Gondwana-Land goes Europe

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Abstract

One of the most long-lasting scientific achievements of Eduard Suess was the recognition of the terrestrial, particularly interglacial Upper Paleozoic (Permian) flora (incl. Glossopteris sp.) on different southern continents and he coined the term Gondwana-Land for this paleogeographic entity. He believed that the southern continents were connected by land bridges crossing the oceans. Later, the name Gondwana was used for the southern supercontinent, which formed during the Pan-African orogeny, and Gondwana collided with Laurussia, together forming the Pangea supercontinent during the Variscan orogeny. In this contribution, the fact is reviewed that pieces of West Gondwana became detached and crossed the Paleo-Tethys and Rheic Oceans to accrete to the northern continental block, Laurussia, during the Variscan orogeny. Based on published U-Pb detrital zircon ages from Variscan and Alpine Europe, all with a significant 1.0 to 1.2 Ga-age population, four potential paleogeographic derivations of Variscan Europe are discussed: (1) the classical hypothesis with an origin in North Africa, (2) the NW-Africa/South America (Amazonia) hypothesis, (3) a NE African/ Arabian origin with a close relationship to the Early Paleozoic Gondwanan super-fan originating in the East Africa-Antarctica orogen and (4) a far-travelled microplate from the eastern part of the Prototethys.

Eine der wichtigsten wissenschaftlichen Konzepte mit Langzeitwirkung von Eduard Suess war die Erkenntnis des Vorkommens von terrestrischen, teilweise interglazialen jungpaläozoischen (permischen) Floren (einschließlich Glossopteris sp.) auf verschiedenen südlichen Kontinenten, wobei er für diese paläogeographische Einheit den Ausdruck Gondwana-Land prägte. Suess glaubte, dass diese südlichen Kontinente durch Landbrücken verbunden waren. Später wurde der Name Gondwana für den südlichen Superkontinent gebraucht, der u. a. während der panafrikanischen Orogenese gebildet wurde. Gondwana kollidierte schließlich während der variszischen Orogenese mit Laurussia und bildete den Superkontinent Pangäa. In diesem Beitrag wird das Faktum behandelt, dass während des Altpaläozoikums kontinentale Stück von Westgondwana absplitterten und nach Durchquerung der Paläotethys bzw. des Rheischen Ozeans an den nördlichen („europäischen“) Laurussia-Kontinent angelagert wurden. Basierend auf publizierten U-Pb-Altern von detritischen Zirkonen des variszischen und alpinen Europas, die alle einen signifikanten Anteil einer Population mit Altern von 1.0 bis 1.2 Ga führen, werden vier potenzielle Hypothesen der paläogeographischen Herkunft des variszischen Europas diskutiert: 1., die klassische Hypothese mit einer Herkunft von Nordafrika, 2., die Herkunft von Nordwestafrika/Südamerika (Amazonia-Hypothese), 3., eine Herkunft aus Nordostafrika bzw. Arabien mit einer engen Beziehung zum panafrikanischen Ostafrika-Antarktis-Orogen und 4., eine Herkunft als weitgereister Mikrokontinent vom östlichen Teil der Prototethys.

1. Introduction

One of the important and long-lasting achievements of Eduard Suess (1885) was the recognition and naming of Gondwana-Land. In his first book “Das Antlitz der Erde” (The Face of the Earth), he described the continental pieces of Africa, the Arabian Peninsula, Madagascar, and eastern India as the regions characterized by the Late Paleozoic Gondwana flora. Likely based on an earlier report (Medlicott and Blanford, 1879), Suess also described similarities between non-marine and terrestrial, particularly glacial strata. He believed that these continents were somehow connected across oceans. Other authors, such as Neumayr (1887) believed that oceans represent sunken submarine continents, and the concept of land bridges was introduced. Later, Suess (1888) extended Gondwana-Land to South America but he never included Antarctica, simply due to the lack of detailed knowledge on Antarctian geology at that time. The early history of the term Gondwana-Land, the precursor studies leading to this concept, and paleogeographic consequences are described in Thenius (1981). Particularly important is the influence of the existing Gondwana continent on the development of the continental drift theory by Wegener (1912).

Gondwana now receives much attention because the modified concept of the Gondwana supercontinent, which formed in late Neoproterozoic times and was stable over at least 300 Myr from Cambrian to Triassic times, is obviously successful. Regular large biannual conferences on research on Gondwana are held by the International Association for Gondwana Research (IAGR) and their journal “Gondwana Research” is now one of the most influential Earth Sciences journals. International research groups reflect the importance of the Gondwana concept at present but ironically also the political fact that Gondwana continental remnants largely correspond to newly Industrializing Economies and developing countries. Students of Gondwana geology developed a professional scientific society capable of competing with the established geological societies of northern industrialized countries.

2. Present usage of Gondwana

The present usage of the term Gondwana-Land and Gondwana is as follows (see also Leviton and Aldrich, 2012). As "wána" in Dravidian means land or country, Gondwána consequently means "the country of Gonds" (Şengör, 1991). Land in Gondwana-Land in the sense of continent means, therefore, "the continent of the country of Gonds" (Şengör, 1991). Gondwana-Land was originally used for the Permian continent hosting the Glossopteris flora but is no longer commonly used in this sense. The term Gondwana instead presently refers to the southern supercontinent, which was formed by amalgamation of southern continents including Africa, Arabia and South America (then often called West Gondwana) by the Panafrican/Brasilian orogeny in late Neoproterozoic times and their amalgamation with India, Antarctica and Australia, together constituting East Gondwana (Fig. 1; Torsvik and Cocks, 2013; Nance et al., 2014). This supercontinent occupied the southern hemisphere during Late Neoproterozoic to Triassic times and stretched from the South Pole to the equator. Gondwana and ribbon-like continental pieces at its front gradually drifted northwards and amalgamated with Laurentia/Baltica to form Pangea during the Variscan orogeny in Carboniferous times (Stampfli et al., 2002, 2011; Torsvik and Cocks, 2013; von Raumer et al., 2013). Destruction of Gondwana and Pangea started in Early Jurassic times as a result of the opening of the mid-Atlantic ocean, whereas the South Atlantic and Indian Oceans did not open until the Early Cretaceous (Stampfli and Borel, 2002 and references therein). In summary, this means that the term Gondwana was gradually used for the coherent Early Paleozoic southern supercontinent. The formation and existence had a significant influence on the evolution of biota (Squire et al., 2006; Meert and Lieberman, 2008).

Consequently, Gondwana-Land was a continent in existence for more than 300 Myrs surrounded by oceans and this continent is now generally referred to as Gondwana or the Gondwana supercontinent. After its formation, Gondwana was surrounded by the Panthalassa Ocean and subduction prevailed only along the northeastern margin of West Gondwana (e.g., Nance and Murphy, 1994; Stern, 1994). Later, rifting was the

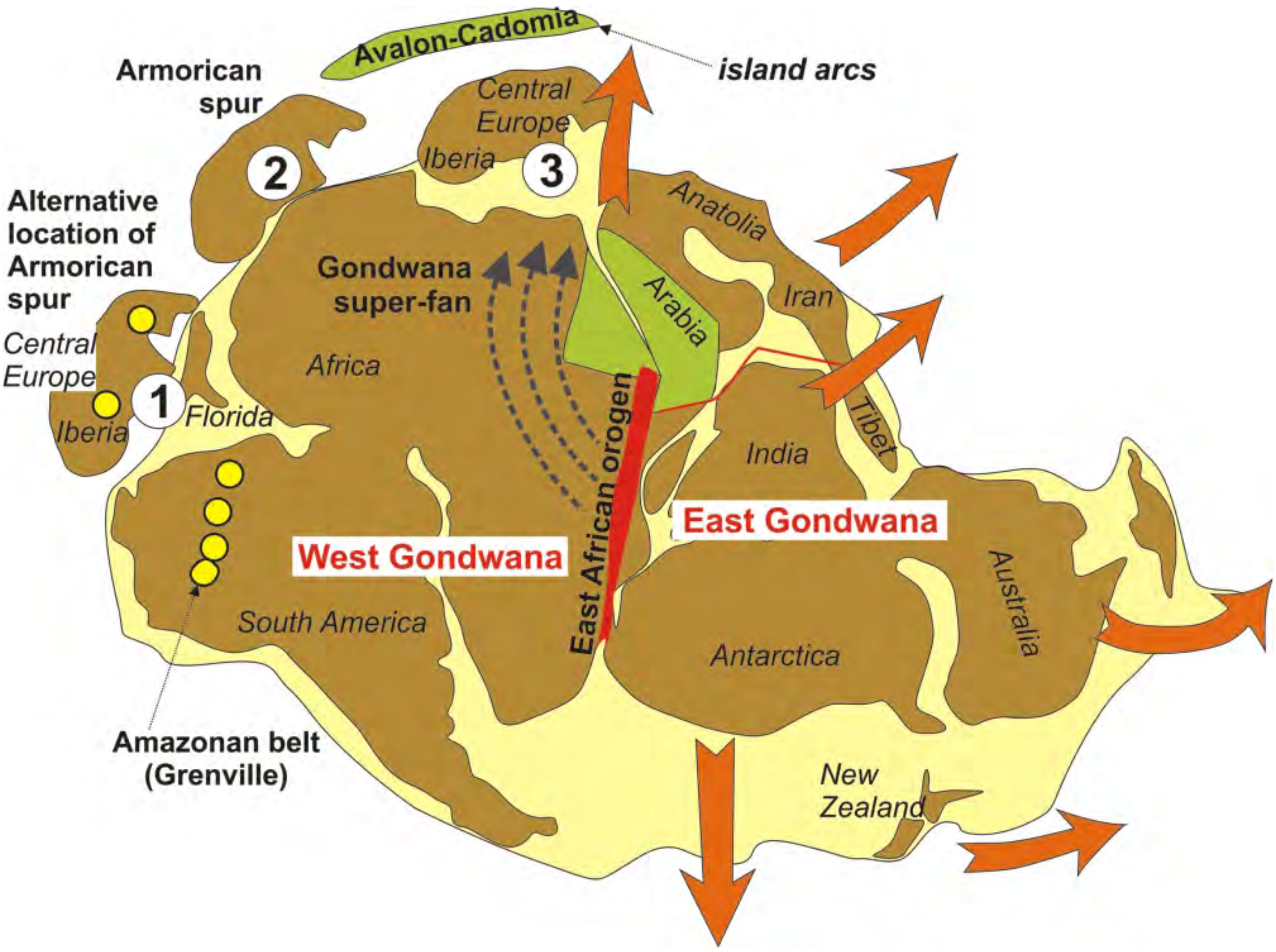

Figure 1: The Gondwana supercontinent after amalgamation of West and East Gondwana resulting from the formation of the East African orogen. Kroner and Romer (2013) recently postulated a northern continental prolongation called the Armorican Spur, which largely corresponds to the western part of the European Variscides. The Armorican Spur might have been located much further to the west close to the Amazonian belt ("Alternative location of the Armorican spur"). Early Paleozoic Gondwana super-fan dispersing material from the East African orogen is shown after Meinhold et al. (2013). Encircled 1, 2 and 3 relate to models discussed in the text. Red arrows show the direction of Paleozoic dispersal of Gondwana-derived terranes.

predominant process along most other margins during Paleozoic times (e.g., von Raumer et al., 2003, 2013 and references therein; see below). The Gondwana-Land continent was stable from ca. Cambrian to Late Triassic. The Permian Glossopteris flora was the main argument of Suess for postulating the Gondwana-Land supercontinent.

3. Present models on formation of the Gondwana continent

Gondwana was formed by amalgamation of West and East Gondwana as a result of the Panafrican closure of the Mozambique Ocean between the East and West Gondwana continents, and the Mozambique shear belt is the result of the closure (Fig. 1; Shackleton, 1996; Windley, 1995; Grantham et al., 2003; Fritz et al., 2005, 2013; Squire et al., 2006; Viola et al., 2008; Abu-Alam et al., 2013; Nance et al., 2014). The Panafrican, respectively the Brasilian orogenic events are characterized by amalgamation of subordinately Archean and dominating Lower Proterozoic cratons by continent-continent collision over a wide span of events ranging from ca. 670 to 500 Ma (Veevers, 2004). In all these orogenic belts, amphibolite-/migmatite- to granulite-grade metamorphism are common, together with widespread intrusions of leucogranites. Orogenic belts are often overprinted by strike-slip shear belts (e.g., Fritz et al., 2005). Subduction zones only existed along a few margins, particularly in future northeast Africa (consisting of Arabia, eastern Egypt, Sudan and Ethiopia). These terrains are occupied by island arc successions dominated by plutons and volcanics and various types of ophiolites whereas high-temperature metamorphism is subordinate. Within West Gondwana, Grenvillian tectonic elements occur mainly in the interior and, along northern Gondwana margins, only in the Amazonian shield in South America (Nance et al., 2014).

4. Gondwana remnants in Europe

As mentioned before, the Gondwana-Land concept refers to Permian paleogeography of a southern supercontinent and the term was later extended back until its formation during late Proterozoic "Panafrican"/Brasilian tectonic events (Kennedy, 1964, for the term Panafrican). In plate tectonic models since the advent of new global tectonics, continental fragments incorporated within Alpine-Mediterranean mountain belts in southern Europe, e.g. the Adriatic microplate, were often considered to represent fragments of Africa and to have moved together with Africa (e.g., Channell et al., 1979; Dewey et al., 1989; Handy et al., 2010 as the most recent review with references therein). The knowledge on elements with Gondwana affinity within the European fragments gradually grew, recognizing Ediacaran to Cambrian island arc successions within Caledonian and Variscan Western Europe such as the Cadomian-Avalon belts (see von Raumer et al., 2009; Nance and Murphy, 1994; Nance et al., 2002 for discussion of earlier papers), which were correlated with those exposed in the Arabian shield (Neubauer, 1991; Stern, 1994).

Several methods were applied to reveal the Gondwana affinities: (1) lithostratigraphic correlations like the distribution of mature Ordovician Armorican Quartzite and biogeographic considerations (Paris and Robardet (1990) and Robardet (2003 and references therein), (2) paleomagnetism and paleoclimate indicators (Tait et al., 2000; Cocks and Torsvik, 2002, 2011; Edel et al., 2013; Torsvik and Cocks, 2013). Although earlier multi-grain U-Pb zircon and $^{40}Ar/^{39}Ar$ white mica analysis recognized Panafrican elements in Variscan and Alpine Europe (e.g., Dallmeyer and Neubauer, 1994), single-grain U-Pb zircon and $^{40}Ar/^{39}Ar$ white mica provenance studies confirmed that nearly all portions of Variscan and Alpine Europe show a provenance relationship to West Gondwana (e.g. Linnemann et al., 2004, 2007; Nance et al., 2008; Neubauer et al., 2007). In this review, mainly detrital U-Pb zircon ages are used for discussion although an update of biogeographic data might allow many further insights (Schönlaub, 1993; Cocks and Torsvik, 2002).

Aside from some sedimentary units of western Europe such as the Ordovician Armorican Quartzite within Armorica (Fig. 1; Fernández-Suarez et al., 2002a and references therein), for which sedimentary linkages to northern Africa were postulated in the past, potential West Gondwana-Land tectonic elements dispersed and incorporated within other orogenic belts could be characterized by one of the following three combinations of characteristic features (for references, see next paragraph): (1) Late Proterozoic island arc successions sometimes associated with ophiolites; (2) Panafrican metamorphic and plutonic detritus with ages ranging from 500 to 670 Ma, often in combination with inherited zircons with U-Pb ages of ca. 2.0 to 2.2 Ga; (3) Panafrican metamorphic and plutonic detritus with ages ranging from 500 to 670 Ma, often in combination with inherited zircons with U-Pb ages of ca. 2.0 to 2.2 Ga and Grenvillian ages (ca. 0.9 to 1.3 Ga; Friedl et al., 2000; Nance et al., 2008).

Based on these three criteria, Gondwanan affinities were postulated within the last two decades, and these are briefly discussed. Details can be found in overview papers including Neubauer (1991, 2002), Yilmaz et al. (2013), von Raumer et al. (2013), Kroner and Romer (2013) and Nance et al. (2014).

Avalonia is a Neoproterozoic to Ordovician island/continental magmatic arc succession, which accreted to the Laurussian continent during Silurian times (Kroner and Romer, 2013; von Raumer et al., 2013, and Willner et al., 2013 and references therein). Some bear Early and Middle Proterozoic detritus, arguing for continental pieces within Avalonia (Murphy et al., 2004; Willner et al., 2013). Other major continental magmatic arc successions occur in several areas. These comprise Northern Armorica, there forming the Cadomian belt (with Lower Proterozoic crustal pieces attached in the north), the Tepla-Barrandian unit within the Bohemian Massif, the basement of the Tauern Window in the Eastern Alps as well as parts of the Austroalpine basement units together with the Speik ophiolite (Melcher and Meisel, 2004), and can also be found in the Balkan region (Kounov et al., 2012). All these units are regarded to represent one or several parts of a Cadomian belt, which continues from southeastern Europe further to the east to the Arabian-Nubian shield (Stern, 1994).

The combination of Panafrican and Early Proterozoic detrital zircon ages is quite common in metasedimentary basement units of the European Variscides and Alpine Mediterranean mountain belts, e.g. in the Rhenohercynian zone (Eckelmann et al., 2014) and in the Saxothuringian zone of the Bohemian Massif (Linnemann et al., 2004, 2007, 2012, 2014), and Austroalpine units of the Eastern Alps (Drost et al., 2011; Heinrichs et al., 2012; Klötzli, 1999; Schulz et al., 2004; Siegesmund et al., 2007) and Hellenides (Zulauf et al., 2007).

The combination of Panafrican with usually small proportions of Grenvillian detrital U-Pb zircon ages is more decisive and is typical for the Ordovician Armorican Quartzite of Armorica (Fernández-Suarez et al., 2002a, 2002b; Gutiérrez-Alonso et al., 2007), metasediments in the Ossa-Morena zone in the Iberian massif (Linnemann et al., 2008), the Central Iberian zone (Bea et al., 2010), the Mid-German crystalline rise (Zeh et al., 2001), and the Bohemian Massif (Friedl et al., 2000, Košler et al., 2014, Mazur et al., 2012), although the zircon ages of ca. 500–550 Ma are often related to Avalonia. Interestingly, recent reports argue for a similar Grenvillian detritus within Avalonia (e.g., Willner et al., 2013). Similar combinations can be found in Austroalpine units of the Eastern Alps (Klötzli, 1999; Schulz et al., 2004; Siegesmund et al., 2007; Heinrichs et al., 2012), and the Eastern and Southern Carpathians (Balintoni et al., 2010, 2011; Balintoni and Balica, 2013) and southeastern Europe (Keay and Lister, 2002; Zlatkin et al., 2014). A similar combination also occurs in southern Turkey (Anatolia in Fig. 1; Kröner and Şengör, 1990). All these units are generally derived from northern West Gondwana. Friedl et al. (2000) proposes a close paleogeographic origin in the Amazonian belt although Grenvillian units are known to be widespread within the Gondwana continent (Nance et al., 2014) but not along its northern margin. Ustaömer et al. (2011) describe Grenvillian detritus from the Istanbul terrane of northern Turkey.

Based on the hypothesis of the existence of a large Cambrian to Ordovician Gondwana super-fan transporting material from central-southern parts of the East African Orogen to the north (Squire et al., 2006), Meinhold et al. (2013) recently demonstrated a significant proportion of a Grenvillian zircon age population (ca. 1.1–0.95 Ga) in Cambrian to Upper Ordovician sandstones in eastern North Africa (overlying the Saharan metacraton) forming part of the eastern part of this Gondwana super-fan. Consequently, these authors also proposed an origin of the Grenvillian zircon age population within Variscan Europe from the eastern part of North Africa.

5. Discussion: Gondwana-Land goes Europe

Suess (1885, 1888) considered Gondwana-Land with its terrestrial Glossopteris flora to have been a Permian southern continent. Later, it became apparent that Gondwana was a supercontinent in existence from Cambrian to Triassic times. This goes back much further in time than Suess likely envisaged. The new provenance data, particularly of the last two decades, revealed that continental pieces broke away from the northern margin of Gondwana and moved northwards. Avalonia formed an island arc and moved rapidly towards the north, finally attaching to Laurussia in the Silurian after the closure of

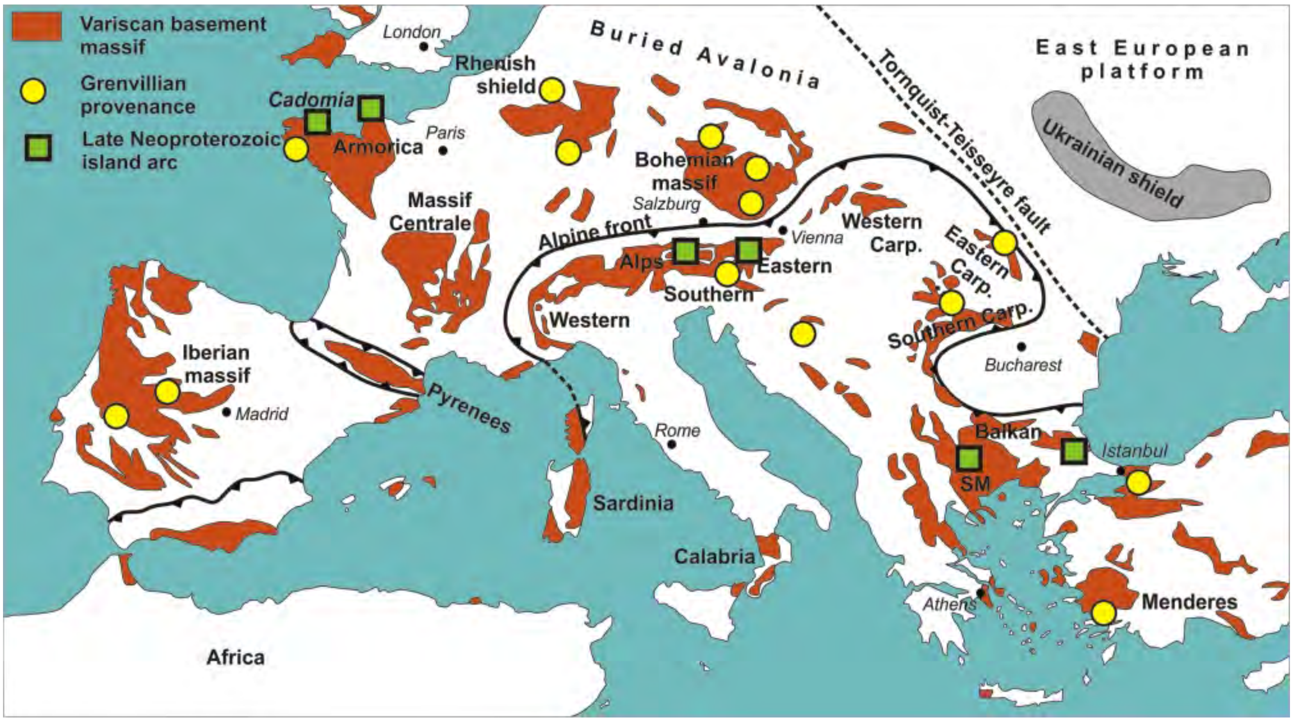

Figure 2: Basement terranes in Southern and Central Europe and record of Cadomian/Panafrican orogeny (modified after Neubauer, 2002). See text for data sources and discussion.

the Iapetus Ocean (Nance et al., 2014). Recent models argue for the motion of a major continental piece, which detached from Gondwana during Ordovician times and moved towards Laurussia and eventually collided with it (Fig. 3) after consumption of the Rheic (or Rhenohercynian) Ocean (Kroner and Romer, 2013; von Raumer et al., 2013), which may correspond to the Proto-Tethys further to the east. Based on lithological indicators of palaeoclimate and palaeobiogeographical data of Early Paleozoic strata of Western Europe and West Gondwana, Robardet (2003) concluded that the southern European regions remained permanently closely connected with Gondwana, composing the northern margin during Early Paleozoic times.

Paleogeographic relationships and detrital zircon U-Pb ages, particularly the common occurrence of Panafrican (500 – 670 Ma) and Grenvillian (1.0 to 1.2 Ga) age populations allow to distinguish four potential paleogeographic derivations of Variscan and Alpine Europe: (1) the classical hypothesis (model 1 in Fig. 1) assumes an origin close to Amazonia (e.g., Friedl, 2000); (2) another hypothesis postulates the origin as an Armorican promontory along NW Africa (model 2 in Fig. 1); (3) a recent hypothesis assumes an origin close to NE Africa and Arabia fed by the Lower Paleozoic Gondwana super-fan with its origin in the East Africa-Antarctica orogen (Meinhold et al., 2013; model 3 in Fig. 1), and (4) a far-travelled Variscan microplate from the eastern part of the Prototethys cannot be excluded.

All models also include major dextral wrenching between Gondwana and Laurussia, implying that potential Grenvillian units within Gondwana, like the Amazonian zone in the classical hypothesis (e.g., Friedl et al., 2000; model 1 in Fig. 1) or from northeastern Africa (Armorican promontory; Meinhold et al., 2013; model 2 in Fig. 1), moved away to form the future European Variscides. The wrench zone or zones are considered to be parallel to oceanic tracts (Fig. 3). Further major Grenvillian pieces may be incorporated within the Tethyan Alpine-Himalayan orogenic belt as some are known along its eastern end, in the Qinling Mountains (e.g., Dong et al., 2011).

Consequently, Central and Southern Europe was part of Gondwana, probably unlike Eduard Suess envisaged it. The Gondwana-Land concept of Suess (1885) appears to be one of his most important ideas and survived the huge accumulation of data and concepts since that time. The question is why this concept is so successful. It appears that the simplicity of

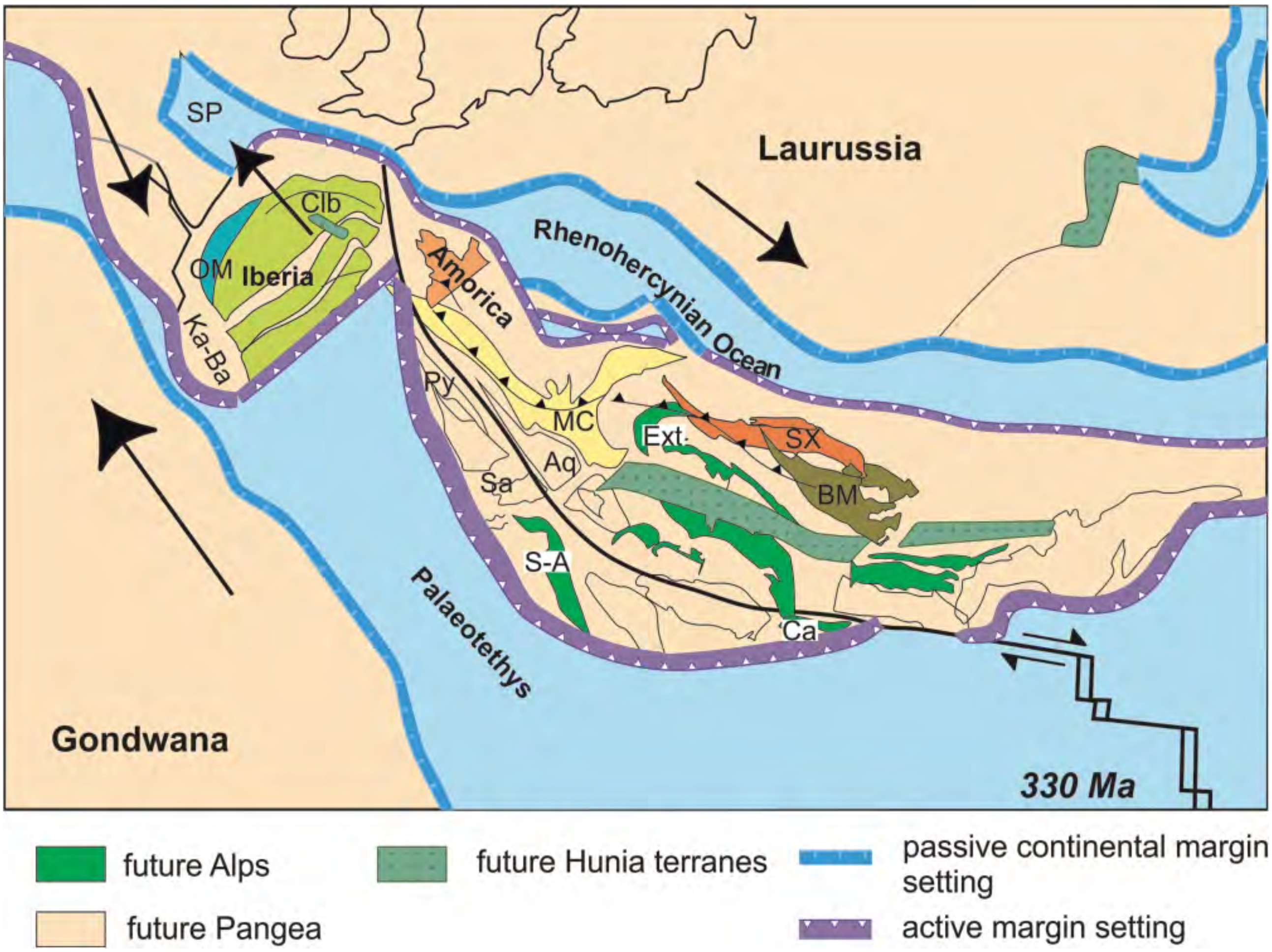

Figure 3: Paleogeographic evolution of units along northern margins of Gondwana (slightly modified after von Raumer et al., 2009, and Stampfli et al., 2013). Abbreviations: Aq: Aquitaine; BM: Bohemian Massif; Ca: Carnic Alps; CIb: Central Iberian; Ext: External Alpine domains; Ka–Ba: Kabyles– Baleares; MC: Massif Central; OM: Ossa Morena; Py: Pyrenees; Sa: Sardinia; S-A: Southern Alps; SP: future South-Portuguese Zone; SX: Saxothuringian.

the observation is the success. It was based on the observation that terrestrial plant fossils occur on different and distant continents within terrestrial rock successions, implying that all these continental pieces must have once been connected.

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References

Abu-Alam, T. S., Santosh, M., Brown, M. and Stüwe, K., 2013. Gondwana collision. Mineralogy and Petrology, 107, 631–634.

Balintoni, I. and Balica, C., 2013. Carpathian peri-Gondwanan terranes in the East Carpathians (Romania): A testimony of an Ordovician, North-African orogeny. Gondwana Research, 23, 1053–1070.

Balintoni, I., Balica, C., Seghedi, A. and Ducea, M.N., 2010. Avalonian and Cadomian terranes in North Dobrogea, Romania. Precambrian Research, 182, 217–229.

Balintoni, I., Balica, C., Ducea, M.N. and Stremţan, C., 2011. Peri-Amazonian, Avalonian-type and Ganderian-type terranes in the South Carpathians, Romania: the Danubian domain basement. Gondwana Research, 19, 945–957.

Bea, F., Montero, P., Talavera, C., Abu Anbar, M., Scarrow, J. H., Molina, J. F. and Moreno, J. A., 2010. The paleogeographic position of Central Iberia in Gondwana during the Ordovician: evidence from zircon chronology and Nd isotopes. Terra Nova, 22, 341–346.

Channell, J.E.T., D'Argenio, B. and Horvath, F., 1979. Adria, the African promontory in Mesozoic Mediterranean paleogeography: Earth-Science Reviews, 15, 213–292.

Cocks, L.R.M. and Torsvik, T.H., 2002. Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. Journal of the Geological Society London, 159, 631–644.

Cocks, L.R.M. and Torsvik, T.H., 2011. The Palaeozoic geography of Laurentia and western Laurussia: A stable craton with mobile margins. Earth-Science Reviews, 106, 1–51.

Dallmeyer, R.D. and Neubauer, F., 1994. $^{40}Ar/^{39}Ar$ age of detrital muscovites, Carnic Alps: evidence for a Cadomian linkage in the Eastern Alps. Journal of the Geological Society London, 151, 591–598.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W. and Knott, S. D., 1989. Kinematics of the western Mediterranean. In: Coward, M. P., Dietrich, D. and Park, R. G. (eds.), Alpine Tectonics, Geological Society Special Publication, 45, 265–283.

Dong, Y., Zhang, G., Neubauer, F., Liu, X., Genser, J. and Hauzenberger, C., 2011. Tectonic evolution of the Qinling orogen, China: review and synthesis. Journal of Asian Earth Sciences, 41, 213–237.

Drost, K., Gerdes, A., Jeffries, T., Linnemann, U. and Storey, C., 2011. Provenance of Neoproterozoic and early Palaeozoic siliciclastic rocks of the Teplá-Barrandian unit (Bohemian Massif): Evidence from U-Pb detrital zircon ages. Gondwana Research, 19, 213–231.

Eckelmann, K., Nesbor, H.-D., Königshof, P., Linnemann, U., Hofmann, M., Lange, J.-M. and Sagawe, A., 2014. Plate interactions of Laurussia and Gondwana during the formation of Pangaea — Constraints from U–Pb LA–SF–ICP–MS detrital zircon ages of Devonian and Early Carboniferous siliciclastics of the Rhenohercynian zone, Central European Variscides. Gondwana Research, 25, 1484–1500.

Edel, J. B., Schulmann, K. Skrzypek, E. and Cocherie, A., 2013. Tectonic evolution of the European Variscan belt constrained by palaeomagnetic, structural and anisotropy of magnetic susceptibility data from the Northern Vosges magmatic arc (eastern France. Journal of the Geological Society, 170, 785–804.

Fernández-Suarez, J., Gutiérrez-Alonso, G., Cox, R. and Jenner, G.A., 2002a. Assembly of the Armorica microplate: A strike-slip terrane delivery? Evidence from U-Pb ages of detrital zircons. Journal of Geology, 110, 619–626.

Fernández-Suarez, J., Gutiérrez-Alonso, G. and Jeffries, T. E., 2002b. The importance of along-margin terrane transport in northern Gondwana: insights from detrital zircon parentage in Neoproterozoic rocks from Iberia and Brittany. Earth and Planetary Science Letters, 240, 75–88.

Friedl, G., Finger, F., McNaughton, N. J. and Fletcher, I. R., 2000. Deducing the ancestry of terranes: SHRIMP evidence of South-America derived Gondwana fragments in Central Europe. Geology, 28, 1035–1038.

Fritz, H., Tenczer, V., Wallbrecher, C. A., Hauzenberger, E., Hoinkes, G., Muhongo, S. and Mogessie, A., 2005. Central Tanzanian tectonic map: a step forward to decipher Proterozoic structural events in the East African Orogen. Tectonics 24, TC6013, http://dx.doi.org/10.1029/2005TC001796.

Fritz, H., Abdelsalam, M., Ali, K.A., Bingen, B., Collins, A.S., Fowler, A.R., Ghebreab, W., Hauzenberger, C.A., Johnson, P.R., Kusky, T.M., Macey, P., Muhongo, S., Stern, R.J. and Viola, G., 2013. Orogen styles in the East African Orogen: A review of the Neoproterozoic to Cambrian tectonic evolution. Journal of African Earth Sciences 86, 65–106.

Grantham, G. H., Maboko, M. and Eglington, B. M., 2003. A review of the evolution of the Mozambique Belt and implications of the amalgamation and dispersal of Rodinia and Gondwana. In: Yoshida, M., Windley, B. F. and Dasgupta, S., (eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Geological Society London, Special Publication, 206, pp. 401–425.

Gutiérrez-Alonso, G., Fernández-Suárez, J., Gutiérrez-Marco, J. C., Corfu, F., Murphy, J. B. and Suárez, M., 2007. U-Pb depositional age for the upper Barrios Formation (Armorican Quartzite facies) in the Cantabrian zone of Iberia: Implications for stratigraphic correlation and paleogeography. In: Linnemann, U., Nance, R.D., Kraft, P. and Zulauf, G. (eds.), The evolution of the Rheic Ocean: From Avalonian-Cadomian active margin to Alleghenian-Variscan collision. Geological Society of America Special Paper, 423, pp. 287–296.

Handy, M.R., Schmid, S., Bousquet, R., Kissling, E. and Bernoulli, D., 2010. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. Earth-Science Reviews, 102, 121–158.

Heinrichs, T., Siegesmund, S., Frei, D., Drobe, M. and Schulz, B., 2012. Provenance signatures from whole-rock geochemistry and detrital zircon ages of metasediments from the Austroalpine basement south of the Tauern Window (Eastern Tyrol, Austria). Geo.Alp, 9, 156–185.

Keay, S. and Lister, G.S., 2002. African provenance for the metasediments and metaigneous rocks of the Cyclades, Aegean Sea. Geology, 30, 235–238.

Kennedy, W.Q., 1964. The structural differentiation of Africa in the Pan-African (±500 m.y.) tectonic episode. Leeds University Research Institute of African Geology, Annual Report, 8, 48–49.

Klötzli, U. S., 1999. Resolving complex geological histories by zircon dating: a discussion of case studies from the Bohemian Massif and the Eastern Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft, 90, 31–41.

Košler, J., Konopásek, J., Sláma, J. and Vrána, S., 2014. U–Pb zircon provenance of Moldanubian metasediments in the Bohemian Massif. Journal of the Geological Society, London, 171, 83–95.

Kounov, A., Graf, J., von Quadt, A., Bernoulli, D., Burg, J.-P., Seward, D., Ivanov, Z. and Fanning, M., 2012. Evidence for a “Cadomian” ophiolite and magmatic-arc complex in SW Bulgaria. Precambrian Research, 212–213, 275–295.

Kroner, U. and Romer, R. L., 2013. Two plates — Many subduction zones: The Variscan orogeny reconsidered. Gondwana Research 24, 298–329.

Kröner, A. and Şengör, A.M.C., 1990. Archean and Proterozoic ancestry in late Precambrian to early Paleozoic crustal elements of southern Turkey as revealed by single-zircon dating. Geology, 18, 1186–1190.

Leviton, A. and Aldrich, M. L. 2012. Contributions of the Geological Survey of India, 1851–1890, to the concept of Gondwana-Land. Earth Sciences History, 31, 247–269.

Linnemann, U., McNaughton, N.J., Romer, R.L., Gehmlich, M., Drost, K., Tonk, C., 2004. West African provenance for Saxo-Thuringia (Bohemian Massif): did Armorica ever leave pre-Pangean Gondwana? – U/Pb–SHRIMP zircon evidence and the Nd isotopic record. International Journal of Earth Sciences, 93, 683–705.

Linnemann, U., Gerdes, A., Drost, K. and Buschmann, B., 2007. The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany). In: Linnemann, U., Nance, D., Kraft, P. and Zulauf, G. (eds.), The Evolution of the Rheic Ocean: From Avalonian-Cadomian active margin to Alleghenian-Variscan collision. Geological Society of America Special Paper, 423, pp. 61–96.

Linnemann, U., Pereira F., Jeffries, T. E. Drost, K. and Gerdes, A., 2008. The Cadomian Orogeny and the opening of the Rheic Ocean: The diachrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). Tectonophysics, 461, 21–43.

Linnemann, U., Herbosch, A., Liégeois, J-P., Pin, C., Gärtner, A., Hofmann, M., 2012. The Cambrian to Devonian odyssey of the Brabant Massif within Avalonia: A review with new zircon ages, geochemistry, Sm–Nd isotopes, stratigraphy and palaeogeography. Earth-Science Reviews, 112, 126–154.

Linnemann, U., Gerdes, A., Hofmann, M., Marko, L., 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton—Constraints from U–Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). Precambrian Research, 244, 236–278.

Mazur, S., Szczepanski, J., Turniak, K. and McNaughton, N.J. 2012. Location of the Rheic suture in the eastern Bohemian Massif: evidence from detrital zircon data. Terra Nova, 24, 199–206.

Meert, J. G. and Lieberman, B. S., 2008. The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran–Cambrian radiation. Gondwana Research, 14, 5–21.

Medlicott, H.B. and Blanford, W.T., 1879. A Manual of the Geology of India. Geological Survey of India, Calcutta.

Meinhold, G., Morton, A. C. and Avigad, D., 2013. New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U–Pb ages. Gondwana Research, 23, 661–665.

Melcher, F. and Meisel, T., 2004. A Metamorphosed Early Cambrian Crust–Mantle Transition in the Eastern Alps, Austria. Journal of Petrology, 45, 1689–1723.

Murphy, J.B., Fernández-Suárez, J., Jeffries, T.E. and Strachan, R.A., 2004. U–Pb (LA-ICP-MS) dating of detrital zircons from Cambrian clastic rocks in Avalonia: erosion of a Neoproterozoic arc along the northern Gondwanan margin. Journal of the Geological Society London, 161, 243–254.

Nance, R. D. and Murphy, J. B., 1994. Contrasting basement isotopic signatures and the palinspastic restoration of peripheral orogens: example from the Neoproterozoic Avalonian–Cadomian belt. Geology, 22, 617–620.

Nance, R. D., Murphy, J. B. and Keppie, J. D., 2002. A Cordilleran model for the evolution of Avalonia. Tectonophysics, 352, 1–21.

Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutiérrez-Alonso, G., Fernández-Suárez, J., Quesada, C., Linnemann, U., D'Lemos, R. and Pisarevsky, S.A., 2008. Neoproterozoic–early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes: Amazonian v. West African connections. Geological Society, London, Special Publications, 297, 345–383.

Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A. and Woodcock, N. H., 2010. Evolution of the Rheic Ocean. Gondwana Research, 17, 194–222.

Nance, R. D., Murphy, J. B. and Santosh, M., 2014. The supercontinent cycle: A retrospective essay. Gondwana Research, 25, 4–29.

Neubauer, F., 1991. Late Proterozoic and Early Paleozoic Tectonothermal Evolution Of The Eastern Alps. In: Dallmeyer, R. D. and Lecorché, C.P. (eds.), Westafrican orogens and their correlatives. Berlin (Springer), pp. 307–314.

Neubauer, F., 2002. Evolution of late Neoproterozoic to early Paleozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. Tectonophysics, 352, 87–103.

Neubauer, F., Friedl, G., Genser, J., Handler, R. Mader, D. and Schneider, D., 2007. Origin and tectonic evolution of Eastern Alps deduced from dating of detrital white mica: a review. Austrian Journal of Earth Sciences, 100, 8–23.

Neumayr, M., 1887. Erdgeschichte II. Beschreibende Geologie. XII + 880 p., (Bibl. Inst.), Leipzig.

Paris, F. and Robardet, M., 1990. Early Palaeozoic palaeobiogeography of the Variscan regions. Tectonophysics, 177, 193–213.

Robardet, M., 2003. The Armorica ‘microplate’: fact or fiction? Critical review of the concept and contradictory palaeobiogeographical data. Palaeogeography Palaeoclimatology Palaeoecology, 195, 125–148.

Schönlaub, H. P., 1993. Stratigraphy, biogeography and climatic relationships of the Alpine Palaeozoic. In: von Raumer, J. and Neubauer, F. (eds.), The Pre-Mesozoic Geology in the Alps. Springer, Berlin, Heidelberg, New York, 65–92.

Schulz, B., Bombach, K., Pawlig, S. and Brätz, H., 2004. Neoproterozoic to Early-Palaeozoic magmatic evolution in the Gondwana-derived Austroalpine basement to the south of the Tauern Window (Eastern Alps). International Journal of Earth Sciences (Geologische Rundschau), 93, 824–843.

Şengör, A. M. C., 1991. Difference between Gondwana and Gondwana-Land. Geology, 19, 287–288.

Shackleton. R.M., 1996. The final collision zone between East and West Gondwana: where is it? Journal of African Earth Sciences, 23, 271–287.

Siegesmund, S., Heinrichs, T., Romer, R.L. and Doman, D., 2007. Age constraints on the evolution of the Austroalpine basement to the south of the Tauern Window. International Journal of Earth Sciences, 96, 415–432.

Squire, R.J., Campbell, I.H., Allen, C.M. and Wilson, C.J.L., 2006. Did the Transgondwanan Supermountain trigger the explosive radiation of animals on Earth? Earth and Planetary Science Letters, 250, 116–133.

Stampfli, G.M. and Borel, G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth and Planetary Science Letters, 196, 17–33.

Stampfli, G.M., von Raumer, J. F. and Borel, G., 2002. The Paleozoic evolution of pre-Variscan terranes: from Gondwana to the Variscan collision. In: Martinez Catalan, J., Hatcher, R. D., Jr., Arenas, R. and Díaz García, F. (eds.), Variscan-Appalachian Dynamics: the Building of the Late Paleozoic Basement. Geological Society of America Special Paper, 364, pp. 263–280.

Stampfli, G. M., von Raumer, J. F. and Wilhem, C., 2011. The distribution of Gondwana derived terranes in the early Paleozoic. In: Gutiérrez-Marco, J.C., Rábano, I. and García-Bellido, D. (eds.), The Ordovician of the World. Instituto Geológico y Minero de España, Cuadernos del Museo Geominero (Madrid), 14, pp. 567–574.

Stampfli, G. M., Hochard, C., Vérard, C. Wilhem, C. and von Raumer, J., 2013. The formation of Pangea. Tectonophysics, 593, 1–19.

Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African orogen: implications for the consolidation of Gondwanaland. Annual Reviews of Earth and Planetary Sciences, 22, 119–151.

Suess, E., 1885. Das Antlitz der Erde I-III/2. Prag & Leipzig (Tempsky & Freytag) 1885.

Suess, E., 1888. Das Antlitz der Erde, Zweiter Band. Tempsky, Prague, 703 pp.

Thenius, E. 1981. Das „Gondwana-Land" Eduard SUESS 1885 Der Gondwanakontinent in erd- und biowissenschaftlicher Sicht. Mitteilungen der Österreichischen Geologischen Gesellschaft, 74/75, 1981/82, 53–81.

Tait, J., Schätz, M., Bachtadse, V., Soffel, H., 2000. Palaeomagnetism and Palaeozoic palaeogeography of Gondwana and European terranes. In: Franke, W., Haak, V., Oncken, O., Tanner, D. (eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society London Special Publication, 179, 21–34.

Torsvik, T. H. and Cocks, L. R. M., 2013. Gondwana from top to base in space and time. Gondwana Research, 24, 999–1030.

Ustaömer, P. A., Ustaömer, T., Gerdes, A. and Zulauf, G., 2011. Detrital zircon ages from a Lower Ordovician quartzite of the Istanbul terrane (NW Turkey): evidence for Amazonian affinity. International Journal of Earth Sciences, 100, 23–41.

Veevers, J.J., 2004. Gondwanaland from 650–500 Ma assembly through 320 Ma merger in Pangea to 185–100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. Earth-Science Reviews, 68, 1–132.

Viola, G., Henderson, I. H. C., Bingen, B., Thomas, R. J., Smethurst, M. A., and de Azavedo, S., 2008. Growth and collapse of a deeply eroded orogen: Insights from structural, geophysical, and geochronological constraints on the Pan-African evolution of NE Mozambique. Tectonics, 27, TC5009, doi:10.1029/2008TC002284.

von Raumer, J. F., Stampfli, G.M. and Bussy, F., 2003. Gondwana-derived microcontinents: The constituents of the Variscan and Alpine collisional orogens. Tectonophysics, 365, 7–22.

von Raumer, J. F., Bussy, F. and Stampfli, G. M., 2009. The Variscan evolution in the External massifs of the Alps and place in their Variscan framework. Compte Rendue Geoscience, 341, 239–252.

von Raumer, J. F., Bussy, F., Schaltegger, U., Schulz, B. and Stampfli, G. M., 2013. Pre-Mesozoic Alpine basements – their place in the European Paleozoic framework. Geological Society of America Bulletin, 125, 89–108.

Wegener, A., 1912. Die Entstehung der Kontinente. Petermanns Mitteilungen, 58, 185–195, 253–256, 305–309, Gotha.

Willner, A. P., Barr, S. M., Gerdes, A., Massonne, H.-J. and White, C. E. , 2013. Origin and evolution of Avalonia: evidence from U–Pb and Lu–Hf isotopes in zircon from the Mira terrane, Canada, and the Stavelot–Venn Massif, Belgium. Journal of the Geological Society London, 170, 769–784.

Windley, B.F., 1995. The Evolving Continents. Third edition. Wiley, Chichester, pp. XVI + 526.

Yilmaz, Ş., Aysal, N., Gungör, Y., Peytcheva, I. and Neubauer, F., 2013. Geochemistry and U-Pb Zircon Geochronology of Metagranites in Istranca Zone, NW Pontides, Turkey: Implications for the Geodynamic Evolution of Cadomian Orogeny. Gondwana Research, doi.org/10.1016/j.gr.2013.07.011.

Zeh, A., Brätz, H., Millar, I.L. and Williams, I. S., 2001. A combined zircon SHRIMP and Sm-Nd isotope study of high-grade paragneisses from the Mid-German Crystalline Rise: Evidence for northern Gondwanan and Grenvillian provenance. Journal of the Geological Society London, 158, 983–994.

Zlatkin, O., Avigad, D. and Gerdes, A. 2014. Peri-Amazonian provenance of the Proto-Pelagonian basement (Greece), from zircon U–Pb geochronology and Lu–Hf isotopic geochemistry. Lithos, 184–187, 379–392.

Zulauf, G., Romano, S.S., Dörr,W. and Fiala, J., 2007. Crete and the Minoan terranes: age constraints from U–Pb dating of detrital zircons. In: Linnemann, U., Nance, R.D., Kraft, P. and Zulauf, G. (eds.), The Evolution of the Rheic Ocean: From Avalonian–Cadomian Active Margin to Alleghenian–Variscan Collision. Geological Society of America Special Paper, 423, pp. 401–411.

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