritrea Ethiopia Boundary Commission based in Asmara, Eritrea with the United Nations. Vince also worked for the United Nations on the Israel/Lebanon boundary and Cameroon/Nigeria boundary. He was appointed as an Expert to the Permanent Court of Arbitration Sudan Tribunal in 2009 and from 2010-2013 he was project manager on the Kuwait/Saudi Arabia International Boundary Project. Vince is currently project manager for the digital mapping of Kuwait, a 3 year project starting this year and Director of Sounds Surveying Ltd.

CONTACTS

Assoc. Prof. Don Grant,
School of Science,
RMIT University,
GPO Box 2476
Melbourne,
VIC 3001
AUSTRALIA
Tel. +61 3 9925 2424
Email: donald.grant@rmit.edu.au
Web site: http://www1.rmit.edu.au/staff/don-grant

William Robertson

Director of Bill Robertson & Associates
3 Eskdale Rd.,
Porirua 5024,
NEW ZEALAND
Tel. 64 4 233 1768
E-mail: billrobertson@xtra.co.nz

Vince Belgrave
Director of Sounds Surveying Ltd
297E Waikawa Road
Picton 7220
NEW ZEALAND
Tel: +64 3 5735446
Email: vincebelgrave@gmail.com