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The dark art of interpretation in geomorphology

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ABSTRACT

The process of interpretation, and the ways in which knowledge builds upon interpretations, has profound implications in scientific and managerial terms. Despite the significance of these issues, geomorphologists typically give scant regard to such deliberations. Geomorphology is not a linear, cause-and-effect science. Inherent complexities and uncertainties prompt perceptions of the process of interpretation in geomorphology as a frustrating form of witchcraft or wizardry — a dark art. Alternatively, acknowledging such challenges recognises the fun to be had in puzzle-solving encounters that apply abductive reasoning to make sense of physical landscapes, seeking to generate knowledge with a reliable evidence base. Carefully crafted approaches to interpretation relate generalised understandings derived from analysis of remotely sensed data with field observations/measurements and local knowledge to support appropriately contextualised place-based applications. In this paper we develop a cognitive approach (Describe-Explain-Predict) to interpret landscapes. Explanation builds upon meaningful description, thereby supporting reliable predictions, in a multiple lines of evidence approach. Interpretation transforms data into knowledge to provide evidence that supports a particular argument. Examples from fluvial geomorphology demonstrate the data-interpretation-knowledge sequence used to analyse river character, behaviour and evolution. Although Big Data and machine learning applications present enormous potential to transform geomorphology into a data-rich, increasingly predictive science, we outline inherent dangers in allowing prescriptive and synthetic tools to do the thinking, as interpreting local differences is an important element of geomorphic enquiry.

1. Introduction

The process by which geomorphologists interpret physical landscapes has significant implications in scientific and managerial terms. However, approaches to interpretation are seldom explicitly specified and are subject to limited scrutiny. This paper explores the dark art of interpretation in geomorphology. We contend that interpretation is far from a prescriptive, linear, cause and effect process. Rather, geomorphologists interpret multiple forms of information from a range of sources to create a logical and rational argument that is appropriately supported by evidence. Much depends upon the experience and training of the person (or team) who is making interpretations (Montgomery and MacDonald, 2002; Sauer, 1956). Instinctive capabilities come to the fore, sometimes accompanied by a healthy dose of serendipity, as geomorphologists make sense of the patterns, behaviour and evolution of landforms that make up a particular landscape.

Building on observations that identify and describe landforms, geomorphologists explain why particular features are found at a particular locality, what processes formed them over what timeframe, and how those landforms interact with each other. Magnitude-frequency analyses of formative processes are related to controls upon longer-term evolution to interpret how each landscape is a palimpsest that retains a selective memory of what has gone before (Brierley, 2010; Phillips, 2006). Interpretation of observations and measurements transforms data into evidence that supports a coherent account of events that created a given landscape. Resulting explanations inform predictions of prospective futures.

Interpretation in geomorphology is inherently indeterminate. Combinations of attributes, relationships, processes, drivers, legacy effects and sequences of events create contingent circumstances that fashion complex arrays of responses to disturbance events and emergent evolutionary traits (Church, 1996; Downs and Piégay, 2019; Schumm, 1991; Wohl et al., 2019). Timeless relations of theoretical physics operate alongside timebound realities of a given place to shape the character, behaviour and evolution of each landscape (Grant et al., 2013). Individual circumstances are not always readily generalisable in a naughty

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world (Kennedy, 1979) of perfect landscapes (Phillips, 2007). As noted in concerns for biodiversity management, exceptionalism is important as local differences matter, often a lot (Brierley et al., 2013; Cullum et al., 2017).

The availability of Big Data and machine learning techniques presents unprecedented potential to support place-based analyses of landscapes, transforming geomorphology into an increasingly data-rich predictive science (e.g., Piégay et al., 2020; Reichstein et al., 2019). Novel geospatial technologies have enabled the acquisition of remote sensing imagery and the generation of digital elevation models at much higher spatial and/or temporal resolution than has previously been possible (e.g., Amatulli et al., 2020; Bizzi et al., 2016; Guillon et al., 2020). Used effectively, this enhances prospects to *respect diversity*, explaining landscape variability in space and time from microscale material analyses through to landform and landscape analyses, regional comparisons and global/planetary scale investigations (Bizzi et al., 2019; Boothroyd et al., 2021a, 2021b; Piégay et al., 2020). Careful processing of data enhances interpretations and knowledge of geomorphological concepts such as (i) process-form associations, (ii) event sequencing and magnitude-frequency relations, (iii) the geomorphic effectiveness of disturbance events, and (iv) measures of sensitivity and resilience of landscapes (e.g., Schumm, 1991). This enhances our capacity to appraise system morphodynamics and changing process relationships over *time*, thereby informing interpretations of *evolutionary trajectory* (Brierley and Fryirs, 2009, 2016; Downs and Piégay, 2019; Fryirs and Brierley, 2016).

However, the availability of Big Data does not necessarily equate to knowing and understanding landscapes in better and more reliable ways. The meaning of interpretations reflects the ways in which data are collected, filtered and processed. While Big Data offer prospect to capture local variability and contextualise local circumstances in relation to big picture understandings, technological advances in their own right do not necessarily provide appropriate insight to explain local differences (Fryirs et al., 2019). Allowing artificial intelligence and machine learning applications to 'do the thinking' prioritises particular perspectives over others. Lazy applications of geomorphic insight based on over-simplified representations of reality fail to support management applications that give due regard to local values. In resolving this tension, much depends upon the ways in which emerging datasets and techniques are used alongside conventional (tried and tested) applications.

Effective use of geomorphic insight to support management applications builds upon the best available evidence, regardless of its source, appropriately situating place-based interpretations of landscapes in context of generalised (theoretical) understandings (e.g., Brierley et al., 2013; Burt, 2005; Rhoads, 2020; Schumm, 1991; Wohl, 2018). Unless geomorphic investigations incorporate the painstaking work of historical sleuthing (Montgomery, 2008), applying forensic detective-style investigations that bring together understandings from a wide range of methods and sources, place-based investigations and applications are likely to be diminished. A plural knowledges lens (Howitt and Suchet-Pearson, 2003) promotes investigations that relate synthetic artificial intelligence appraisals of landscapes alongside other sources of insight, including local knowledges of residents or long-lived experiences of indigenous peoples (e.g., Hikuroa et al., 2021; Koppes and King, 2020; Wilcock et al., 2013; Wilkinson et al., 2020).

Other than the general account presented by Frodeman (1995), earth scientists give little attention to the hermeneutics of practice that underpin scientific approaches to landscape analysis. Although deductive analyses provide reliable insights into process relationships under controlled experimental conditions, this only provides partial understanding of the specific circumstances at a given place. At the same time, inductive reasoning may fail to support generalised understandings. Geomorphic interpretation of physical landscapes is inherently shaped by abductive reasoning, making the best of the information at hand in seeking the likeliest possible explanation for an inherently incomplete set of observations (Downs and Piégay, 2019). Abductive reasoning can be understood as inference to the best explanation, striving to develop a rational and logical argument that creates knowledge with an appropriate evidence base.

Although generic principles that underpin efforts to read the landscape may help (Fryirs and Brierley, 2013), there is no manual for abductive reasoning. Inherent complexities and uncertainties may prompt perceptions of the process of interpretation in geomorphology as a frustrating form of witchcraft or wizardry — a dark art. Alternatively, acknowledging such challenges can be perceived as part of the fun to be had in puzzle-solving encounters that seek to make sense of landscapes. For sake of clarity, the inherent mystery and uncertainty that underpins the dark art of geomorphic interpretations is differentiated here from the hidden nature of 'Dark Knowledge' that hinders collective engagement and sharing of insight at the science-management interface (Jeschke et al., 2019). In this paper we urge greater acknowledgement of, and deeper professional engagement in, the dark art of landscape interpretation.

This paper outlines a multiple lines of evidence approach to landscape interpretation that seeks to explain how a given landscape looks, functions and changes (i.e., its character, behaviour and evolution). Our paper is structured as follows. First, we provide a snapshot of changing approaches to enquiry in geomorphology. This is followed by a conceptual synthesis of the processes by which data are transformed into knowledge. An interpretation interface merges understandings derived from field observations and measurement, local/traditional insights, and Big Data and modelling applications to 'Read the Landscape'. From this, we show how geomorphologists generate an evidence base that supports logical and coherent interpretations from which knowledge is created. We then use examples from fluvial geomorphology to demonstrate this approach. However, overarching principles that underpin the dark art of interpretation are considered to be relevant across geomorphology as a whole.

2. A brief history of approaches to analysis in geomorphology

In general terms, approaches to enquiry in Earth and Environmental Sciences lack the reproducibility of experimental method afforded to practitioners of physics and chemistry, or controlled conditions of applications in engineering and biology, where repeatable phenomena can be mapped out and analysed in mathematical terms such that a guaranteed conclusion can be reached. As geomorphic systems are notoriously 'open' (Chorley, 1962), practical applications are ill-suited to deductive analyses of 'closed' thermodynamic systems in which forces and matter can be fully accounted for (Grant et al., 2013). While the operation of physical or numerical models may be entirely predictable, such timeless relations and linear, cause and effect reasoning play out in quite different ways in real world situations (Phillips, 2003). Geography and history matter, as timebound realities of a given landscape determine the outcomes of geomorphic process relations in space and time (Strahler, 1952). Landscapes are phenomena that are inherently contingent, emergent and uncertain (Schumm, 1991). Each place retains a selective memory of what has gone before (Brierley, 2010; Phillips, 2006).

Geomorphology emerged as the scientific study of landscapes out of holistic concerns for natural history in the late nineteenth and early twentieth centuries. An initial focus on landscape description and explanation was progressively enhanced by measurements of earth surface processes in the second half of the twentieth century (Preston et al., 2011). Over time, the discipline adopted quite distinctive pathways in Geography and Geology (Church, 2010), the former emphasizing socially contextualised applications, while the latter embraced a more technical focus.

Early efforts to explain morphodynamics and rates of flux in relation to landscape evolution encompassed field-based cross-disciplinary endeavours at the interface of geology, hydrology, pedology, weathering and Quaternary Sciences. This entailed relating local observations and process relations to general understandings and theoretical principles. Increasing emphasis upon sub-disciplinary components of landscapes (hillslopes, glaciers, rivers, coasts, deserts, etc.) in an era of 'if it moves, measure it' (Preston et al., 2011) prompted Baker and Twidale (1991) to call for a 're-enchantment of geomorphology', re-engaging with traditional concerns for landscape-scale interpretations. In recent decades, advances in remote sensing and modelling applications have enhanced systematic analyses and the reliability of predictions, often with an increasing emphasis upon management applications (e.g., Piégay et al., 2020). Increasingly, Big Data, artificial intelligence, machine learning applications and a vast range of modelling toolkits are supplanting conventional components of field-based enquiry and associated skillsets used to explain and predict landscape form, process, adjustment and change (cf., Roering et al., 2013). All too often, such practices push aside concerns for the dark art of interpretation in landscape science.

3. From data to knowledge: the process of interpretation

Fig. 1 presents a summary of the process of interpretation that transforms *data* into *knowledge*. Nomothetic (theoretical) principles strive to produce law-like statements that encompass a number of individual cases. In contrast, an idiographic (empirical) way of thinking emphasises concerns for the uniqueness of individual phenomena or events. The latter encompasses concerns for exceptionalism (Schaefer, 1953), wherein the general rule is not applicable to particular instances (Marshall, 1985). Burt (2005) notes that the terms idiographic and nomothetic are not opposite in meaning; rather, they identify attributes that are distinct from one another but are by no means mutually incompatible (i.e., they are complementary rather than competitive; Marshall, 1985). In the process of geomorphological enquiry, precision of the specific is often sacrificed for efficiencies of the general. However, effective practices meaningfully relate knowledge of particular instances to broader, generalised understandings (i.e., scientific laws, rules and principles). This provides a basis to make claims that go beyond available observational data, whereby inferences underpin predictions about cases that have not yet been examined (Burt, 2005). Theories unite logic and fact to produce order out of chaos.

On their own, data and information have no meaning. They must be processed cognitively to understand something, thereby adding meaning and creating knowledge. Interpretation entails a mix of *competencies* and analytical *processes* (Fig. 1) many of which are influenced by training and experience on the one hand, and intuitive insights on the other (Montgomery and MacDonald, 2002; Sauer, 1956). As a competency, *situational context* frames the questions being asked or hypotheses being tested in their environmental, cultural or historical context (Fig. 1). Institutional and personal *assumptions* reflect current and prior experience, memory and instinct (Fig. 1). Working memory, a part of short-term memory, is defined as the set of processes with which the brain stores and manipulates temporary information and data to carry out reasoning. Interpretation also draws on long-term memory, whereby current experiences and interpretations are related to past experiences or interpretations. Intuition, unlike memory, involves knowing something directly without analytical reasoning (e.g., flowing water is wet). Intuition is also related to instinct, having a sense of whether a particular answer or meaning makes sense or something is missing or wrong. A range of *concept* understandings contributes to a person's competence and ability to interpret (Fig. 1). For example, Fryirs and Brierley et al. (2013) outline steps that can support an ability to Read the Landscape.

Cognition is arguably the most important competency in the process of interpretation (Fig. 1). This includes *perception*, the ability to capture, process, and actively interpret sensory information. In geomorphology, this includes the sense of sight that allows a practitioner to observe, identify, visualise and picture the landscape. *Attention* includes both focussed attention, defined as the brain's ability to concentrate on a target stimulus for any period of time, and sustained attention, defined as the ability to focus on an activity or stimulus over a long period of time, or for as long as it takes to find a solution (e.g., complex problem solving). *Logic* is the analysis and appraisal of arguments that lead to the acceptance of one proposition (the conclusion) on the basis of a set of other propositions (premises). Logic helps decipher the most likely solution

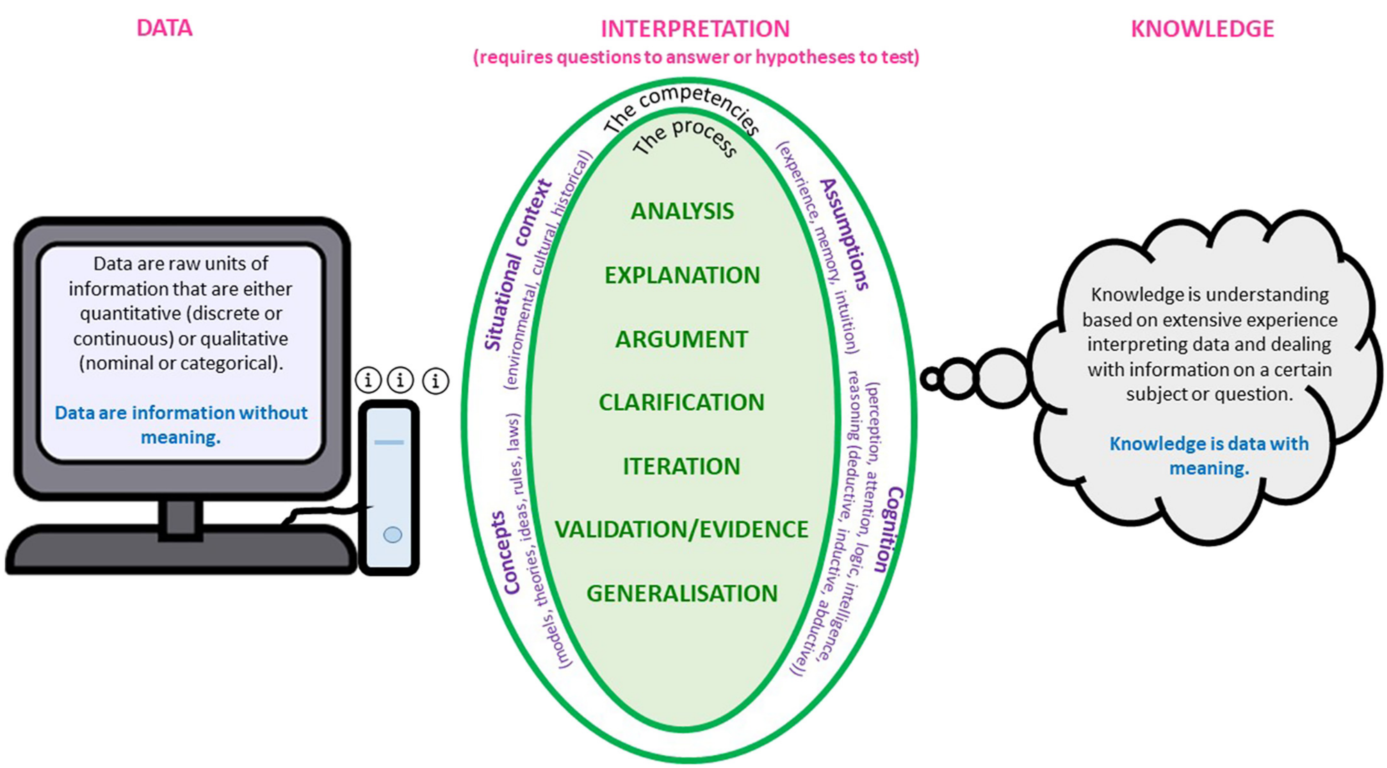

Fig. 1. Transforming data into knowledge using interpretation.

to a problem. Cognition also includes *intelligence*, defined broadly as the mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience. Finally, cognition includes the ability to *reason* (Medawar, 2008; Peirce, 1878). Deductive reasoning starts with the assertion of a general rule and proceeds to a guaranteed specific conclusion or application. Inductive reasoning begins with observations that are specific and limited in scope, and proceeds to a generalised conclusion that is likely, but not certain, in light of accumulated evidence. It involves gathering evidence, seeking patterns, and forming multiple working hypotheses or theories to explain what is observed. Abductive reasoning derives the likeliest possible explanation for an inherently incomplete set of observations, making the best of the information at hand (Tversky and Kahneman, 1974). Often, this entails making an educated guess after observing a phenomenon for which there is no clear explanation. In this form of logical inference, the premises do not guarantee the conclusion. As several lines of reasoning may explain a particular phenomenon or pattern, abduction is open to subjectivity with a high risk of confirmation bias (Curtis, 2012).

With these competencies, the *process* of interpretation involves *analysis*, *explanation*, *argument*, *clarification*, *iteration*, *validation* and the presentation of *evidence*, and *generalisation* (Fig. 1). Validation entails proof, wherein sufficient evidence is derived through tests, experiments and/or examination to establish a fact or produce belief. Generalisation involves determination of patterns and relations among variable aspects of objects and the ability to apply and test concepts and classification criteria across a range of contexts and environments. Collectively, these various competencies and processes support the transformation of data divorced from meaning into knowledge with meaning.

Processes of interpretation in geomorphology are circumstantial and contextual, striving to make best possible use of best available information and insight in a multiple lines of evidence approach to enquiry and reasoning. Whenever possible, it pays to adopt a plural knowledges framework (Howitt and Suchet-Pearson, 2003), relating conventional approaches to scientific analysis of landscapes to local and traditional knowledges, often expressed through narratives and stories that express landscape histories (e.g., Díaz et al., 2015; Hill et al., 2020; Koppes and King, 2020; Wilcock et al., 2013; Wilkinson et al., 2020). Incorporating multiple techniques can provide additional lines of evidence that support a particular interpretation. Undue adherence and advocacy of a single model with a prescriptive set of procedures may present a significant barrier in efforts to improve interpretation (Curtis, 2012). Just as multiple working hypotheses present a useful platform to conduct analyses, the use of multiple models can help to improve interpretations (Bond, 2015). As noted by Bond et al. (2007, p. 10): “geological interpretation is a model that needs testing”.

Fig. 2 presents a conceptual framing that demonstrates how geomorphologists can apply a multiple lines of evidence approach to interpret landscapes. This *Describe-Explain-Predict* approach integrates field insights with Big Data to inform management applications. Top-down analyses of virtual landscapes derived from technical analyses are integrated with bottom-up analytics derived from field-based analyses that Read the Landscape in an iterative, non-deterministic process (Fryirs and Brierley, 2013). Place-based local and traditional understandings are integrated with these analyses at an interpretation interface where human cognition provides the intellectual and practical resources to support geomorphologically-informed management applications (Fryirs et al., 2019). This process typically entails a combination of hard graft, occasional good fortune (serendipity), personal ‘aha’ (lightbulb) moments of inspiration, and recurrent frustrations of countless cul-de-sacs and blind alleys. Experience helps, as it pays to appreciate and understand the significance of what is being observed. Sometimes bright sparks and firework events mark step-changes in understanding that may reconceptualise understandings and approaches to enquiry (Fig. 2). A profound sense of satisfaction arises when a logical line of reasoning makes sense of available evidence to tell a compelling story about a puzzling situation, especially when further confirmatory evidence comes to light in support of a particular argument.

The interpretation interface that lies at the heart of Fig. 2 relates meaningful description to clearly justified explanation, which in turn generates an appropriate basis for prediction. Blue boxes representing

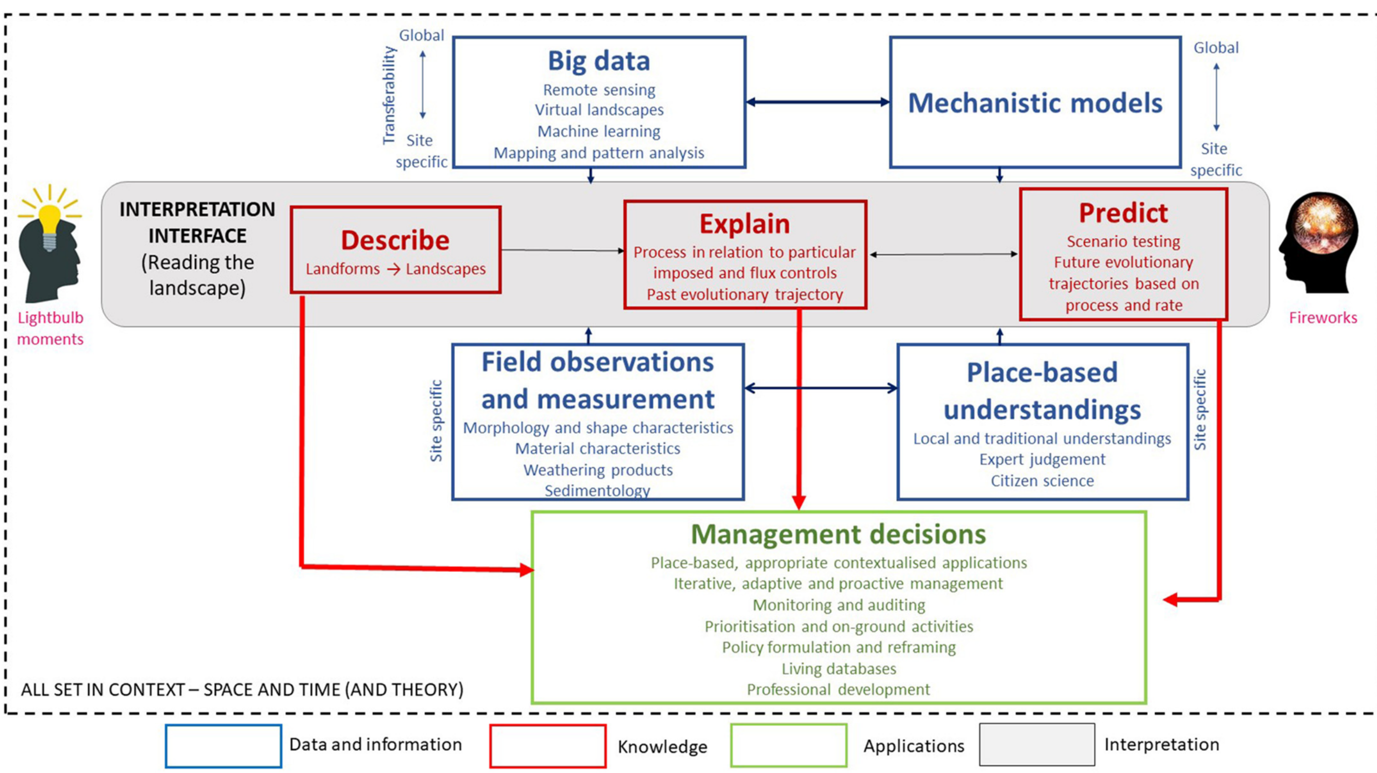

Fig. 2. An approach to interpretation in geomorphology.

different types of data feed the interpretation interface where knowledge is created (red boxes). The arrow that links Describe and Explain encompasses multiple insights from an appropriate blend of skillsets that interweave data and understandings from a range of sources (e.g., remotely sensed, field observations and measurements, modelling analyses, local insights). Technical prowess is combined with instinctive, intuitive flair to generate and test multiple working hypotheses that present realistic accounts that explain the information in-hand. These understandings are contextualised in relation to theoretical and geographic considerations, thereby guiding appraisals of the representativeness and transferability of insight from one situation to another. The arrow that links Explain to Predict is similarly situated in context of place, space, time and theory. However, this arrow represents the use of explanations to run forecasting scenarios using modelling techniques. Prediction sometimes incorporates expert judgement to conceptualise scenarios and predictions. In turn, simulations supported by Big Data test the efficacy of interpretations and understandings in reconstructing the evolutionary history of a given system (i.e., validation). Management applications and decisions (green box) should only be applied after interpretation has transformed data into knowledge (Fig. 1) using the Describe-Explain-Predict approach (Fig. 2).

Inherently, ***describing*** is a process of structured observation. It involves analysis of the morphology, shape, size and position of landforms, identifying, defining and interpreting their patterns and interactions (connectivity) at the landscape (catchment) scale (Fryirs and Brierley, 2013). These could be considered as *what* questions, such as *what* landforms are present (or absent), *what* types of landscapes are created, *what* are adjacent landscape features? Identification and mapping of features is a critical starting point for such analyses. This is an interpretation exercise in its own right (e.g., Wheaton et al., 2015). Ideally, outputs of top-down, automated mapping of features (and associated analyses of the energy conditions under which they are found) are verified by bottom-up field observations and measurement (e.g., Roering et al., 2013). For example, in analysing river adjustment and change it is important to measure and monitor forms and rates of adjustment, contextualising contemporary traits in relation to long-term landscape evolution. Inductive reasoning relates intuitive and experiential insights into formative processes to design measurement and monitoring programmes that appraise magnitude-frequency relationships to analyse rates of process activity and their geomorphic consequences. Sedimentological analyses and derivation of geochronologies help to construct evolutionary trajectories that relate contemporary morphodynamics to past events and associated legacy effects. This provides a basis to interpret forms, rates and patterns of responses to disturbance events, appraising how catchment scale interactions shape the evolutionary trajectory of the system.

Explaining involves answering *how* and *why* questions, such as *how* and *why* are certain landforms found in particular locations, *how* and *why* they behave as they do, and *how* and *why* particular mixes of boundary conditions control patterns of landforms or landscapes (Fryirs and Brierley, 2013). Efforts to unravel causality seek to explain how and why a landscape has adopted the form it has, what processes created it (and why), and how and why that system adjusts and evolves as it does. These understandings are required to differentiate the causes from the symptoms of degradational influences. Sometimes field analyses that 'look beneath the surface' reveal findings that do not fit with current explanations, thereby requiring an alternative interpretation (e.g., Hoyle et al., 2008; Roering et al., 2013). A quirky piece of evidence can transform an interpretation in the quest to develop a rational and logical argument to create knowledge with an appropriate supporting evidence base. For example, discovery of an old bottle or a chocolate bar wrapper within a sediment exposure provides confirmatory evidence that the body of sediment was deposited in the period since human settlement of that landscape (see Gregory et al., 2008). Multiple working hypotheses provide accounts of what is found where and what is missing in these timebound appraisals of processes and sequences of events that determine system-specific behaviour and evolution. Framing analyses in their theoretical context helps to relate findings from one situation to another. Hence, the outer box (dotted line at the edge of Fig. 2) represents the theoretical lens within which work is conducted. As indicated on Fig. 1, this is a key competency for interpretation.

Prediction involves undertaking forecasting exercises (Wilcock and Iverson, 2003). This entails asking *what if* questions, such as *if* X, Y, Z controlling variable is manipulated or adjusted, *what* are the range of possible future scenarios, outcomes, trajectories of adjustment and rates of adjustment or change. Modelled or conceptual forecasting can interpret how the landscape will likely look and work in the future, as it responds to changing boundary conditions including management interventions (e.g., Fryirs et al., 2012). Prediction helps determine what is/is not possible, and the likelihood and associated confidence of a given scenario occurring over a particular timeframe. Management applications that build on an incomplete information base, or an inaccurate approach to geomorphic analysis and interpretation, are destined to fail (e.g., Brierley and Fryirs, 2009; Kondolf et al., 2001; Simon et al., 2007).

In the following sections we use examples from fluvial geomorphology to show how interpretations of river character, behaviour and evolution are conducted and how misinterpretations can go terribly wrong, potentially leading to unintended consequences.

4. Geomorphic interpretation in practice

Fig. 3 shows examples of rights and wrongs in interpretations of river character at landform, reach and catchment scales. Fig. 4 extends this to consider interpretations of river behaviour, and Fig. 5 provides an example of steps made in interpreting landscape evolution. These examples are by no means inclusive or comprehensive. We simply use them to demonstrate the data-interpretation-knowledge sequence in practice, showing how errors are compounded if misinterpretation occurs early in the process. Essentially, our use of examples applies a scaffolding approach, starting with easier interpretations of character (Fig. 3) then extending this to more complex interpretations as we ramp things up in terms of space and time considerations (behaviour in Fig. 4 and evolution in Fig. 5).

4.1. Interpreting river character at the landform (geomorphic unit), reach and catchment scale

Landform-scale analysis involves identification and interpretation of geomorphic units (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013; Wheaton et al., 2015). In our fluvial example, channel and floodplain landforms are created and reworked by a distinctive set of erosion and/or deposition processes (Fig. 3A). Several types of information support identification and mapping of geomorphic units. This includes the elevation or height of the unit and its shape, and the nature of the boundaries and breaks in slope with other units. If these data are used incorrectly and misinterpretations occur, then the identification, mapping and labelling of geomorphic units will be wrong. Units A-C in Fig. 3A are out-of-channel features. Differentiation of a terrace from a floodplain (Units A and B) reflects the periodicity of inundation of that surface (i.e., whether this feature is formed by the contemporary river, or is inherited from the past). Identification of Unit C as a chute channel implies active reworking of a bar or other depositional units within the channel, while correct identification as a floodchannel indicates the high energy of flow that short circuits a floodplain pocket at overbank flood stage. This distinction (i.e., interpretation) is informed by position of the unit (e.g., in-channel versus floodplain), consideration of flow alignment at different flow stages (e.g., bankfull versus overbank) and the shape of the features (e.g., chute channels tend to be straighter). Unit D is a bank-attached geomorphic unit. Analysis of material properties is required to determine whether the feature has been eroded from

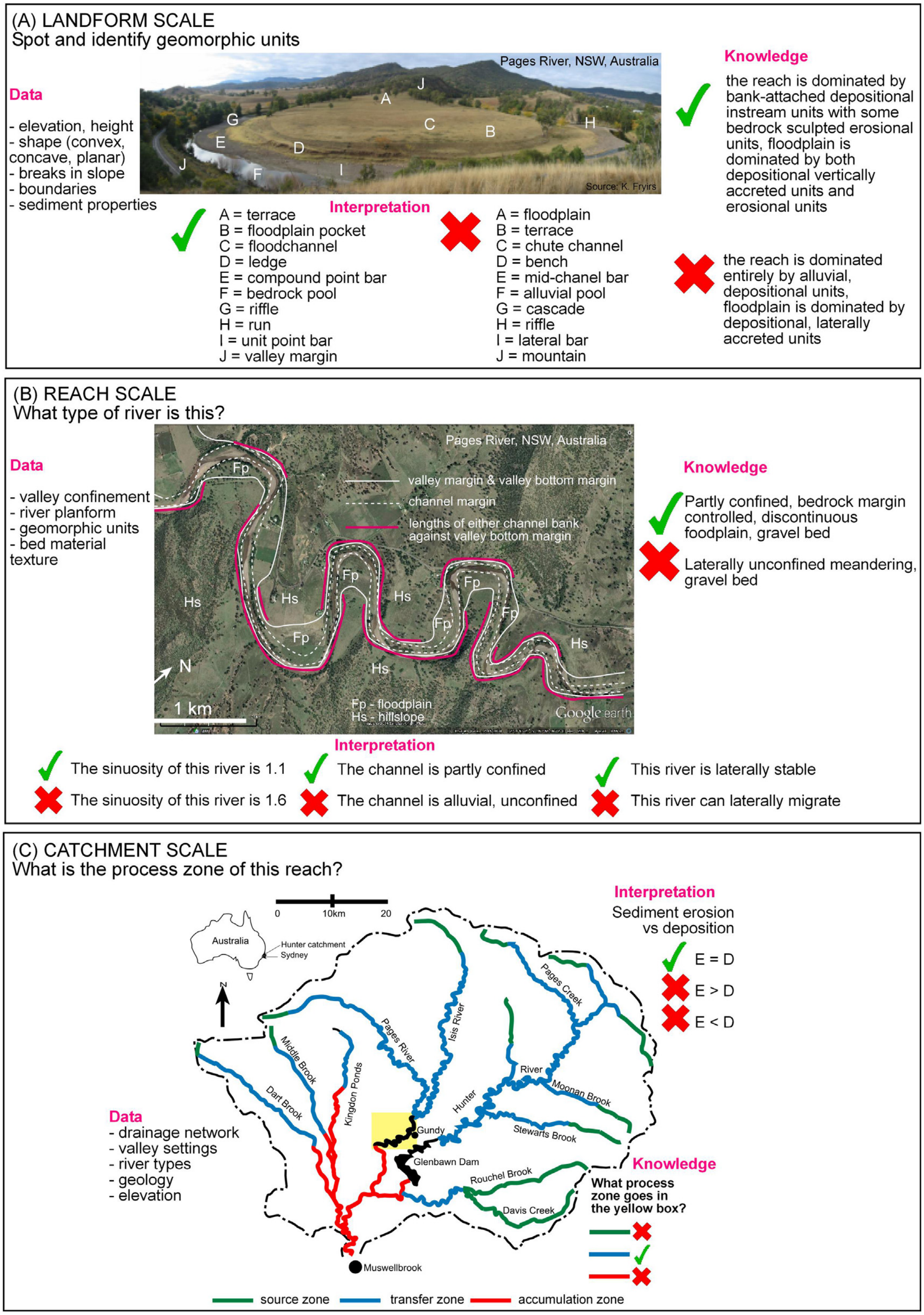

Fig. 3. The process of interpreting data to generate knowledge about **river character** at the (A) landform, (B) reach, and (C) catchment scale. If interpretation of data is incorrect, the knowledge generated can be terribly wrong. Features and processes and the red crosses indicate incorrect interpretations that could be made based on the same data.

the floodplain by an incising and/or expanding channel and has the same material properties as the floodplain (i.e., a ledge), or whether the unit is comprised of a mix of bedload and suspended load materials that are distinct from the floodplain materials and have therefore been deposited against the channel bank as the channel contracts (i.e., a bench) (Fryirs and Brierley, 2013). Analysis of position within the channel and material properties is also required to differentiate among instream geomorphic units (E–I). Careful interpretation of these features, in particular differentiation of forced (e.g., by bedrock) and alluvial features, helps to appraise the erosion-deposition dynamics of the channel and its capacity to adjust and rework its boundaries.

Fig. 4. Crafting and interpreting data to generate knowledge about **river behaviour**. The data-interpretation-knowledge process is demonstrated for three different types of river that may look similar and to the untrained eye may all be classed as meandering rivers. Incorrect interpretation of data results in flawed knowledge of river behaviour. (A) is the same type of river as in Fig. 3 and (B, C) are new examples. If mistakes and incorrect knowledge are carried over from previous interpretations (e.g., of river character; Fig. 3), such that they create flawed baseline data for more sophisticated interpretations and knowledge generation (e.g., river behaviour), the ripple effect of erroneous analyses further permeates the interpretation process, and any applications that ensue.

Analysis of the position, pattern and package of units along a river reach (i.e., the assemblage of geomorphic units) provides foundation interpretations that are subsequently used to generate knowledge about the range of process variability of the river, the forms of adjustment that can occur, and the ease with which adjustments take place. In the instance shown in Fig. 3A, the river has a strong imprint of bedrock

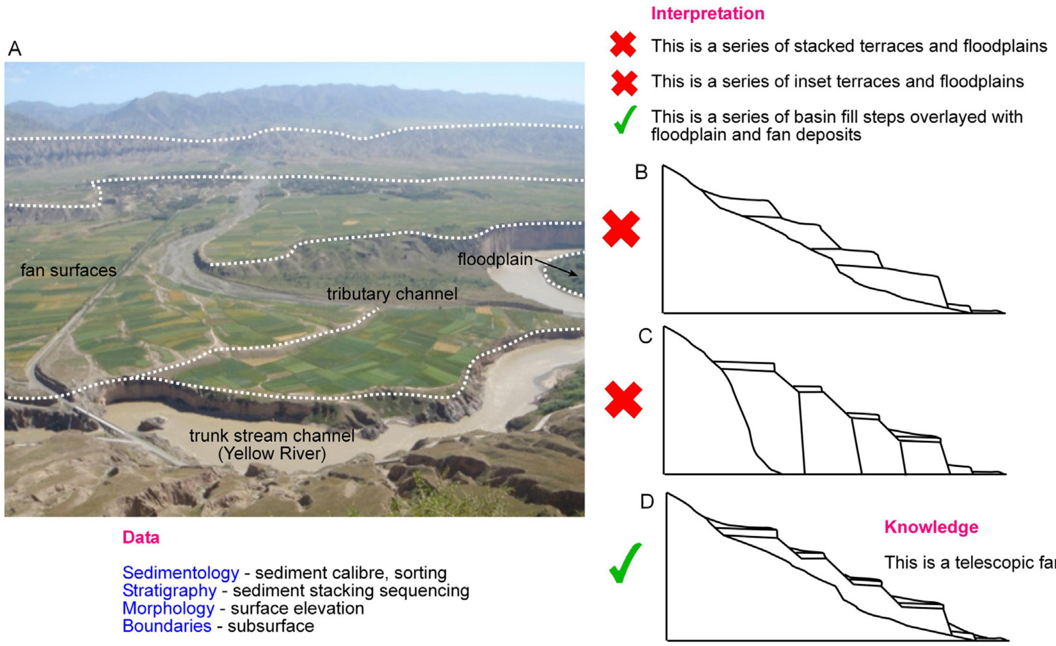

Fig. 5. Interpreting **landscape evolution**: geomorphic analysis of a telescopic fan in the Tongde basin, Upper Yellow River, China.
Source: Aiken and Brierley, unpublished data.

control and resultant sculpted erosional geomorphic units (Fryirs and Brierley, 2013). Depositional units occur where the channel has capacity to adjust (i.e., expand and contract) or the floodplain aggrades and degrades (e.g., vertical floodplain accretion and stripping). Hence, the reach shown in Fig. 3A is not fully alluvial — its morphology is largely forced.

Analysis of the assemblage of geomorphic units at the reach-scale is the key factor used in river reach analysis and identification of River Styles (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013, 2018; Kellerhals et al., 1976). In the case shown in Fig. 3B, unless floodplains are clearly identified and mapped, interpretation of river type may be wrong. This river is not alluvial, nor is it migrating laterally. Valley confinement is high (in the order of 80%; see Fryirs et al., 2016), alternating floodplain pockets occur along its length and the sinuosity of the river is low (around 1.1). As a result, this laterally stable river is identified as a partly confined, bedrock margin controlled, discontinuous floodplain, gravel-bed river, not a meandering river (e.g., Fryirs and Brierley, 2010, 2018).

Careful identification of river types, and their position and pattern across a catchment, is used to interpret how erosion/deposition dynamics of the river shown in Figs. 3A and B operate in terms of its process zone or domain (Montgomery, 1999; Schumm, 1977) and by extension its (dis)connectivity to other reaches (Brierley et al., 2006; Fryirs et al., 2007). This reflects, and indicates, how the reach responds to input of materials (i.e., whether those deposits are stored or transported through that section of river). In Fig. 3C, the case study reach is positioned in the middle reaches of the catchment, is partly confined and readily conveys materials that are made available to it, so it is interpreted as a transfer zone.

4.2. Interpreting river behaviour at the reach scale

Analysis of river character and identification of river type can support interpretations of river behaviour, so long as careful attention is given to reach-specific assemblages of geomorphic units (i.e., knowledge of formative processes that determine river character outlined in Fig. 3). Interpretation of the processes by which geomorphic units are formed and/or reworked, and the capacity for the channel to adjust in lateral, vertical or wholesale dimensions, provide insights into river behaviour at low flow, bankfull and overbank stages (Brierley and Fryirs, 2005). Although geomorphologists have good knowledge of processes that determine river character, many challenges remain in developing clear pedagogic (even didactic) guidelines to teach or train a practitioner how to identify landforms, interpret formative and/or reworking processes and assess how units fit together as assemblages/patterns at the reach scale.

Fig. 4 shows three examples of rivers with a sinuous outline that to the untrained eye may all be classed as meandering rivers (cf., Fryirs and Brierley, 2018). Misinterpretation of river planform or river type creates knock-on effects in terms of interpretation of form-process associations, capacity for adjustment and river behaviour. This is best demonstrated by Fig. 4A, which is the same river type with the same river character as that in Fig. 3A and B. The river in Fig. 4A has limited capacity for adjustment. It has an imposed morphology with the channel abutting against the bedrock valley margin along 50–85% of the reach length (Fryirs et al., 2016). As this river has incised into bedrock, and has discontinuous floodplain pockets, it can only adjust in the vertical dimension. Geomorphic units are dominantly forced and floodplains accrete vertically. River behaviour is controlled to a significant extent by bedrock forcing elements, and is quite different to an alluvial meandering river (Figs. 4B and C). Misinterpretation of river character and thence behaviour generates knowledge that is wrong.

Fig. 4B and C are meandering rivers. In these cases, accurate analysis of data is required to differentiate a passive variant (Fig. 4B) from an actively adjusting variant (Fig. 4C). Identifying the absence of instream point bars, floodplain meander cutoffs (billabongs, oxbows) and ridges and swales in the passive variant (Fig. 4B), and the prominence of these features in the active variant (Fig. 4C) is a key element of interpretation. This determination shapes interpretation of the capacity for adjustment. Cohesive fine-grained sediments limit adjustment for the passive variant. In contrast, readily reworked sands fashion significant adjustment in the active variant. This differentiation is reflected in the range of geomorphic units in each instance. Sculpted fine-grained instream geomorphic units and uniform floodplains, sometimes with palaeochannels, are evident in passive variants (Fryirs and Brierley, 2013). A wider range of instream and floodplain features characterises the active meandering river, with variable mixes of bedload and/or suspended load materials. Analysis of material properties aids interpretation of the behaviour of these rivers. The passive variant is dominated by sculpting erosion processes, suspended load deposition and vertical accretion whereas the active variant is dominated by mixed load erosion and deposition and lateral migration/accretion. Getting this nuanced interpretation and knowledge generation wrong can have knock-on consequences for interpretations of geomorphic river sensitivity or resilience (e.g., Fryirs, 2017; Reid and Brierley, 2015). Such misinterpretations may significantly compromise analyses of treatment responses emplaced as part of process-based approaches to river management (Schmidt et al., 1998). For example, placing bed and bank control structures along partly-confined rivers (e.g., Fig. 4A) reflects misinterpretations of the character and behaviour of such rivers (e.g., Spink et al., 2009).

4.3. Interpreting landscape evolution

All landscapes are products of their history. But, to what degree? How readily and recurrently do contemporary processes rework and reshape a particular landscape? How have human activities altered process interactions at a given place? Interpretations of landscape evolution seek to answer such questions.

Each landscape can be conceptualised as a palimpsest that contains glimpses into what has gone before and how that shapes what we can see today. In a sense it is like a jigsaw puzzle that is inherently complete, but is actually comprised of multiple incomplete pictures that are superimposed upon each other. Each image reflects a particular phase of evolutionary adjustment. Collectively, these pictures make up the landscape mosaic. Interpreting landscape evolution strives to tell a logical and rational story backed by supporting evidence. This entails unravelling how changing boundary conditions and controls (e.g., geological, climatic, anthropogenic factors) interact with disturbance events to produce adjustment or change in landscapes. Geochronological analysis of phases of adjustment underpins generation of timeslices that characterise landscape evolution.

Availability of data to support interpretations of landscape evolution is inherently incomplete. By definition, erosional events disrupt depositional records. In fluvial geomorphology, for example, processes that created the valley are often quite different to processes that create and rework the contemporary river. Disturbance events rework sediment sequences that record past phases of landscape formation. Hence interpretations of evolution are premised by things that are known and for which evidence exists, alongside things that are inferred based on what we think is absent. For example, particular landscape signals such as erosional contacts and discontinuities in sediment profiles may tell us something about change and what data may have been removed. Trained geomorphologists are able to tell if something does not fit, such that it presents contradictory evidence, or the story is either incomplete or wrong. Such are the dark art limitations, frustrations and exhilarations of forensic science.

To demonstrate how the process of data-interpretation-knowledge sequence is used to analyse landscape evolution, Fig. 5 presents a basin fill-terrace-fan-floodplain sequence from the Upper Yellow River near Tongde as a case study (Aiken and Brierley, unpublished data). In Fig. 5A, the critical starting point is the observation of prominent, multi-stepped surfaces that are asymmetrical in terms of their position in the valley and either flat or gently inclined towards the contemporary river channel. The channel is inset within thick sequences of deposits. A tributary channel cuts through the steps, prior to joining the trunk stream. To interpret the evolution of this landscape requires that first we identify and map the landforms that make up these different surfaces. Are they aggradational surfaces that have built vertically and are stacked atop each other (Fig. 5B)? Are they terraces that have become perched as the channel has incised into the landscape (Fig. 5C)? Or, are they more complex structures containing erosional strath-like terraces created within palaeo-basin fill sediments and atop which floodplain and fan deposits have been deposited (Fig. 5D)? The correct answer in this instance is Fig. 5D. This is a telescopic alluvial fan, a feature that can be defined as: fan-shaped deposits that form at the break in slope when a stream or river debouches from its source zone in a mountain range or other confined drainage system. Incision and valley expansion create sufficient accommodation space to allow generation and preservation of sequences of discrete, progressively lower fan or cone shaped topographic surfaces constructed from reworked and stacked coarse grained fluvially transported sediment (e.g., stream flow, sheet-flooding and/or debris flows) where the radial extent of each surface is greater than the preceding topographic surface.

To determine that Fig. 5D is correct required identification and mapping of the different surfaces, examining their pattern (asymmetry), shape (flat vs slightly convex), and their position and juxtaposition relative to each other and the tributary and trunk stream channels. This was followed by looking below the surface to interpret the sedimentology and stratigraphy of the sediments and the nature of contact boundaries between units (i.e., erosional or depositional surfaces). Other lines of evidence include dating, aerial photograph and remote sensing analysis, geophysical techniques, and local anecdotal information. With this information in-hand, the jigsaw can be put together as a sequence of timeslices. The flat surface of an inland draining basin formed prior to the generation of asymmetrical steps that reflect phases of incision. Generation of accommodation space associated with incision and lateral widening supported the formation of the telescopic alluvial fan atop these steps.

This interpretation is also informed by ergodic reasoning, wherein space for time substitution provides a logical account of the patterns of features that make up this landscape (Fryirs et al., 2012). Key relationships can be identified at two scales. First, the contemporary Yellow River that flows through downstream basin fills has much greater space to adjust than at the study site (Fig. 5). This reflects the timeframe over which basin fill deposits have been reworked (Craddock et al., 2010; Nicoll et al., 2013). Upstream-migrating knickpoints are yet to cut through the basin fill deposits upstream of Tongde, so the contemporary Yellow River sits atop the basin fill in this area. Second, ergodic components of the incision story are mirrored at a smaller scale in the valley morphology of the tributary stream at Tongde, with notable downstream widening at the confluence with the Yellow River, while upstream parts of the tributary lie atop the basin fill.

This brief account of the evolutionary story of a telescopic fan could easily have been misinterpreted if it was based on component parts of the data set, rather than the package of available information as a whole.

5. Discussion: reinvigorating the dark art of interpretation in geomorphology

Many methodological challenges accompany the ongoing revolution in geomorphology from a data-poor to a data-rich discipline. Building on long-standing diversity in approaches to geomorphic enquiry (Jennings, 1973), much depends on the questions we choose to ask, the ways data are collected, and approaches to analysis and interpretation (Ashmore, 2015; Fonstad and Zettler-Mann, 2020; Mould et al., 2018). Diversity is strength — so long as there is agreement upon ground rules in the quest for coherent synthesis! Under ideal circumstances, divergent threads of enquiry come together to create a coherent picture, so that a well-reasoned and logical argument creates a common platform for explanation with an agreed-upon evidence base. Such situations exemplify consilience, wherein various lines of evidence that are independent from, but in agreement with each other all point to the same conclusion (Wilson, 1999). In many instances, however, different interpretations may arise from a given set of information/data (Bond et al., 2007). This may reflect the theoretical lens (paradigm) through which investigations are conducted (Kuhn, 1962). Although they are often concealed, value-laden deliberations reflect the training and experience of practitioners, as cultural ideals shape human biases that influence the way prior knowledge is used to interpret data (Haraway, 1988; see also Lave et al., 2014; Tadaki et al., 2012, 2015).

As an historical and interpretive science (Frodeman, 1995), geomorphology relies heavily on observations and interpretations of patterns in landscapes, whether in the field or in remotely sensed applications. Explaining difference is a key theme of enquiry (Baker, 1999). It pays to remember that exceptions to rules and laws sometimes represent the very things that we seek to protect and look after (e.g., biodiversity management; Cullum et al., 2017). Implicitly, methodical observation of natural variation within or between sites, and along gradients where hypothesized forcing factors are thought or known to vary, provides a platform from which to discern unexpected or anomalous findings (i.e., something that is unusual, or does not seem to fit; Mogk and Goodwin, 2012).

A multiple lines of evidence approach to landscape interpretation is not a linear analytical process that can be easily taught and meaningfully performed using formulaic sets of procedures. Experience, patience and persistence can help, as an ability to get your eye in surely helps efforts to find that quirky piece of evidence in the field. This is not entirely serendipitous. It entails an instinctive sense of where to look in the first instance, and intuitive appreciation of the significance of what you may be looking at when you find it. Conventional field skills include a foundation ability to read the landscape, framing analyses of material properties (e.g., pedology, sedimentology, weathering processes) in context of understandings of Quaternary Science. Depending on circumstances, incorporation of local and traditional understandings may be required alongside numerical competencies, computer programming and data science skillsets (e.g., Hikuroa et al., 2018).

Interpretation in geomorphology is not all about modernity and the whizz-bang excitement of new technologies. As prescriptive tools and algorithms selectively seek particular attributes and behaviours, such practices hear and analyse particular voices of a landscape, possibly missing elements of the chorus that reflect the full suite of orchestral movements (Brierley, 2020). Digital worlds of virtual landscapes reflect a contemporary preoccupation with computational programming and technical excellence, increasingly pushing aside conventional concerns for training in Reading the Landscape (Fryirs and Brierley, 2013).

Fig. 6 presents an example of complementary learnings generated when emerging modelling applications are viewed alongside conventional approaches to interpretation in geomorphology. This figure compares a semi-automated approach to reading the landscape for a reach of the Padsan River in the Philippines with an expert manual approach. The Geomorphic Unit Tool (GUT; Williams et al., 2020) was used to map river character from a national-scale DEM that was acquired using airborne IfSAR technology (Grafil and Castro, 2014). Fig. 6A shows the unit shape and form output from GUT. Fig. 6B shows change in the planimetric position and extent of the Padsan River's active channel between 1989 and 2020, using Landsat satellite imagery and a computational workflow implemented in Google Earth Engine (GEE; Boothroyd et al., 2021a, 2021b). The expert manual approach was undertaken by a trained geomorphologist using visual assessment of boundaries and shapes, position and distinctiveness to map geomorphic units (Fig. 6C). Each unit is named using a conventional set of procedures (see Fryirs and Brierley, 2018; Wheaton et al., 2015). Different shades, distinctiveness and positions relative to the thalweg inform the interpretation of units and assessment of river adjustments over time (Fig. 6D). A synergy is evident between the geographic extent of topographic unit shapes and forms identified by GUT (Fig. 6A) and the geomorphic units that are mapped using the expert manual approach (Fig. 6C). This is despite the use of different input data (topography for GUT; imagery for expert manual). However, it should be noted that GUT only resolves units within the bankfull extent whereas the expert-manual approach extends the classification to the floodplain. The maps produced for river adjustment (Fig. 6B) are different in the interpretations that they enable. The interpretation of the map produced from an analysis of Landsat imagery in GEE quantifies past change based on a historic record. River migration is evident between 1989/90 and 2009/10 but the Padsan River narrows between 2009/10 and 2019/20. Although this information, by itself, does not explain why such narrowing occurred, geomorphic interpretations can contextualise and explain these adjustments. The expert manual interpretation of river adjustment is based upon logical and likely sequences of adjustment that are expected for this type of river using one image taken at one time (2018). If historical images had also been used and stacked (as per GEE workflow), timeframes of adjustment could have been added, aiding interpretation of the pattern of channel narrowing identified by GEE.

Modelling simulations and machine learning applications of a virtual world provide a valuable resource to compare against, helping to determine what does not fit. However, they cannot explain such differences. Hence, such applications should be conceived as an additional tool within the geomorphic armoury, to be used alongside field insights and local/traditional knowledges to enhance the dark art of interpretation in geomorphology, not as a replacement (Roering et al., 2013; see Fig. 2). Unless handled appropriately, emerging datasets and techniques will not achieve their generative potential. Rather, they will merely reflect another instance of “new wine in old bottles” (cf., Fonstad and Zettler-Mann, 2020; Sack, 1992).

In the rush to technological maturity, conceptualised as a world that is driven by artificial intelligence, it is important to remember the power of imagination and the role of the brain as a conscious and ethical filter that generates understanding and ascribes meaning. These are deeply moral and ethical concerns (cf., Inkpen, 2018; Inkpen et al., 2020). Used effectively, emerging datasets, technologies and modelling applications present unprecedented opportunities to develop and apply place-based geomorphic understandings. Systematic data availability and associated understandings of landscapes present intriguing prospects for the democratisation of geomorphic knowledge, supporting management applications that work with each and every landscape. Living databases and careful use of archetypes increasingly aid comparison of like-with-like to support reliable transfer of understandings from one situation to another (Cullum et al., 2017; Eisenack et al., 2021). How are we going to meet the generative potential presented by these prospects? Who gets to derive and tell these stories? Who fashions and writes the algorithms that interpret landscapes or create digital/virtual representations of these systems (Brown and Pasternack, 2019; O'Neil, 2016)? Who determines what counts as data or evidence in such deliberations? What approaches to analysis and interpretation do we choose to use? How do we interrogate machine learning outputs that are pre-configured in particular ways? Who decides upon numerical modelling strategies for calibration and sensitivity analysis? Are outputs verifiable and considered to be knowledge? How can these developments meaningfully and reliably support busy river managers who do not have the time to undertake intensive field investigations? In the process of ascribing meaning, it is important to remember that just because increasingly sophisticated models and toolkits are increasingly less wrong, it does not make them right (cf., Oreskes et al., 1994). What constitutes evidence or proof of notional truths, relative to rumour or mischievous misinterpretations? Who acts as the gatekeeper of knowledge in such deliberations (Jeschke et al., 2019)? Inappropriate use of algorithms is not fake news, it is simply bad science. Sadly, the manipulators of fake news, with their malicious intent to systematically pollute information with misleading interpretations, care little for such concerns.

Although we consider the dark art of interpretation to lie at the heart of landscape science, we are not arguing that all geomorphologists need to do this. However, unless specialist skills are incorporated within generalist analyses that use best available information to describe and explain landscape phenomena, we limit prospects for reliable prediction of prospective landscape futures. By extension, management practices that build upon such understandings will fail to meet their potential. Hence, all interpretations should be subject to testing and verification to appraise the reliability of inferences and associated predictions. Inevitably, findings are open to re-interpretation in light of changing

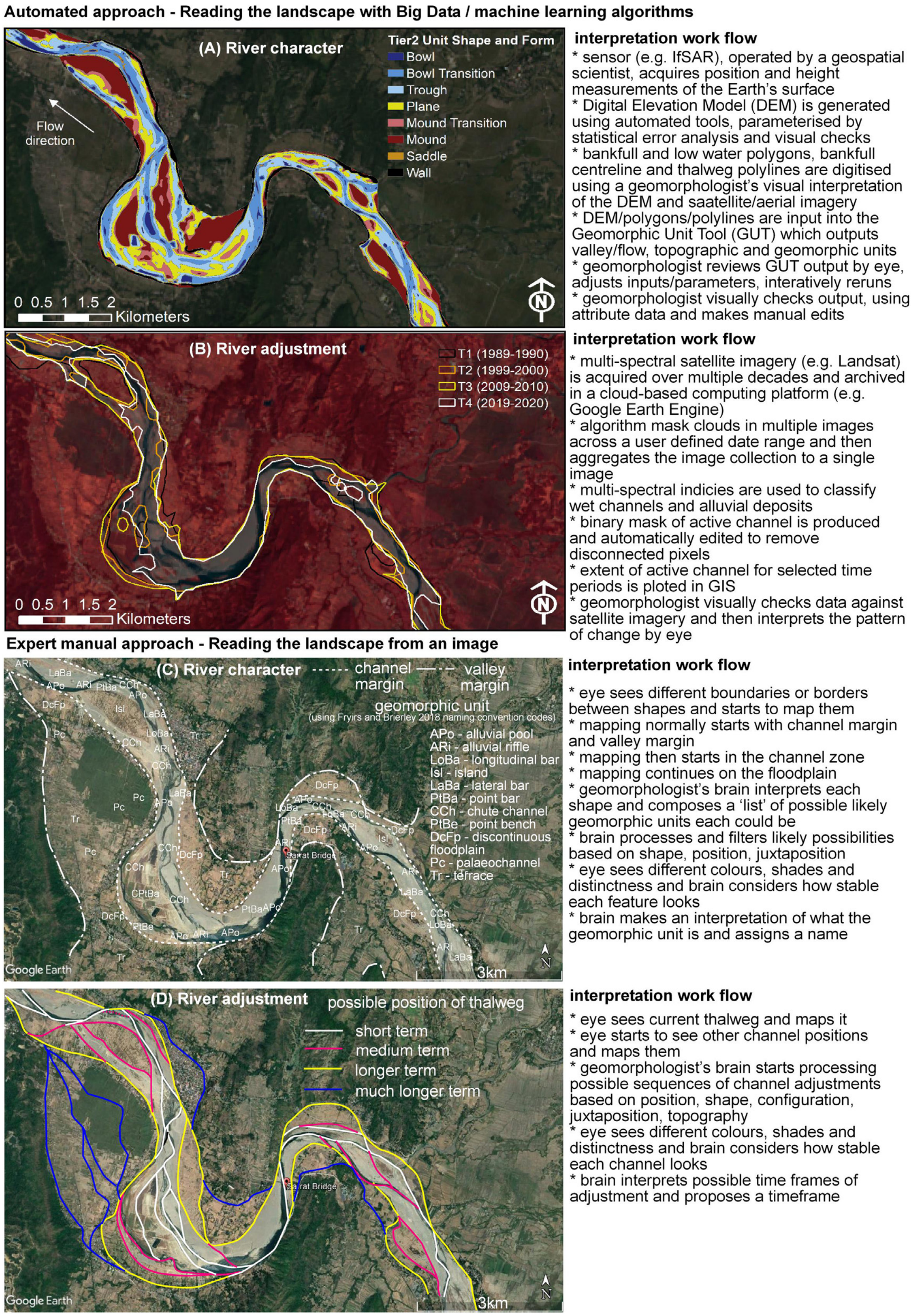

Fig. 6. Comparison between an automated approach and expert manual approach to Reading the Landscape. Base image in (A) is a false colour image of Landsat short-wave infrared, red and green bands, (B) is a Landsat true colour image, and (C) and (D) are true colour images from Google Earth.

circumstances and new understandings that provide more powerful explanations. As highlighted by Kennedy (2008), scientific framings and available chronologies shape changing ways of knowing the world that build iteratively, and selectively, on what has gone before.

Ultimately, interpretations must make demonstrable sense in the field, accompanied by confirmatory evidence. Such deliberations are not always entirely rational. Sometimes interpretations, answers and notional solutions simply do not feel right. In the quest for rational explanations it pays to remember that just because we cannot empirically prove something (yet), it does not mean that it is not right. Such are the uncertain and emergent realities of geomorphic enquiry. But therein lies unlimited potential for playful and generative encounters. To us, the dark art of interpretation needs to emerge from the shadows, taking its rightful place at heart of geomorphic endeavour.

6. Concluding comment

Geomorphologically-informed management practices respect and represent place-based values, appropriately contextualising empirical observations and understandings in relation to general (theoretical) principles (Brierley et al., 2013). Processes of interpretation are critical to such goals, carefully acknowledging and openly documenting the rationale and underlying assumptions at each stage of the investigative process, such that the premises of the supporting evidence base are laid bare and are open to interrogation. The dark art of geomorphic interpretations of landscapes outlined in this paper integrates field-based insights, local understandings and Big Data in a quest to support locally grounded management applications. Just as management actions should have a clearly specified rationale and justification, such that decision-makers can be held accountable for their determinations, scientifically-informed interpretations and explanations should be fit-for-purpose, with an accompanying evidence base and comment on associated reliability of assertions and predictions.

Here we contend that geomorphology will not meet its potential to inform management applications unless data-rich *descriptions* of landforms and landscapes are accompanied by careful interpretations that *explain* how and why landscapes look and behave as they do, thereby guiding reliable *predictions* of landscape behaviour and evolution. Essentially, we see Big Data and the technology revolution as an opportunity to compliment, confirm, speed-up or value-add supporting evidence to read a landscape using a Describe-Explain-Predict approach (Figs. 1 and 2). Efforts to respect the inherent diversity of landscapes are conceptualised as an open-minded process of exploration — a mental quest to explain particular circumstances in an appropriately contextualised manner.

Declaration of competing interest

The authors express that there is no conflict of interest in the conduct of this research and the writing of this paper.

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