INTRODUCTION

The West African Craton (WAC) consists of two Archean nuclei in the north-western and south-western parts of the craton juxtaposed against an array of Palaeoproterozoic domains made up of greenstone belts, sedimentary basins, domains of extensive granitoid-TTG plutons and large shear zones, which are overlain by Meso- and Neoproterozoic and younger sedimentary basins (Bessoles, 1977; Feybesse et al., 1989; Feybesse and Milési, 1994; Kouamélane et al., 1997; Caby et al., 2000; Hirdes et al., 1992). The region has a thousand-year history of gold mining, and numerous gold deposits are shown in the 1934 Gold Coast Geological Survey map of what is now southern Ghana (Junner, 1934). The WAC is typically referred to as a gold province, although it also hosts world-class iron ore and bauxite deposits (Milési et al., 1992; Markwitz et al., 2016). As early as 1916, systematic regional geological mapping was being carried out by Henry Hubert, a French Government official working in what was then French West Africa (Hubert, 1934). A period of data acquisition by colonial and post-colonial geological surveys ensued, followed by collaborations funded by transnational agencies (principally the UN, the World Bank, and the European Union), which enabled regional maps and geophysical surveys to be compiled for much of the craton. Building on this information, the WAC has seen a major increase in exploration and mining activity over the last 10 years, which in turn has incited renewed research interest in the tectonics and metallogenesis of the highly prospective Palaeoproterozoic Birimian Terrane.
The AMIRA International P934 West African Exploration Initiative (WAXI) is a collaboration between the principal actors in the large-scale minerals sector of West Africa (Figure 1). The first (pilot) phase of the project ran from September 2006 to March 2008 (with 13 industry sponsors), the second phase ran from March 2010 until July 2013 (with 20 industry and government sponsors) and the third phase started in September 2014 and will run until August 2018 (with 13 industry sponsors to date). The overall aim of WAXI is to enhance the exploration potential of the West African Craton (WAC) through an
A comprehensive program of research and data gathering into its 'anatomy', and to augment the capacity of local institutions to undertake this form of work.

In the following sections, we summarize the principal research and capacity building outcomes of the project, which for ten years has supported the minerals industry via the acquisition and synthesis of exploration data, and supported West African institutions in the training of geoscientists and the management of exploration-focused geoscience data. This project has resulted in positive outcomes for all partners, and the lessons learned in this project help provide an improved model for collaborative research in developing countries.

THE NEED FOR INTEGRATED RESEARCH AND DEVELOPMENT

The Archean and Paleoproterozoic West African Craton extends over 2.5 million square kilometres, and is hosted by 13 countries that use three administrative languages1. Every country in the region shares at least one border with a country that uses a different administrative language. This has resulted in a fragmentation of effort and is a barrier to integrated research, as data are held by each country in different languages and formats, and with very heterogeneous levels of detail. Publically available syntheses are principally limited to harmonized regional-scale maps (e.g., Milési et al., 2004). The Paleoproterozoic granite-greenstone terranes represent one of the world’s most important gold provinces, with output increasing from approximately 50 t/year to 220 t/year between 1993 and 2103 (Goldfarb et al., 2017), and this period saw some countries, such as Burkina Faso, becoming significant gold producers for the first time.

The shared challenges facing geoscientists wishing to undertake scientific research in West Africa (from industry, governments and academia) include the limited flow of scarce government resources to STEM activities in general, and geoscience research in particular. In 2014, the Science, Technology, Engineering, and Mathematics (STEM) sector made up only 29% of all research in Sub-Saharan Africa (excluding South Africa, World Bank and Elsevier, 2014). National research priorities across Africa do include a range of activities related to geoscience research, in particular Energy, Natural Resource Management and Information and Communications Technology. Nevertheless, the low proportions of the Gross Domestic Product (GDP) spent on research in West Africa (often less than 1%) coupled with the overall low levels of GDP, mean that even as priority areas the available budgets are small, and funds available for basic research are limited. This contrasts with the significant revenue flow that many West African countries receive as the result of mining activity, and the costs of managing the environmental impacts of mining (and in particular by variably regulated artisanal mining).

The WAXI project has a series of overlapping research goals, and is globally aimed at improving our understanding of the tectonics, metallogenesis and landform evolution of the West African Craton. In parallel, the project aims to support the development of geoscience capabilities in the short, medium and long term. Immediate support for company staff improves their capacity to undertake exploration in the region; training geological survey staff improves their ability to provide geoscience data to end users, and scholarships and access to equipment for graduate students prepares them for work in all sectors of minerals geoscience, and trains the next generation of university lecturers.

RESEARCH ACTIVITIES

The WAXI research program was designed after a process of consultation with industry in a pilot phase, during which a detailed data and information audit and gaps analysis was carried out. Its main focus is on the collection and synthesis of geological, regolith, metallogenic, geochemical and geochronological datasets from across the WAC. The resulting research program comprises a set of integrated research modules, which are grouped into three themes: architecture and timing; mineralizing systems; and surface processes.

The results of the research program have been progressively published over the last ten years (see http://www.tectonique.net/waxi3 for a complete list of papers and access to the thesis collection), but in particular as four special issues that were compiled following the end of confidentiality for stage two of the project (Jessell and Liegeois, 2015; Jessell et al., 2016a; Hein, 2016; Goldfarb and André-Mayer, 2017).

Integrated Geophysical Analysis

The WAXI research program has taken a multi-scale approach to understanding the craton. At the largest scale, we have examined existing and newly compiled geophysical representations of the WAC in terms of its large-scale tectonic
architecture, which provides a framework for specific regional studies (Figure 2; Jessell et al., 2016b). The different geophysical methods suggest a partitioning of the WAC into two tectonic domains at the largest scale, based on seismic tomographic data, lithosphere–asthenosphere boundary models and long wavelength gravity signals. A single 450 km magnetotelluric and gravity profile was acquired across southwest Burkina Faso and north-west Ghana, which showed that many of the structures mapped at the surface extend deep into the crust and even into the upper mantle. (Le Pape et al., 2014).

At the belt scale a number of studies have integrated geological mapping with the interpretation of regional geophysical datasets (magnetics, gravity, radiometrics and in some cases electromagnetic data). These studies share a common geodatabase so that we can produce seamless maps across country boundaries and between belts (Figure 3; Tshibubudze et al., 2009, 2015; Baratoux et al., 2011; Metelka et al., 2011; Perrouty et al., 2012; Block et al., 2016; McFarlane, 2016). Combined with petrophysical acquisition campaigns, these maps provide important constraints for belt-scale 3D models (Metelka et al., 2015; Perrouty et al., 2014; Diene et al., 2015). In South West Ghana this analysis led to the proposition of a model for the main regional-scale controls on gold mineralization to the southeast of the main Ashanti Belt by highlighting the lithological distribution and geometry of geological structures in 3D. The South West Ghana 3D model has also been used as a test case for more theoretical studies in geophysical inversion and the analysis of 3D lithological uncertainty (Lindsay et al., 2013a, b; Martin et al., 2013).

As in other cratons, the availability of airborne magnetic data allowed us to build up a comprehensive map of mafic dykes, and we are currently in the processes of systematically dating each swarm thanks to a collaboration with the Supercontinent consortium (Figure 4; Jessell et al., 2015c; Baratoux et al., 2016), http://www.supercontinent.org/). This work has shown that more than two dozen dyke swarms intrude the WAC, with 8 newly dated swarms having ages ranging from 2700 Ma to 200 Ma. These Large Igneous Provinces form important constraints for our understanding of the relative position of West Africa during successive supercontinent cycles. There are also variations in spatial density of dyke swarms that may reflect underlying variations in the lower crust or mantle.

We have also undertaken a research program that characterized West Africa’s regolith and landform evolution using airborne geophysical data and ground surveys, which has produced the first paleo-topographic map in the region (Grimaud et al., 2014, 2015), has identified a previously unrecorded 230 km-long paleochannel in the Volta Basin (Jessell et al., 2015b) and produced the first spectral library of rocks and regolith for West Africa (Figure 5, Metelka et al., 2015), which demonstrated that although weathering alters the spectral signature of the fresh rock, indicative absorption features located in the short-wave infrared region remain detectable.

**Integrated Geospatial Analysis**

An extensive geochronological sampling program, together with isotopic studies, has allowed us to define large-scale spatial variations in magmatic evolution of the southern WAC, which shows a systematic diachronous cessation of magmatic activity from east to west, which implies an intriguing rate of migration of tectonic activity of 3.5 cm per annum (Figure 6, Parra-Avila et al., 2016). Spatial mapping of LuHf model ages and detrital zircons is helping us to define lithospheric-scale domains in the southern WAC (Parra-Avila, 2015).

**Stratigraphic Synthesis**

Starting with the stratigraphic synthesis of Baratoux et al. (2011), the project has systematically re-analyzed existing and new data to produce 30 harmonized stratigraphic columns across the southern WAC. Although this has shown many similarities in stratigraphic succession across the craton, there are also second-order variations that are helping us to define sub-domains within the Birimian belts. When combined with the lithospheric-scale geophysical data and the geochronological record we can see coincident signals suggesting a major lithospheric break running through Côte d’Ivoire.

**Deposit Analysis**

At the mineral deposit scale, the research program has characterized 25 deposits across the craton, principally gold deposits, which reflect the economic focus of much of the industry in the region over the last ten years. This includes grain-scale studies to characterize structural, mineralization, metamorphic and fluid evolution histories within and outside of ore deposits (Figure 7, Block et al., 2015; Fougerouse et al., 2016; Masurel et al., 2017; Lebrun et al., 2017; Le Mignot et al., 2017; Salvi et al., 2016a, 2016b), and these studies show the remarkable diversity of host-rocks, structural controls and mineral associations found in what are still generally classed as orogenic gold systems. The dispersion of elemental and isotopic anomalies around these deposits has shown that 206Pb/207Pb ratios in barren soils and ferruginous crusts are much higher compared to those in gossan and related altered rocks (Kríbek et al., 2016).

**Exploration Database**

This research represents one form of support of economic development in the region, as it provides key datasets (in GIS-ready formats) that help to reduce geological risk in the minerals exploration decision-making process. The development of an integrated exploration GIS has proved to be a very efficient approach for transferring information to partners, all of whom have access to an exploration GIS, which has now expanded into a more than 650 Gigabyte, 180-layer online and static GIS database of metadata and data related to West African exploration. More than 80 of these layers consist of new data or compilations developed by project partners. In particular we have developed new georeferenced syntheses of harmonized geological maps covering 650,000 km²; a geochronology database with over 1000 zircon ages; a database of more than 8000 whole rock geochemical and isotope analyses for rocks and regolith; a new map of mafic dyke swarms; regolith maps; outcrop databases; petrophysical databases including a spectral library of fresh and weathered rocks; a new mineral deposit database for the region; a database of metamorphic observations; as well as compilations of several global geophysical datasets, such as receiver function data.

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The text provided above is a continuation of the work described in the previous pages, focusing on the integration of geophysical, geological, and geochemical data to understand the evolution and mineralization of the West African Craton (WAC). The research involves developing a comprehensive dataset that includes geologic, geophysical, and geochemical information, which is essential for understanding the tectonic, magmatic, and mineralization history of the region. The project has involved collaborations with various stakeholders, including the Supercontinent consortium, to develop a harmonized stratigraphic framework that spans across multiple sub-domains within the Birimian belts of the WAC. This approach allows for a more detailed understanding of the spatial and temporal evolution of the WAC, which is crucial for economic development and mineral resource assessment in West Africa. The integration of geospatial analysis with geochronological data provides insights into the timing of geological events, while deposit analysis helps in identifying potential economic deposits that could drive the mineral industry in the region. The exploration database developed as part of this research is a valuable resource for partners and stakeholders, as it facilitates informed decision-making in the exploration and development of mineral resources in West Africa.
Figure 3: 650,000 km$^2$ of new harmonized geophysically constrained mapping. Multi-coloured zones: WAXI Stage 1 & 2 mapping (Metelka et al., 2011; Baratoux et al., 2011; Perrouty et al., 2012; Tshibubudze and Hein, 2015; Block et al., 2016; Miller et al., 2016 unpublished; McFarlane, 2016); shades of red WAXI 3 mapping (still confidential); greyscale modified from BRGM SIGAfrique map (Milési et al., 2004).

Figure 4: Mafic dyke swarms identified and mapped from airborne magnetic data and subsequently dated. Derived from Baratoux et al. (2016) and Jessell et al. (2015c).
Figure 5: Relative reflectance of basalts and andesites. Mean reflectance (solid line), plus and minus one standard deviation (dashed line). Absorption features are indicated with vertical lines and horizontal brackets (Metelka, 2011; Metelka et al., 2015).

Figure 6: Geospatial analysis of geochronology data. Longitudinal variations in magmatic activity: zircon and monazite U-Pb age distribution as a function of longitude for the age bracket 2300-2000 Ma (455 ages). The progressive cessation of the magmatic activity from east to west during this period in the southern West African Craton (lower grey arrow) equates to a migration of approximately 35 km/Myr. Over 95% of all ages plot above the “magmatic front”. There is also a suggestion that the start of magmatism is diachronous, (red arrow) however the signal is less strong (Parra-Avila, 2015).
In order to provide immediate access to new datasets, we developed a WMS Web Client to provide online access to the latest data sets (Figure 8). This same Web Client has also been supplied to the International Mining for Development consortium in support of their OpenData Initiative (http://opendata.im4dc.org/).

**CAPACITY BUILDING ACTIVITIES**

Based on UNESCO/Geological Society of Africa data, there are currently 38 public higher education institutions that provide geoscience training in West Africa (including Schools of Mines), of which 29 are in Nigeria. In the last ten years, the African Union via the African Mining Vision (AMV) and its associated action plan (African Union Commission, 2011), the World Bank and the African Development Bank have recognized the need for renewed investment in higher education to support the growing African population, which is predicted to have the world’s largest labour force by the year 2040 (Africa Development Bank, 2014). These groups recognize the need for a broader spectrum of higher education models to meet the demand for a skilled workforce that does not necessarily have to involve degree-based courses. The African Development Bank, UNESCO’s Earth Science Initiative in Africa, the AMV and African Network of Earth Sciences Institutions (ANESI) share many proposals in terms of enhanced regional collaboration, better integration of the private sector and the minerals industry, in particular via Public-Private Partnerships, and the use of ICT-based training programs as supports for Africa’s education needs. Many of these same themes are also found in the UN’s Sustainable Development Goals, and map directly to WAXI activities (Table 1).

The capacity building program is jointly led by the Luxembourg-based NGO Le Soleil dans la Main and the professional training centre Teng Tuuma Geoservices (I-TTG) based in Ouagadougou, Burkina Faso. Direct capacity building activities are supported in the form of student scholarships, financial support for student research, and in continuing education for industry, university and geological survey staff.

**Graduate Scholarships and Research Support**

The different stages of the project, together with associated one-on-one industry projects and university-funded scholarships, have allowed us to support a total of 35 PhD projects, 35 Masters and Honours projects, and six Postdoctoral fellowships, with more than half of these being African. Nevertheless, the demand for scholarships, and in particular projects which provide support for research costs, far outstrip the capacity of the WAXI project’s resources, and partnering with other training schemes provides a partial solution to meeting this demand, as many outside scholarships do not provide research funds.

Most if not all of the 70 Honours, Masters and PhD projects integrated combinations of geological, geophysical and geochemical datasets to arrive at their conclusions, so that the next generation of West African geoscientists are being taught the value of integrating multiple datasets.
Professional Training

Up until the end of 2017, the project has supported 23 three- to five-day field and classroom training courses to over 350 industry, university and geological survey personnel. The courses have been held in Ghana, Burkina Faso, Côte d’Ivoire and Senegal. The vast majority of the attendees of these courses were African geoscientists. Many of these courses focus on integration of datasets for robust interpretation including integrating geology and geophysics in 2 and 3 dimensions; geochemical interpretation of the regolith; structural controls of ore deposits; and a minerals systems approach to prospectivity analysis. In addition to these technical courses, we organized a five-day course on research management aimed at West African university and geological survey personnel. (Figure 9, Table 2). Finally, two international conferences (in Ouagadougou, Burkina Faso in 2007, and Dakar, Senegal, in 2015) were held to stimulate new research ideas in the region and present project outcomes.

CONCLUSIONS

The success of the WAXI program comes from the commitment of the individuals and organizations that have been involved over the last ten years, and equally from the recognition that these different organizations have different drivers: industry benefits in the short term by the acquisition of new datasets and their interpretation, and in the long term through the availability of better trained existing and incoming staff; geological surveys benefit from better collaboration across the region, better trained staff and the opportunity to explore common goals with industry; and the higher education sector benefits from access to student scholarships and research funds, which result in a supply of young well-networked researchers to take on the challenge of training the next generation of geoscientists, with a particular focus on data integration skills. The WAXI program has also partnered with a number of other research and capacity building initiatives working in West Africa which have complementary goals (including IGCP638, the GEOLOOC online training platform, the AEGOS data infrastructure program, the Côte d’Ivoire-focused T2GEM project, a proposed Burkina-Faso Geoscope project focusing on the Boromo Belt, together with several one-on-one projects between partner research organizations and industry).

The WAXI project forms part of a broad range of development geoscience initiatives in Africa that have overlapping aims that partially fulfil the aims of the African Mining Vision and the Sustainable Development Goals. This initiative demonstrates the significant achievements that become possible when the different stakeholders in the minerals sector (industry, academia, government and non-government organizations) partner together to combine datasets and knowledge across national borders in order to achieve their diverse goals.

Figure 8: Web Feature Service and on-disk delivery of 650 GB geoscience database using custom web client serving a Geoserver PostgreSQL/PostGIS database. (De Boyer, 2011).
ACKNOWLEDGEMENTS

We wish to gratefully acknowledge AMIRA International and the 34 industry sponsors, as well as AusAid and the ARC Linkage Project LP110100667, for their support of the different stages of the WAXI P934 series of projects. We are also appreciative of the contribution of the 12 geological surveys/departments of mines in West Africa who joined as sponsors in kind, as without their ongoing logistical support and provision of a range of country-level datasets, this project would not have been possible. Finally, we wish to recognize our research colleagues from 20 institutions from around the world.


REFERENCES


Amponsah, P.O., Salvi, D. Béziat, M. Jessell, L. Siebenaller, and L. Baratoux, 2015, Geology and geochemistry of the shear-


African Mining Vision Action Plan | West African Exploration Initiative
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**Programme cluster 2 – Geological and mineral information systems**
Support regional economic communities to:
- adopt and implement sub-regional mapping and mineral inventory programmes including the use of modern remote sensing techniques.
- scale up efforts to standardize geological information management methods and approaches (e.g., stratigraphy, cadastre, legends, etc.).
- promote collaboration between the different national geological and mining-related institutions (Ministries, Universities, Research Centres, etc.).

- Integrated regional geological and geophysical mapping programs and development of new maps (Baratoux et al., 2011; Hein, 2010; Metelka et al., 2011; Perrouty et al., 2012; Tshibubudze et al., 2014; Block et al., 2015).
- Mineral Atlas Monograph and other special volumes as online resources material (Markwitz et al., 2016).
- Compilation of historical, geological, geographical and geophysical data in ArcGIS and MapInfo platforms (Jessell, 2013).

**Programme cluster 3 – Building human and institutional capacities**
- At national level: Diversify education, academic and professional training funding sources to include private sector; strengthen continuing professional development through short courses; align human resources development to AMV policy direction and needs of industry.
- At sub-regional level: Establish strong inter-university collaborative programmes; improve cross-country accessibility of learning centres.

- Industry and government supported academic training at the postgraduate level with 70 current and completed MSc and PhD theses, over 60% from Africa.
- Training for academic staff. Collaborative agreements between universities, e.g., University of the Witwatersrand and Ecole Nationale d’Ingenieurs (Mali).
- Research exchange programs for West African researchers to France, South Africa and Australia.

**Programme cluster 6 – Research and development**
- At national level: Improve funding for minerals research including focus on improved mineral extraction processes as well as environmental and social impacts.
- At sub-regional and regional levels: Develop strategies to enhance collaboration between R & D centres with a view to knowledge-sharing and technology transfer; develop exchange of information networks to enhance exchange of data and good practices.

- Total research and scholarship funding to West and South African universities: $500,000.
- Combined WAXI GIS available to all West African partner organizations.
- Improved data access (Data Metallogenica).

**Programme cluster 8 – Linkages and diversification**
- At national level: Develop institutional arrangements that combine the minerals industry, trade and science, technology and innovation complexes.
- At sub-regional and regional levels: Develop best practice on new institutional arrangements combining the minerals industry, trade and science, technology and innovation complexes for regional economic communities and member states.

- Annual meetings bringing together universities and geological survey organizations from partner countries across West Africa.

Table 1: Action items from the action plan of the African Mining Vision that are addressed by the WAXI project.
<table>
<thead>
<tr>
<th>Course Title</th>
<th>Course type and location(s)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Management</td>
<td>Classroom- Burkina Faso</td>
<td>2013</td>
</tr>
<tr>
<td>Field Geomorphology and Regolith Mapping</td>
<td>Field course - Burkina Faso</td>
<td>2013, 2017</td>
</tr>
<tr>
<td>Mineral systems and metallogeny of the Birimian Craton and applications for exploration targeting: A regional to deposit scale perspective</td>
<td>Classroom and field - Burkina Faso</td>
<td>2016, 2017</td>
</tr>
<tr>
<td>Back to the basics applied structural geology and mapping</td>
<td>Field course - Ivory Coast, Burkina Faso</td>
<td>2017</td>
</tr>
<tr>
<td>Mineral alteration footprints and portable field techniques (ASD, XRF, etc.)</td>
<td>Classroom and field – Burkina Faso</td>
<td>2017</td>
</tr>
<tr>
<td>Field and litho-structural mapping and integration of geophysical data (radiometrics, magnetics): to be announced</td>
<td>Classroom and field - Senegal</td>
<td>2018</td>
</tr>
</tbody>
</table>

Table 2: Professional Training Courses.