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Comment on “Relict Basin Closure and Crustal Shortening Budgets During Continental Collision: An Example From Caucasus Sediment Provenance” by Cowgill et al. (2016)

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Key Points:

- Cowgill et al.’s model for Greater Caucasus Basin closure at 5 Ma is not supported by any sedimentological, provenance, or structural data
- Oligo-Miocene samples were instead deposited in the southern foreland of the Greater Caucasus following basin closure at ~35 Ma
- Their sparse Jurassic to Eocene provenance data set is insufficient to provide any meaningful insights into the former width of the basin

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Plain Language Summary The southern slope of the Greater Caucasus mountains is the site of a former rift basin. In order to explain shortening deficits, plate deceleration, and the ~5 Ma reorganization of the Arabia-Eurasia collision zone Cowgill et al. (2016) proposed that this basin closed ~5 Myrs ago. Within the western Greater Caucasus, at least, careful examination of sedimentological, provenance, and seismic data, however, supports an earlier ~35 Ma basin closure age. Basin closure cannot therefore be the driving mechanism for the ~5 Ma deceleration of the Arabian plate and reorganization of the Arabia-Eurasia collision zone.

1. Introduction

Cowgill et al. (2016) presented a provocative model for the tectonic development of the southern flank of the Greater Caucasus that linked the 5 Ma closure of a “relic ocean basin”, the Greater Caucasus Basin, to Arabian plate deceleration and the reorganization of the Arabia-Eurasia collision zone. They also used a ~350–400 km width estimate for the former basin to reconcile postcollisional shortening deficits across the Arabia-Eurasia collision zone.

While Cowgill and his coauthors provided a succinct summary of the tectonic setting of the Greater Caucasus mountain belt and highlighted many aspects of the Arabia-Eurasia collisional system that remain to be fully constrained, our views diverge considerably from the tectonic model they proposed, as summarized below.

1. Relic ocean basin closure at 5 Ma is not supported by any sedimentological, provenance, or structural data.
2. Instead, multiple data sets, including the development of successor foreland basins, indicate closure of, at least the western segment of, the Greater Caucasus Basin at the Eocene-Oligocene transition.
3. Data excluded from their study, from farther west in Russia, provide key insights into the architecture and development of the basin. The allochthonous nature of some of the sediments here, and farther to the east, do not diminish their value in this regard.
4. They misinterpret the geological context of Oligocene to Upper Miocene provenance samples from the southern flank of the range in west Georgia. These were not deposited in a still open, narrowing basin (or on its southern flank) but in one of a series of foreland basins that developed from the Oligocene onward in response to loading of the southern margin of the former basin.
5. Their sparse Jurassic to Eocene provenance data set is insufficient to provide any meaningful insights into the former width of the basin.
6. Implicit reference to oceanic spreading within the Greater Caucasus Basin is not supported by field or geochemical data.

These points will be addressed in turn, after some brief geological background to the Greater Caucasus Basin.

2. Geological Background

The Greater Caucasus Basin or Trough, a region of relatively deepwater “flysch” sedimentation in the Southern Slope Zone of the Greater Caucasus, has been long recognized and is extensively documented in the Russian and International geological literature (e.g., Adamia et al., 1977; Adamia, Alania, et al., 2011; Adamia et al., 1992; Barrier & Vrielynck, 2008; Belousov, 1976; Dotduyev, 1986; Goguel, 1938; Golonka, 2004; Kaz’min & Tikhonova, 2006b; Khain & Milanovsky, 1963; Lavrishchev et al., 2011; McCann et al., 2010; Milanovsky & Khain, 1963;

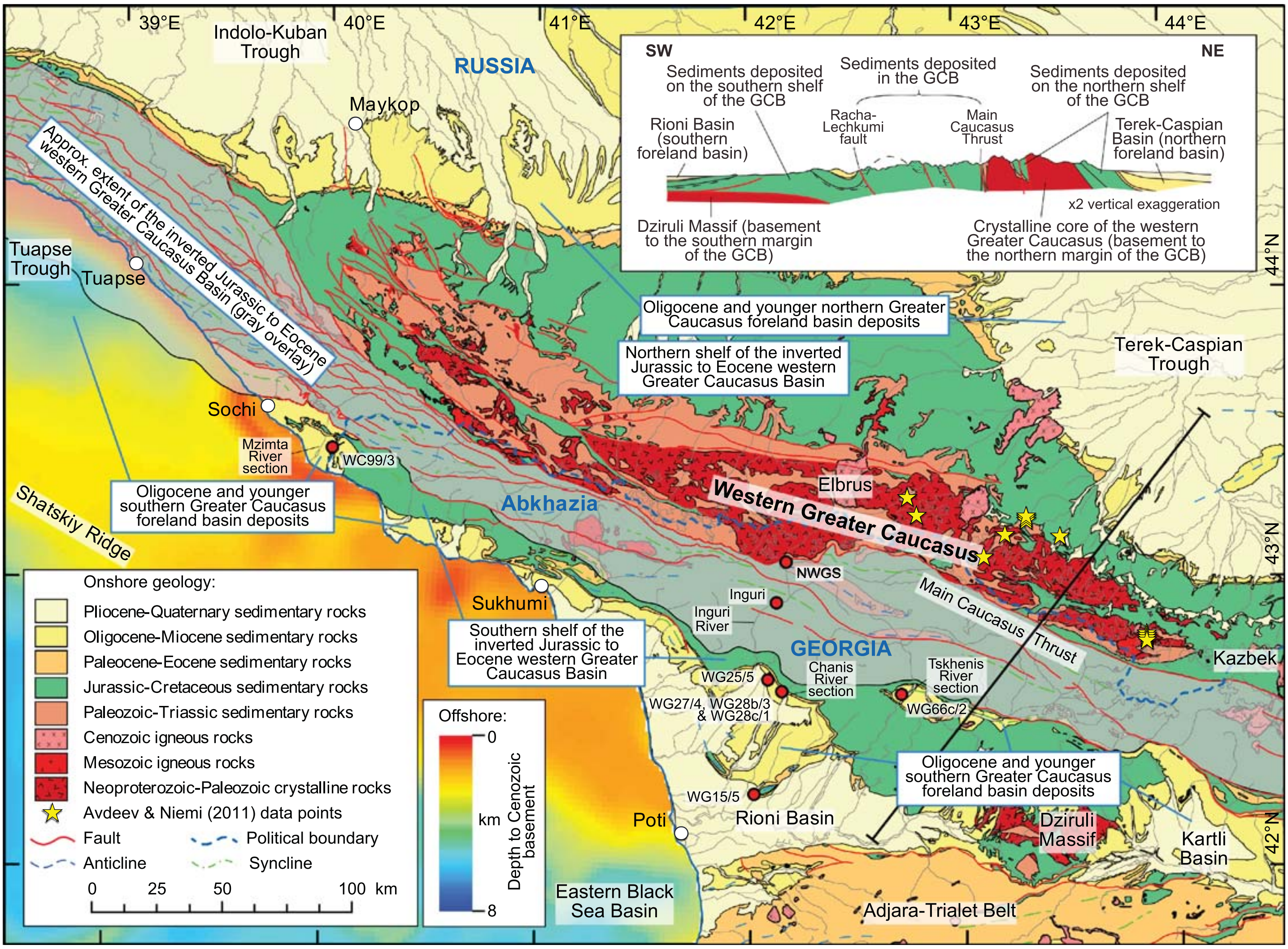

Figure 1. Geological map and simplified cross section of the western Greater Caucasus showing the approximate extent of the now inverted (and shortened) western Greater Caucasus Basin (gray overlay), its southern and northern shelves, and successor foreland basins. Selected provenance samples discussed in the text, from Vincent et al. (2013) and Cowgill et al. (2016), are located. Depth to Cenozoic basement in the eastern Black Sea is from Tugolesov (1989).

Nikishin et al., 2012; Renngarten, 1929; Rostovtsev, 1992; Ruban, 2006; Saintot et al., 2006; Vincent et al., 2016). The basin is bound by Variscan basement fragments exposed in the core of the western part of the range to the north and in the Dziruli Massif to the south (Figure 1 and, schematically, in Figures 6 and 8 of Cowgill et al., 2016). Thinner successions of age equivalent, typically shallower-water sediments, including reefs, were deposited on this basement and define the basin's margins (see Figure 3 of Vincent et al., 2016).

The Greater Caucasus Basin evolved during upper plate extension and/or transtension along the southern margin of Laurasia/Eurasia, due to the northerly subduction of Neotethys to the south (Adamia et al., 1977; Dercourt et al., 1986; Golonka, 2004; Zonenshain & Le Pichon, 1986). It had a protracted rift history (Adamia, Alania, et al., 2011; Kaz'min & Tikhonova, 2006b). Its main opening phase occurred in the early Middle Jurassic (McCann et al., 2010; Vincent et al., 2016) when ~7.4 km of rift-related subsidence occurred in its Russian sector, north of Sochi (Vincent et al., 2016). Subsequent secondary rift phases during the latest Jurassic to earliest Cenozoic (Paleogene) may provide insights into the rift history of the adjacent Eastern Black Sea (Saintot & Angelier, 2002; Vincent et al., 2016). Both the geochemical character of Lower and Middle Jurassic volcanic rocks and an absence of a Jurassic or younger oceanic suture zone, with ophiolite or ophiolitic mélange, subduction-related arc magmatism and accretionary prism in the Greater Caucasus suggest that rifting did not result in oceanic lithosphere generation and subsequent removal by subduction.

The Greater Caucasus Basin extended from eastern Crimea in the west to either the eastern Greater Caucasus or the South Caspian Basin in the east (Brunet et al., 2003; Dotduyev, 1986; Kaz'min & Tikhonova, 2006a; Nikishin et al., 1998; Zonenshain & Le Pichon, 1986). Some models suggest that it may have been subdivided into eastern and western segments (Adamia et al., 1977; Adamia, Alania, et al., 2011; Adamia et al., 1992; Kaz'min & Tikhonova, 2006b; Nikishin et al., 2012). In this comment we focus on the western segment of the basin in Russia, Abkhazia, and west Georgia, where its location, nature, and evolution are best constrained (see Vincent et al., 2016) (Figure 1).

The Greater Caucasus Basin preserves Jurassic to Eocene sediments. It is temporally and geodynamically distinct from the Tuapse-Rioni-Kartli-Kura foreland basin system to its south and the Indolo-Kuban and Terek-Caspian basins to its north that contain Oligocene and younger sediment. These typically shaped flexural basins developed as a consequence of its closure by inversion tectonics (sensu Cooper & Williams, 1989) and the growth of the Greater Caucasus (Mikhailov et al., 1999; Nikishin et al., 2003; Nikishin, Ershov, & Nikishin, 2010). Progressive subaerial uplift and unroofing of the fill of the Greater Caucasus Basin occurred from the Oligocene onward (Lozar & Polino, 1997; Vincent, Hyden, et al., 2014; Vincent et al., 2007; Vincent et al., 2011) by thick-skinned thrusting along previously rift related normal faults (Nemčok et al., 2013; Vincent et al., 2016). This was followed by thin-skinned thrust deformation that propagated into the adjacent foreland basins, a process that continues to the present day (Forte et al., 2013; Mosar et al., 2010; Tibaldi et al., 2017; Vezzoli et al., 2014). The High Atlas, Morocco and the Pyrenees, France and Spain are examples of other mountain chains built by inversion tectonics of a rift, with initial thick- and later thin-skinned thrust sheet development resulting in flexural basin formation on either side of an exhumed basin infill (e.g., Beauchamp et al., 1999; Beaumont et al., 2000; Muñoz, 1992).

Fault patterns, GPS motions, and seismicity data (Mosar et al., 2010; Mumladze et al., 2015; Reilinger et al., 2006) indicate that, at present, the eastern and western segments of the Greater Caucasus have distinct geodynamic settings. The boundary between these two regions occurs roughly at ~44°E to the north of the NE-SW trending Northeast Anatolian fault zone (Copley & Jackson, 2006; Jackson, 1992). It is unclear for how long the geodynamic difference between the segments has been manifested, such that it may not be appropriate to apply the evolutionary model for the western segment of the Greater Caucasus Basin, outlined below, farther east.

3. Detailed Points

3.1. There Is no Evidence for 5 Ma Basin Closure

Like Nikishin et al. (2001), Saintot and Angelier (2002), Vincent et al. (2007), and Mosar et al. (2010), Cowgill et al. (2016) proposed that the southern slope of the western Greater Caucasus represents the exhumed former fill of a hyper-extended Mesozoic rift basin, named the Greater Caucasus Basin, which began to invert in the latest Eocene (~35 Ma) as a result of initial Arabia-Eurasia collision. Our views diverge, however, in relation to the subsequent evolution of the western part of the region. They proposed that a relic ocean basin remained open during its northerly subduction/underthrusting until ~5 Ma when hard collision commenced.

Cowgill et al. (2016) presented no sedimentological, provenance, or structural data to support a 5 Ma relic ocean basin closure age. Evidence is based solely on a limited number of apatite fission track and (U-Th)/He analyses from Avdeev and Niemi (2011) from a geographically restricted, magmatically affected, region of the western Greater Caucasus (Figure 1). They postulated that this zone of relatively recent cooling extends westward and is undetected by earlier studies using the apatite fission track methodology (e.g., Král & Gurbanov, 1996; Vincent et al., 2011). While possible, this has yet to be proven. Furthermore, without supporting evidence from other data sources for the 5 Ma closure of the Greater Caucasus rift basin, an alternative driving mechanism for ~5 Ma deceleration of the Arabian plate, reorganization of the Arabia-Eurasia collision zone, and limited Caucasus cooling is preferred here. A change from a free to constrained eastern margin of the collision zone (Allen et al., 2011) and/or orogenic uplift of the Zagros and adjacent regions (Austermann & Iaffaldano, 2013) provides two such plausible mechanisms.

3.2. Closure of the Western Segment of the Basin Had Occurred by the Beginning of the Oligocene

By the early Oligocene, Greater Caucasus Basin closure by inversion tectonics of rift-related basement faults led to the proto-western Greater Caucasus becoming a subaerial sediment source (Barrier & Vrielynck, 2008;

Khlebnikova et al., 2014; Lozar & Polino, 1997; Milanovsky & Khain, 1963; Popov et al., 2004; Saintot & Angelier, 2002; Vincent et al., 2007) with elevations estimated to be around 2 km (Vincent et al., 2016). Crustal thickening (loading) resulted in the lithospheric flexure of the former southern margin of the basin to form the Tuapse-Rioni foreland basin system (Figure 1). This flexure is identified in subsidence modeling (Vincent et al., 2016) and is well imaged in offshore seismic data (Afanasenkov et al., 2007; Finetti et al., 1988; Nikishin et al., 2010; Nikishin et al., 2015). An elastic thickness of 2.3 km has been estimated for this flexed margin by matching its curvature with predicted curves for a point-loaded broken elastic beam (Shillington et al., 2008). This modeling also implies that flexure will only be observed when a point load is applied less than 70 km away from an observation point (their Figure 7d). It is difficult to conceive how flexure, clearly evidenced at this margin, could therefore be achieved if, as proposed by Cowgill et al. (2016), the basin was still close to its maximum ~350–400 km width during the initial Oligocene "subduction" of its northern, leading edge, beneath the proto-Greater Caucasus (their Figure 8). Oligocene and younger provenance data from Cowgill et al. (2016) and preexisting studies should therefore be interpreted within the context of their deposition in an evolving foreland basin, rather than in a closing relic ocean basin, as will be demonstrated in sections 3.4 and 3.5.

If a relic ocean basin had remained open until ~5 Ma, Oligo-Miocene basinal sediment would have been incorporated into a growing subduction wedge at its northern margin and might be expected to be preserved in thrust sheets along the southern slope of the Greater Caucasus in its "cryptic suture zone." We are not aware of such deposits.

3.3. Data From the Russian Western Greater Caucasus Provide Key Insights Into Basin Architecture and Development

Cowgill et al. (2016) largely restricted their study of the western segment of the Greater Caucasus Basin to the area east of 41.5°E (although they did incorporate preexisting provenance data from as far west as 37°E). This cutoff roughly coincides with the border between Georgia and the Autonomous Republic of Abkhazia. There is no geological rationale for the exclusion of data from farther west, and this restriction may, in part, explain our differing views on the evolution of the region.

Recent Russian mapping immediately to the west and north of the Russian-Abkhazian border (Korsakov et al., 2000; Korsakov et al., 2002, 2004; Lavrishchev et al., 2000; Lavrishchev et al., 2002) makes this area, west of the Cowgill et al. (2016) study area, the geologically best constrained part of the Greater Caucasus mountains. Russian geologists here have grouped areas of sedimentary and volcanic rocks with similar ages, facies, and paleoenvironments into a series of northwest-southeast trending tectonostratigraphic zones. These define a central zone of Jurassic to Eocene basinal facies, the Greater Caucasus Basin, along with its shelfal equivalents to the northeast and southwest (see Vincent et al., 2016) (Figure 1). Guo et al. (2011) also documented a number of barrier reef facies belts in the same region. Two of these face each other across the Greater Caucasus Basin and were deposited on the footwall highs of tilted fault blocks or the shoulders of the rift during the Late Jurassic.

The northern extent of the former basin is marked by the Main Caucasus Thrust (MCT). Several small tilted basins in the crystalline basement just north of the MCT contain outer shelfal sediments, such that the MCT can be considered an inherited paleotectonic structure marking the external-most part of the tilted block margin of the northern shelf. Contrary to Figure 2 of Cowgill et al. (2016), there is no evidence for basinal facies of the Greater Caucasus Basin north of exposed crystalline (Variscan) basement in the western Greater Caucasus.

The southern extent of the former basin is obscured by the southward emplacement of Alpine thrust sheets. Around Sochi, para-autochthonous shelfal sediments (the Abkhazia Zone) are overthrust by Upper Jurassic, north-facing basin margin reefal carbonates (the Akhtsu Zone). These occur in the footwall of a detached thrust comprising Paleocene and Eocene basinal sediments (the Chvezhipsin Zone) (see Figure S1 of Vincent et al., 2016). Thus, the southern shelf to basin transition is preserved in this region but in a compressed form. Syn-tectonic sedimentation imaged in the Tuapse Trough suggests that shortening and flexure began during Maykop Series deposition (Oligocene to Early Miocene) (Afanasenkov et al., 2007; Nikishin et al., 2015). Note that sample WC99/3, described as being located north of the inferred Greater Caucasus Basin suture zone by Cowgill et al. (2016) (p. 2931), occurs to the south of the former basin in the para-autochthonous Abkhazia Zone and represents part of the southern foreland basin fill of the western Greater Caucasus (Figure 1).

The extent of the western Greater Caucasus Basin is more difficult to extrapolate into Abkhazia and west Georgia due to more limited field access. The northern extent of the basin is again defined by the southern limit of the crystalline core of the range and the continuation of the MCT (Figure 1). Although not the focus of this comment, based on existing data, field observations and geological maps of 1:50,000 to 1:500,000 scale, various strands of the MCT can be traced for over 1,000 km into Azerbaijan (Dotduyev, 1986; Mosar et al., 2010, and references therein). Cowgill et al. (2016) erroneously positioned the MCT east of Mount Kazbeg (cf. Figure 3 of Mosar et al., 2010) as well as the position of relic basin strata in the eastern Greater Caucasus; basinal sediments only crop out to the south of the Main Caucasus Thrust. The MCT thus formed a major boundary on the northern rift margin. The subsequent inversion tectonics and development of the orogeny, rather than developing over a main detachment horizon, thus involve thick-skinned tectonics with main thrusts stepping down into the basement as they formed by reactivation of preexisting paleotectonic boundaries/deep-rooted normal faults (Egan et al., 2009).

The allochthonous southern margin of the western Greater Caucasus Basin is defined in terms of facies by the continuation of the southern Upper Jurassic reef belt. This can be traced from Russia into western Abkhazia as far as Sukhumi. Similar reef bodies at the southern margin of the eastern segment of the Greater Caucasus Basin run from north of the Dziruli Massif toward the east-southeast (see Figure 10 of Adamia et al., 1992). Para-autochthonous Upper Jurassic lagoonal siliciclastic deposits with evaporites represent a continuation of the southern shelf of the basin(s) in the intervening region of west Georgia and eastern Abkhazia. Structurally, the southern margin of the basin is marked by the Racha-Lechkumi fault (Figure 1), a partially inverted normal fault across which Upper Jurassic to Cretaceous sediments thin from 8 km to a maximum of 1 km in thickness (Yakovlev, 2012).

Where thrust development has detached the Oligo-Miocene provenance samples of Vincent et al. (2013) from underlying Upper Jurassic shelfal strata in this region, as discussed by Cowgill et al. (2016, p. 2933), their former palaeogeographic context can still be determined. This is because Oligo-Miocene sections, such as those along the Chanis and Tskhenis Rivers (that include key samples WG28b/3, WG28c/1, WG27/4, and WG66c/2; Figure 1), are in stratigraphic continuity with underlying, precompressional, Eocene foraminiferal grainstones and packstones. Lower to lower middle Eocene nummulitic limestones are widespread across shelfal areas in Crimea and the Caucasus (Lygina et al., 2016), with these authors depicting a north (and south) facing shelf in west Georgia, south of the Greater Caucasus Basin, during the middle Eocene, with paleowater depths of less than 200 m (their Figure 8). This is consistent with our own biostratigraphic work that determined Eocene middle to outer shelfal depths of typically between 30 and 200 m in this region. Thus, while some Oligo-Miocene sediments along the southern margin of the Greater Caucasus are allochthonous, their stratigraphic continuity with older, Greater Caucasus Basin age-equivalent strata indicates that they were deposited south of the earlier Greater Caucasus Basin. Furthermore, their deeper water (largely turbiditic) character points to a southerly depocenter shift with deposition occurring in the successor Rioni foreland basin and not in the relic basin as this had become a subaerial sediment source by this time.

South of the western Greater Caucasus Basin is a crustal segment largely unaffected by rifting, part or all of which have been referred to as the northern Transcaucasus (Adamia et al., 1992), Shatskiy Ridge (Okay et al., 1994), Shatskiy Rise (Kaz'min & Tikhonova, 2006b), Georgian Block (Tsagareli, 1974), or Dzirula Massif (Zonenshain & Le Pichon, 1986). Thus, while Cowgill et al. (2016) correctly placed the Dziruli Massif to the south of the basin (their Figures 6 and 8), they failed to appreciate that this crustal segment separates the inverted western Greater Caucasus Basin from the Eastern Black Sea Basin and Adjara-Trialet Belt (Figure 1). The basins were never contiguous (cf. Cowgill et al., 2016, p. 2941), were geometrically and kinematically independent, and were asynchronous.

3.4. The Geological Context of Oligocene to Upper Miocene Provenance Samples Is Misinterpreted

Detrital U-Pb zircon age data can be extremely useful in provenance studies. However, the resistant nature of zircon means that recycling and inheritance can complicate any interpretation (Andersen et al., 2016). They are best combined with other provenance proxies and fully integrated with basic field observations (e.g., DeCelles et al., 1998; Najman, 2006).

Cowgill et al. (2016) defined two provenance domains based on detrital U-Pb zircon data in isolation: a southern domain characterized by grains younger than 170 Ma and a northern domain characterized by grains older than 230 Ma (p. 2921). They also distinguished within the northern provenance domain Variscan basement grain populations and older, more northerly derived East European Craton grain populations (p. 2928). They interpreted mixtures of these northern grain populations in the Oligocene sample WC99/3 and the middle Miocene sample WG66c/2 of Vincent et al. (2013) to indicate that Greater Caucasus growth had not yet defeated south flowing rivers crossing the East European Craton and Variscan domains and that these sediments were deposited in the northern portion of the Greater Caucasus Basin (p. 2929). We interpret these data differently.

First, as outlined in sections 3.2 and 3.3, Oligo-Miocene sediments along the southern margin of the Greater Caucasus were deposited in a series of foreland basins that developed from the Oligocene onward in response to loading of the southern margin of the former basin. The following outcrop observations need to be interpreted in this context: southerly to southwesterly directed paleocurrents, the presence of plant fragments, reworked Jurassic to Eocene nannofossils and palynomorphs, in situ montane palynomorphs, and sandstone compositions with a Variscan and East European Craton (recycled) provenance. They all indicate a growing sediment source (the Greater Caucasus) to the north (Vincent, Hyden, et al., 2014; Vincent et al., 2007, 2013, 2016). Seismic data from the Tuapse Trough show the spectacular geometries of these depositional systems in the subsurface (Mityukov et al., 2011, 2012).

Unpublished U-Pb detrital zircon grain dating of Jurassic to Eocene sediments deposited in the Russian sector of the western Greater Caucasus Basin indicates that they are dominated by East European Craton-derived zircons (~60–90%) (Vincent, Morton, et al., 2014). Variscan-aged zircons are only dominant in sediments immediately overlying local basement. As a consequence, we interpret that the East European Craton detrital zircon grain component in samples WC99/3 and WG66c/2 represents material recycled during the inversion of the western Greater Caucasus Basin and deposited in the southern foreland of the Greater Caucasus. In this scenario, the Variscan-aged zircon component could be derived either from reworked western Greater Caucasus Basin material with this provenance or directly from local basement within the core of the Greater Caucasus as it was exhumed during inversion tectonics.

The detrital zircon age characteristics of sediments deposited in the west Georgian sector of the western Greater Caucasus Basin are poorly constrained. Sample NWGC is the only published data point. It comes from the immediate footwall of the MCT that carries basement rocks in the core of the Greater Caucasus over the early Jurassic fill of the Greater Caucasus Basin (Figure 1). (Note that it is incorrectly positioned within Variscan basement north of the MCT in Figures 2 and 6 of Cowgill et al., 2016). Its zircons were derived predominantly from local basement. It has yet to be determined whether this is a result of the proximity of the sample to the northern rift shoulder during initial basin opening or is characteristic of the whole of the basin fill in this region. The presence of East European craton-derived grains in modern Inguri River sands, however, indicates that the fill of the western Greater Caucasus Basin in west Georgia received at least some material from this sediment source prior to its inversion.

Aalenian-Bajocian intrusive and extrusive magmatic rocks, typical of the southern provenance domain, also occur in the fill of the Greater Caucasus Basin (e.g., Adamia et al., 1977; Adamia, Zakariadze, et al., 2011; McCann et al., 2010; Vincent et al., 2016). Material derived from the inversion of these magmatic rocks is therefore to be expected. In west Georgia, volcanic rocks in the Greater Caucasus Basin interdigitate with and pass northward into marine shales (Adamia et al., 1992; Melnikov & Popova, 1966). The limited number of 170 Ma zircons present in sands of the south flowing Inguri River is most likely, therefore, a by-product of the sample's location close the northern outcrop limit of Bajocian volcaniclastic sediments. Single ~170 Ma zircon grains in Mio-Pliocene sample WC139/1 from the Taman Peninsula (Vincent et al., 2013) and a modern Volga River sample (Wang et al., 2011) imply airfall dispersion into the sedimentary sources of these sands north of the Greater Caucasus Basin.

Cowgill et al. (2016) noted an increase in the quantity of plutonic and metamorphic rock fragments in the petrographic data set of Vincent et al. (2013) between upper upper Oligocene sandstone samples WG28b/3 and

WG28c/1 in the Chanis River section, west Georgia. They interpreted this increase to indicate sand-grade sediment sourcing with a clear Greater Caucasus crystalline core provenance for the first time at this locality (p. 2933). While correct, it should be noted that there is also an ample evidence for reworking and subaerial sediment derivation from the Greater Caucasus in older (early Oligocene) mudstones from this section (Vincent, Hyden, et al., 2014; Vincent et al., 2007, 2016). Furthermore, early Oligocene sandstones with a Greater Caucasus provenance are developed farther west in Russia (Vincent et al., 2007, 2013).

Cowgill et al. (2016) went on to note similar amounts of plutonic and metamorphic rock fragments to those in upper upper Oligocene sample WG28c/1, in Tortonian and Tortonian-Messinian samples WG22/5 and WG15/5. They interpreted their presence south of a "suture" zone (p. 2934) to be due to a narrowing of the Greater Caucasus Basin (p. 2941). If this were so, it is difficult to conceive how material shed from the north, from eroding Greater Caucasus basement, would have been able to make its way south of the suture, across a still open relic ocean basin, and up onto its southern shelf. A south directed sediment pathway from eroding Greater Caucasus basement into its adjacent flexed foreland proves no such conceptual difficulties.

3.5. Provenance Data Provide no Insights Into the Width of the Greater Caucasus Basin

Cowgill et al. (2016) interpreted a lack of sediment mixing between northern and southern provenance domains as support for an open, wide Greater Caucasus Basin whose width they estimate to be ~350–400 km. However, when Oligocene and younger sediments are excluded from their study (because of their inappropriate geological context), there is insufficient data to determine whether mixing took place. Within the western segment of the basin, just a single sample (NWGC) has been investigated from its fill and this was deposited prior to the generation of 170 Ma and younger zircons that define the southern provenance domain.

We have no specific new insights into the width of the Greater Caucasus Basin. However, it was probably highly segmented, as a result of multiple rift events (Vincent et al., 2016) and a transtensional component (McCann et al., 2010; Saintot et al., 2006), such that turbidite systems are likely to have been bathymetrically confined by axially orientated structures. Sediment mixing within the basin may therefore have been restricted irrespective of its width. The large modern turbidite systems cited by Cowgill et al. (2016) as analogues for the western Greater Caucasus Basin are from nonchannelized basin plain settings (Talling et al., 2007) of the Atlantic margins and may not be appropriate. The presence of a relatively narrow Paleogene transtensional component to the west Georgian sector of the western Greater Caucasus Basin (Cowgill et al., 2016, p. 2932) was envisaged by Vincent, Hyden, et al. (2014) to be the final rift phase within an already open basin. We did not mean to imply that the western Greater Caucasus Basin in west Georgia had a similar (narrow) width to the contemporaneous Adjara-Trialet Basin to the south of the Transcaucasus.

3.6. The Greater Caucasus Basin Is Unlikely to Have Been Floored by Oceanic Crust

Cowgill et al. (2016) were careful not to explicitly apportion a specific crustal type to the Greater Caucasus Basin (p. 2921). However, their repeated use of the phrase "subduction of a relict (Caucasus backarc) ocean basin" (pp. 2919, 2921, 2936, 2937 & 2941), the contrasting of the ease of consumption of the old and cold crust beneath the Greater Caucasus Basin with the more resistive young and warm oceanic crust of the Greater India Basin (p. 2940), the conjectural (their words) depiction of oceanic ridges, transforms and thin crust in their schematic maps and cross sections (their Figure 8), and the reference to a Wadati-Benioff Zone beneath the eastern Greater Caucasus (p. 2937) may give readers the impression that the basin was floored by oceanic crust. It is worth restating, therefore, the conclusions of previous workers (e.g., Ershov et al., 2003; Lordkipanidze, 1980; Lordkipanidze et al., 1989; McCann et al., 2010; Mosar et al., 2010; Nikishin et al., 2001; Saintot et al., 2006; Vincent et al., 2016), who stated that there is no robust geological data to indicate that oceanic lithosphere formed the floor of the Greater Caucasus Basin.

Lower and Middle Jurassic volcanic rocks provide insight into the evolution of the western part of the Greater Caucasus Basin. Volcanism was bimodal. Lower Jurassic volcanic rocks in the region of the central Greater Caucasus Basin are dominated by rhyolites (Lordkipanidze et al., 1989; McCann et al., 2010). They likely represent melting of continental crust during thinning of the continental lithosphere (Lordkipanidze et al., 1989). Rhyolites were also erupted during the Aalenian and Bajocian, although mafic to intermediate series volcanic rocks predominate (Lordkipanidze et al., 1989; McCann et al., 2010). MORB signatures characterize the Aalenian series, while the Bajocian series is predominantly calc-alkaline (McCann et al., 2010). Alkaline basic lavas were also erupted during the Aalenian and Bajocian and some MORB intermediate rocks in the Bajocian. The wide spectrum of coeval mafic types points to a number of mantle sources. Aalenian MOR-basalt generation resulted from an extreme stretching of the continental lithosphere (and melting of the asthenosphere); tension is recorded by syn-sedimentary normal faulting (Saintot et al., 2006) and rapid subsidence (Vincent et al., 2016). Bajocian mafic rocks represent the products of melting at different depths of an old inhomogeneous continental mantle lithosphere down to the asthenosphere/lithosphere boundary. This is likely to represent island arc volcanism (McCann et al., 2010; Saintot et al., 2006).

Crucially, Aalenian continental lithospheric extension did not lead to rupture and the formation of oceanic lithosphere. If it had, extensive tholeiitic basalts would have been erupted and other types of volcanism would have ceased (as the source at a ridge is permanently rejuvenated by primitive mantle ascent). Furthermore, one can reasonably assume that an oceanic ridge would have been superimposed on the Aalenian MORB series eruptive centers in the central part of the western Great Caucasus Basin (i.e., at the thinnest part of the continental lithosphere). Instead, the Bajocian eruptive centers shifted by 100 km to the south of the western Greater Caucasus Basin (McCann et al., 2010) as the Lesser Caucasus arc widened. Similar Lower to Middle Jurassic facies and magmatic rocks are present in the eastern Greater Caucasus, suggesting a similar geological history for the eastern segment of the Greater Caucasus Basin (Alizadeh, 2008; Ali-Zadeh et al., 1997).

In the model of Cowgill et al. (2016), the majority of Greater Caucasus Basin spreading occurred in post-Bajocian to Paleocene times. Scant record of this magmatic history is present along the southern slope of the western Greater Caucasus. Only limited outcrops of Cenomanian pillow lavas north of Sochi are known to the authors.

4. Summary

Cowgill et al. (2016) proposed a provocative model to reconcile shortening deficits, plate deceleration, and the ~5 Ma reorganization of the Arabia-Eurasia collision zone by invoking the presence of a relic ocean basin in the Greater Caucasus. While the presence of a rift basin is unquestioned, within the western Greater Caucasus at least, careful examination of sedimentological, provenance, and seismic data supports a ~35 Ma rather than a ~5 Ma closure age for this basin. As previously argued by Vincent et al. (2016, p. 2958), basin closure cannot therefore be the driving mechanism for the ~5 Ma deceleration of the Arabian plate and reorganization of the Arabia-Eurasia collision zone.

Cowgill et al. (2016) invoked a lack of sediment mixing within the Greater Caucasus Basin as support for a ~350–400 km estimate of the basin's former width, thereby helping to eliminate a perceived deficit between upper crustal shortening and postcollisional convergence estimates in the Arabia-Eurasia collision. Only three pre-Oligocene data points, however, are presented in their work. These are insufficient to test this nonsediment mixing hypothesis. Oligocene and younger sediments utilized in their study typically occur above Eocene and older shelfal sediments deposited on the southern margin of the western Greater Caucasus Basin. They were deposited during later foreland basin development and provide no insights into the rift basin's former width. Even when sufficient pre-Oligocene data become available to test their nonsediment mixing hypothesis, the highly segmented nature of the Greater Caucasus Basin means that it is unclear whether a reliable estimate for basin width can ever be made on sedimentological/provenance grounds.

To date, shortening deficits across the Eurasia-Arabia collision zone have only been determined to the east of the study area, across the Zagros-Alborz-Kopet Dagh system (McQuarrie & van Hinsbergen, 2013) so that it is not clear whether a deficit in the Caucasus sector actually exists. Even if it does, Cowgill et al. (2016) themselves argued (p. 2938) that there is no a priori reason why values of shortening and postcollisional convergence should balance, calling into question the raison d'être for their study.

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