INTRODUCTION

The volcanic activity within the Tethyan realm was widespread during the Triassic. Middle Triassic magmatism has been reported in the Alps, Carpathians, Dinarides and Hellenides (e.g. Beccaluva et al., 2005; Casetta et al., 2019; Castellarin et al., 1988; Goričan et al., 2005; Graciansky et al., 2011; Kovács et al., 2011; Harangi et al., 1996; Knežević et al., 1998; de Min et al., 2020; Pamić, 1984; Pe-Piper, 1998; Pomonis et al., 2004; Smirčić et al., 2018; Storck et al., 2018; Velledits, 2006; and references therein). Different types of lavas and
pyroclastic material as well as rare intrusive rocks mark this magmatic event (e.g. Bianchini et al., 2018; Bonadiman et al., 1994; Casetta et al., 2018; Castorina et al., 2020; Lustrino et al., 2011, 2019; De Min et al., 2020; Saccani et al., 2015; Soman, 1989; Slovenec et al., 2020; Storck et al., 2018; Trubelja et al., 2004; and references therein). The Middle Triassic magmatism has been related to the formation of the Adriatic-Dinaridic carbonate platform(s) and its subsequent disintegration (e.g. Castellarin et al., 1988; Kovács, 1989; McCann, 2008; Philip et al., 1995; Robertson, 2007; Storck et al., 2018; Vlahović et al., 2005; and reference therein). Yet, the geodynamic framework and tectonomagmatic evolution of the area separating Gondwana and Laurasia (the Southern Alps, Dinarides, Hellenides, and the Alpine-Carpathian Belt) remain controversial (e.g. Bortolotti and Principi, 2005; Bortolotti et al., 2013; De Min et al., 2020; Neubauer et al., 2019; Şengör, 1984; Stampfli and Borel, 2004; Stampfli et al., 2013; Zulauf et al., 2018). The magmatism of the Middle to Upper Triassic period has been related to compressional, extensional and/or transtensional geodynamic processes (e.g. Abbas et al., 2018; Beccaluva et al., 2005; Bonadiman et al., 1994; Castellarin et al., 1988; Castorina et al., 2020; Csontos and Vörös, 2004; Lustrino et al., 2019; Schmid et al., 2008, 2019; Stampfli et al., 2002; Storck et al., 2018; and reference therein). Two hypotheses have emerged over the years i) that the continental rift caused the magmatic events (e.g. Aljinović et al., 2010; Crisci et al., 1984; Harangi et al., 1996; Knežević et al., 1998; Kovács, 1992; De Min et al., 2020; Pamić, 1984; Pamić and Balen, 2005; del Piaz and Martin, 1998; Saccani et al., 2015; Veld伊ts, 2004, 2006; and references therein) and ii) that the magmatism was originated by convergent plate movements triggered by the subduction of the Paleotethys lithosphere (e.g. Bébien et al., 1978; Bianchini et al., 2018; Bonadiman et al., 1994; Casetta et al., 2018; Cassinis et al., 2008; Castellarin et al., 1980, 1988; Castorina et al., 2020; Grimes et al., 2015; Kovács, 1992; Obenholzer, 1991; Schmid et al., 2004; Slovenec et al., 2020; Smirčić et al., 2018; Stampfli and Borel, 2002, 2004; Storck et al., 2019; Trubelja et al., 2004; Zanetti et al., 2013; and references therein). The subduction and back-arc extension processes in the Alpine-Carpathian-Dinaridic realm produced diverse magmatisms, among which the calc-alkaline one dominated (e.g. Arculus and Powell, 1986; Avanzinelli et al., 2012; Elliott et al., 1997; Hawkesworth et al., 1991, 1993; Keller, 1982; Pearce, 1982, 1983; Pearce and Parkinson, 1993). Although the calc-alkaline magma was likely coeval with the active subduction it also might have been linked to adiabatic melting of an old, subduction-imprinted, mantle wedge; alternatively the calc-alkaline magma stems from the melting of the continental lithosphere affected by subduction processes (e.g. Cameron et al., 2003; Hawkesworth et al., 1995; Hooper et al., 1995; Johnson et al., 1978; Lustrino et al., 2019; Saccani et al., 2015). Considering a diverse magmatic activity and complex geodynamic processes documented along the continental margins of an emerging Adriatic-Dinaridic carbonate platform(s) in the western part of the Tethys Ocean, research on volcanic and volcano-sedimentary successions is of key importance to explain multiple lithospheric processes.

The Middle Triassic igneous events of the southernmost segment of the geotectonic unit of Southern Alps (sensu Schmid et al., 2008) or the SW portion of the Zagorje-Mid-Transdanubian Zone (ZMTDZ; sensu Pamić and Tomljenović, 1998) (Fig. 1A, B), are manifested in the volcanic-volcaniclastic sequences of Mt. Strahinjščica, Mt. Desinić Gora, Mt. Kuna Gora (Fig. 1C), Mt. Ravna Gora and northern slopes of Mt. Ivanščica. These successions, that sometimes are interstratified with siliciclastic and carbonate sediments, are made of basaltic to rhyolitic lavas and pyroclastic rocks, largely fine-grained and thoroughly altered (e.g. Marci et al., 1982, 1984; Šimunić and Šimunić, 1979, 1997; Šimunić, 1992). Heretofore research on Middle Triassic effusive and pyroclastic rocks of Mt. Kuna Gora was limited to a field survey for the geological map of Socialist Federal Republic of Yugoslavia, scale 1:100,000 (Anićić and Jureša, 1984; Fig. 1C), which included a basic petrographic rock characterization. Studies on analogue rocks of the neighboring Strahinjščica and Ivanščica mountains, also only contain the basic petrographic characterization (e.g. Golub and Brajdić, 1968, 1970; Golub et al., 1969; Goričan et al., 2005; Marci et al., 1982, 1984). One exception is a recent study on the Upper Anisian volcano-sedimentary succession of Mt. Ivanščica by Slovenec et al. (2020) that reports the origin, geodynamic significance, and diagenetic history of pyroclastics and associated chert.

In this contribution, we use mineralogical, petrographical, geochemical, and isotope data of representative samples of effusive and pyroclastic rocks from Mt. Kuna Gora in order to infer the petrogenesis of these effusive and pyroclastic rocks and constrain the period and geotectonic environment in which they formed.

**GEOLOGICAL SETTING**

The mountains of Kuna Gora, Strahinjščica and northern slopes of Mt. Ivanščica render a continuous series of the North Croatian mountains with an E-W elongation. These mountains are the most southern portion of the geotectonic unit of the Southern Alps (sensu Schmid et al., 2008; Fig. 1A). This unit is situated south of the Periadriatic Line and its eastern continuation, the Balaton Line; i.e. south of the ALCAPA (Alpine-Carpathian-Pannonian) Mega-Unit and was derived from continental crustal domains (e.g. Harangi et al., 1996; Haas and Kovács, 2001; Schmid et al.,...
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The above-mentioned North Croatian mountains are commonly referred to as the Intra-Pannonian Inselgebirges (Slovenec et al., 2011), which are part of the southwestern segment of the Zagorje-Mid-Transdanubian Zone (ZMTDZ) (sensu Pamić and Tomljenović, 1998; Fig. 1B) or Sava Unit (Fig. 1A) (sensu Haas et al., 2000). The ZMTDZ strikes in the NE-SW direction for ~120km between the two regional fault systems: the Zagreb-Zemplen Line to the south and the Periadriatic-Balaton Line to the north. The ZMTDZ is characterized by mixed Alpine-Dinaridic tectonostratigraphic and tectonometamorphic units (e.g. Haas et al., 2000; Haas and Kovács, 2001; Pamić and Tomljenović, 1998; Pamić, 2002; Slovenec and Lugović, 2009; Slovenec et al., 2011; Tari and Pamić, 1998) and its origin is still being debated.

The Mt. Kuna Gora is made of Middle Triassic carbonate rocks (dolomite, dolomitic breccia, dolomitic limestone) disconformably overlain by Cenozoic deposits (Fig. 1C). In the northern slopes of Mt. Kuna Gora in the area of Bregi Kostelski, Middle Triassic lavas and associated subordinately represented pyroclastic rocks crop out in an area of about 0.3km² (Fig. 1C). Their contacts with the coeval carbonate rocks (dolomitic limestones, dolomites) and Tertiary clastites are tectonic. The analyzed effusive rocks are disconformably overlain by Quaternary alluvial deposits. The studied rocks are found as massive fine-grained lavas and associated tuffs and ignimbrites(?) (Fig. 2A, B). Only exceptionally, a meter-size and angular “exotic” rocks are found in the lavas (Fig. 2D). These rocks...
are made of fine-grained microcrystalline marine limestone of Anisian age. The marine carbonate mud must have been incorporated into the lava prior to complete lithification, as can be inferred from the preserved “active” contacts (see Fig. 2D). The deposition of carbonate mud must have taken place along the slopes of local relief where disintegrated and fragmented portions of a subsided carbonate platform might have been present. The relation between the lavas and the limestone rocks suggests that the volcanic activity was coeval with the marine carbonate sedimentation during the Late Anisian.

Similar effusive and pyroclastic rocks found elsewhere in the mountains of NW Croatia are all interbeded with Middle Triassic marine sediments (e.g. Goričan et al., 2005; Halamić, 1998; Marci et al., 1982, 1984; Šimunić and Šimunić, 1979; Šimunić, 1992; Slovenec et al., 2020). The volcanic activity of that period was characterized by submarine andesite to basaltic lava flows accompanied by multiple explosive eruptions of volcanic material. The Middle Triassic volcano-sedimentary succession from the ZMTDZ may be correlated with the Triassic volcano-sedimentary successions of the Maliak-Meliata arc-back-arc system (e.g. Goričan et al., 2005) and analogue successions from the Dinarides (e.g. Pamić, 1984, 1997; Smirčić et al., 2018, 2020; Trubelja et al., 2004).

**ANALYTICAL TECHNIQUES**

The mineral composition of two representative samples was analyzed at the Institute of Geosciences (University of Heidelberg, Germany) using a CAMECA SX51 electron microprobe equipped with five wavelength-dispersive spectrometers. Measurements were performed using an accelerating voltage of 15kV, beam current of 20nA, beam size of \( \sim 1\mu m \) (for feldspars \( 10\mu m \)) and 10s counting time for all elements. Natural oxides and silicates were used as standards and for calibration. Raw data was corrected for matrix effects with the PAP algorithm (Pouchou and Pichoir, 1984, 1985) implemented by CAMECA. Calculations of the structural chemical formulas were undertaken using a software package PETERAKI designed by Hans-Peter Meyer (Institute of Geosciences, Heidelberg; hans-peter.meyer@geow.uni-heidelberg.de). This Excel based solution provides information on the error on formula unit cations. The software has been designed to calculate the formulas of standard petrogenetic phases. To calculate formulas of minor minerals, additional information on the total cation and oxygen content and Fe\(^{2+}\)/Fe\(^{3+}\) distribution was required.

Bulk-rock powders for chemical analyses of seven effusive and pyroclastic samples were analyzed by Inductively Coupled Plasma Optical Emission Spectroscopy.
Geologica Acta, 19.2, 1-23 (2021)
DOI: 10.1344/GeologicaActa2021.19.2

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Using the 38Ar spike concentration. After each analysis, σ for the period of measurement was 0.710242±0.000030 and 87Sr/86Sr (t) ratios. 10,000 iterations for programing language (numpy package) was used to calculate the Monte Carlo propagation error through 10,000 iterations for 147Sm/144Nd, 146Nd/144Nd, 87Rb/86Sr and 86Sr/88Sr, ratios.

The K-Ar age data was measured on K-feldspar separated from basalt sample TsKg-1. K-feldspar was separated by an electromagnetic separator and standard heavy liquid techniques and finally was purified by hand picking under a binocular microscope. The K concentration and Ar analysis were determined by ICP and isotope dilution procedure on noble gas mass spectrometry, respectively. The analyses were performed at the Activation Laboratories (Ancaster, ON, Canada). For Ar analysis the aliquot of the sample is weighted into an Al container, loaded into the sample system of the extraction unit, and degassed at ~100°C for 2 days to remove surface gases. The argon is extracted from the sample in a double vacuum furnace at 1700°C. Argon concentration is determined using isotope dilution with an 38Ar spike, which is introduced to the sample system prior to each extraction. The extracted gases are cleaned up in a two-step purification system. Then, pure Ar is introduced into a magnetic sector mass spectrometer (Reinolds type) with Varian CH5 magnet. The ion source has an axial design (Baur-Signer source), which provides more than 90% transmission and extremely small isotopic mass-discrimination. Measured Ar isotope ratios are corrected for mass-discrimination and atmospheric Ar is removed by assuming that all 36Ar originated from air only. The concentration of radiogenic 40Ar is calculated using the 38Ar spike concentration. After each analysis, the extraction temperature is elevated to 1800°C for a few minutes and the furnace is prepared for the next analysis. For K-analysis, a sample aliquot was weighted into a graphite crucible with lithium metaborate/tetraborate flux and fussed using a LECO induction furnace. The fusion bead is dissolved with acid. Standards, blanks and sample were analyzed by an ICP Spectrometer.

X-ray diffraction (XRD) was carried out on a set of three representative tuff samples. For that purpose the material was firstly gently crushed and powdered in an agate mortar and was thereupon placed in the sample holder. The material was analyzed with a Bruker D8-Advanced diffractometer installed at Texas Tech University (Lubbock, TX, United States of America) and run using a step scan in the Bragg-Brentano geometry with CuKα radiation. The measurement settings were 45kV and 40mA with sample mounts scanned from 3 to 70º 2θ. Measurements were completed under air-dried conditions and at a counting time of 2.5s per 0.02º 2θ. Lastly, the peaks of XRD patterns were interpreted and compared with the whole-rock geochemistry generated from ICP-MS to ensure geological fluidity. The Bruker DIFFRACT.EVA diffraction suite was used to analyze diffraction data.

PETROGRAPHY AND MINERAL CHEMISTRY

The effusive and pyroclastic rocks of Mt. Kuna Gora occur in the form of massive lavas (Fig. 2A). These rocks are associated with irregularly interstratified (up to 10cm) pyroclastic rocks (Fig. 2B). Both rock types have the same mineral composition (Figs. 3; 4A-F) and mineral phase chemistry (Table 1). The lavas display porphyritic to plagioclase-seriate textures, homogenous to fluidal structures, indicating a flow of lava (Fig. 4E). The pyroclastic rocks are represented by vitro-crystalloclastic and rarely litho-crystalloclastic ash-flow tuffs (ignimbrites?) of vitrocrystalloclastic texture (Tišlar, 2004 and references therein). The subrounded lithoclasts of effusive and pyroclastic rocks in tuffs vary in size from 0.5 to 4cm, and the subangular autolasts that can be observed in the lavas are up to 5cm in size. (Figs. 2C; 4D). Effusive and pyroclastic rocks are largely made (modal composition up to 45vol.%) of homogenous to slightly sericitized and albitized, subhedral to rarely euhedral phenocrysts or crystalloclasts.

FIGURE 3. X-ray diffraction pattern showing the mineralogy of Mt. Kuna Gora tuffs. Mineral abbreviations after Kretz (1983): C-S= Chlorite-Smectite, Chl= Chlorite, M-S= Mica-Smectite, Kfs= K-feldspar, Qtz= Quartz.
FIGURE 4. Photomicrographs of thin sections of effusive and pyroclastic rocks of Mt. Kuna Gora. A-E) Porfiric/glomeroporfiric andesite-basaltic lavas (N+). F) Vitro-cristaloclastic andesite-basaltic tuffs (N+). Mineral abbreviations after Kretz (1983): Cal= Calcite, Chl= Chlorite, Cpx= Clinopyroxene, Ill= Illite, Kfs= K-feldspar, Mag= Magnetite, Pl= Plagioclase, Ttn= Titanite. Lc= Lithoclaste, Vg= Volcanic glass.
(in pyroclastics) of alkali-feldspar (An$_{0.0}$Ab$_{1.3}$Or$_{96.3-98.9}$; Fig. 5A) up to 3mm in size (Fig. 4A-E). Albition of alkali-feldspar is due to water-rock interaction in an early stage of material deposition/emplacement (e.g. Hövelmann et al., 2010; Kaur et al., 2015). The abundant lath shaped polysynthetic twinning plagioclase (An$_{22.6-45.3}$; Fig. 5A) found in phenocrysts/glomerocrysts and crystalloclasts/porphyroclasts in lavas and pyroclastics, respectively, is slightly sericitized and/or pervasively albitized (An$_{0.2-2.0}$; Fig. 4A-E). Rare phenocrysts of homogenous subhedral clinopyroxene (up to 1.5mm in size) occur in these rocks. Their composition corresponds to augite (Wo$_{34.6-41}$En$_{47-51}$Fs$_{9.3-17}$; Fig. 4C; 5B) with high content of Al$_2$O$_3$ (4.17-5.72wt.%), Cr$_2$O$_3$ (0.21-0.76wt.%) and Mg# (84.6-89.8). The Al$^3$/Al$^6$ varies between 0.53 and 1.17. Fine-grained chlorite (diabantine and pyroclynorite, Hey, 1954; Fig. 5C or Mg-chlorite (clinochlore), Zane and Weiss, 1998; Fig. 5D) is a common secondary phase developed in the matrix of the analyzed effusive and pyroclastic rocks (Fig. 4A-F). Millimeter-scale vesicles are commonly filled with flaky chlorite of analogue chemistry and/or white mica, whereas fine-grained quartz occurs only sporadically. White mica refers to a group of light-colored phyllosilicate minerals such as muscovite, paragonite, margarite, and celadonite (Parry, 1984). Accessory phases are Ti-bearing magnetite (TiO$_2$= 5.18-15.58wt.%; FeO= 36.25-44.88wt.%), zircon, apatite, secondary Fe-bearing Ti-oxide (rutile? TiO$_2$= 98.12wt.%; FeO= 2.90wt.%), ilmenite, hematite and illite (Fig. 4A-B; Table 2). Ti-bearing magnetite may be featured by Fe-Ti oxide (rutile?) extracted along its lamellas (Fig. 6).
Petrographic data suggests the following crystallization order: spinel → clinopyroxene → plagioclase → alkali-feldspar±Fe-Ti oxides. The microcrystalline volcanic rock matrix is holocrystalline to hypocrystalline and is made of devitrified volcanic glass and microlites of plagioclase/albite and alkali-feldspar with some minor ferromagnesian phases (Fig. 4). In the pyroclastic rocks, volcanic glass is the dominant component of the matrix (Fig. 4F). The glassy matrix has been completely altered into a mixture of fine-grained chlorite and white mica (Figs. 3; 4D, F), which likely resulted from high-temperature alterations (e.g. Tillick et al., 2001; Wang et al., 2018). XRD analyses further revealed the presence of chlorite-smectite and mica-smectite (Fig. 3), both attributed to the opening of 10Å and 14Å phyllosilicates during low-temperature eogenetic alterations (Millot, 1971; Zanoni et al., 2016).

GEOTHERMOBAROMETRIC ESTIMATIONS

Estimates on crystallization conditions of andesite-basalt lavas of Mt. Kuna Gora are based either on clinopyroxene phase chemistry, clinopyroxene–whole-rock or alkali-feldspar–whole-rock analyses, which are representative of melt composition. Accordingly, the maximal crystallization temperatures of augite were estimated to fit the range of 880 to 910 (±30)ºC (Lindsey, 1983), while the geobarometer of Nimis (1999) and Nimis and Ulmer (1998) provides equilibration pressures of 1.02 to 1.62 (±0.2)GPa. Slightly higher crystallization temperature of clinopyroxene (1076-1098ºC), along with the more consistent and equilibrated pressure span (1.51-1.58GPa), were calculated using the geothermobarometer of Neave and Putirka (2017). Estimated pressures put constraints on crystallization depths of analyzed andesite-basalts at about 45-49km, which is inconsistent with genesis in deeper portions of an ensialic volcanic arc. Conversely, maximal crystallization temperatures of late magmatic alkali feldspar were estimated to fit the range of 618 to 672ºC (K\textsubscript{D(Al-Ab)}= 0.15-0.23; H\textsubscript{2}O= 3.7-4.6; geothermometer of Putirka, 2008), which corroborates the idea of an abrupt ascent of viscous andesitic melt followed by a rapid and massive crystallization of low-temperature mineral phases in upper lithospheric portions. The temperatures of chlorite formation were between 181.7 and 253.8ºC (Cathelineau, 1988; Jowett, 1991) and 124.9 to 154.5ºC (Kranidiotis and MacLean, 1987), which corresponds to very-low grade hydrothermal alteration processes.

BULK-ROCK CHEMISTRY

The silica concentration ranges representative analyses of the rock suites vary within a narrow range (SiO\textsubscript{2}= 48.40-50.95wt.%), which is typical of mafic rocks (Cox et al., 1979). Potassium content, on the other hand, is high (K\textsubscript{2O}= 8.21-9.62wt.%), Na\textsubscript{2}O is low (0.13-0.81wt.%), and TiO\textsubscript{2} ranges from 0.91 to 1.46wt.% (Table 2). Samples are SiO\textsubscript{2}-saturated with CIPW (Cross Iddings Pirson Washington) normative quartz content (1.24-6.35%) and orthoclase content (up to 61.28%). The Loss On Ignition value (LOI) is between 3.84 and 7.01wt.%, which points to the medium level of sea-floor hydrothermal alteration (e.g. Polat et al., 2002; Polat and Hofmann, 2003). The mobility of certain trace elements has been tested by plotting their abundances against Zr concentration (not shown) as a differentiation index (e.g. Pearce, 1975; Shervais, 1982; Staudigel et al., 1996). Low-level mobilization of some Large Ion Lithophile Elements (LILE), such as Cs, Rb, K and Ba, has been documented. Conversely, High Field Strength Elements (HFSE) like Th, Nb, Ta, Ti, Hf, P, Y and Rare Earth Elements (REE) appear to have remained
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| Mineral | Sample | TiO₂ | Al₂O₃ | Fe₂O₃ | FeO | MgO | CaO | Na₂O | K₂O | H₂O | Total | Ab | An | Or | Wo | En | Fs | Cr | Fe³⁺ | Mg# |
|---------|--------|------|-------|-------|-----|-----|-----|------|-----|-----|-------|----|----|----|----|----|----|----|-----|-----|-----|
|         |        | 0.12 | 0.17  | 0.22  | 0.29| 0.23| 6.05 | 8.6  | 10.91| 11.75| 0.32  | 0.01| 0.02| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
|         |        | 16.7 | 16.05 | 15.91 | 16.3| 15.78| 15.99| 0.51 | 0.61 | 0.86 | 0.02 | 0.01 | 0.02| 0  | 0  | 0  | 0  | 0  | 0  | 0  |
|         |        | 3.005 | 3.012 | 3.012 | 3.012| 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 | 3.012 |
|         |        | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
|         |        | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
|         |        | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
|         |        | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
|         |        | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |

Table 1. Representative chemical compositions and calculated mineral formulae of alkali-feldspar, plagioclase, clinopyroxene, chlorite, magnetite and rutile from the volcanic/pyroclastic rocks from the Mt. Kuna
immobile. In the total alkali silica classification diagram the normalized values of analyzed rocks are plotted in the field of tephri-phonolites and trachyandesites (Fig. 7A). Owing to secondary alterations that are held responsible for somewhat elevated concentrations of K, it has been utilized the classification scheme based on high-field element content. In the classification diagram Nb/Y vs. Zr/TiO₂ x 0.0001 (Winchester and Floyd, 1977), analyzed rocks are plotted in the transition field of sub-alkaline basalts and andesites (andesite-basalts; Fig. 7B), which is typical of lavas formed formed in an island arc environment and along orogenic continental margins (e.g. Hall, 1996).

High-K content coupled with very low Na₂O/K₂O (<0.1), high values of Ce/Yb (9.81-15.05) and Ta/Yb (0.11-0.13) indicate high-K calc-alkaline affinity (Fig. 7C). The lavas show an evolved geochemical character and are moderately fractionated in terms of Mg# and Ni content (59.4-64.4 and 11-19ppm, respectively). An overall uniform content of other compatible trace elements (e.g. Sc, Co, Sr, V; Table 2), with the exception of Cr whose concentrations are rather low (<5ppm), are in line with values typical of mafic lavas (e.g. Hall, 1996; Wilson, 1989). The moderately high content of Zr (115-136ppm) is due to the presence of accessory zircon and apatite.

All rocks show significant LILE (Cs, Rb, K) and Th enrichment ranging from 38 to 133 times relative to N-MORB, and a nearly flat pattern for more immobile elements (Zr to Lu), which ranges from 0.9 to 1.8 times relative to N-MORB (Fig. 8A). The content of HFSEs corresponds to those of orogenic andesites (e.g. Gill, 1981). Nevertheless, all rocks show pronounced negative anomalies of Nb-Ta relative to La ([Nb/La]₀ = 0.32-0.52), as well as of Sr and Ti typical of subduction-related magmas (e.g. Hofmann, 1997; Pearce et al., 1984). The Mt. Kuna Gora effusive and pyroclastic rocks are also characterized by the weak positive Pb spikes relative to Ce ([Pb/Ce]₀ = 1.14-1.18).

The samples define a monotonous trend in a narrow concentration span, which suggests a constant proportion of fractionated phases (Fig. 8B). The normalized REE patterns show moderate enrichment of Light Rare Earth Elements (LREE) over Heavy Rare Earth Elements (HREE) ([La/Lu]₀ = 2.69-4.42) at 23-50 times chondrite relative concentrations. All samples show flat HREE profiles (Fig. 8B). The slight negative Eu anomaly (Eu/Eu* = 0.81-0.88) in the analyzed rocks is typical of fractionation and removal of feldspar in more evolved rock types (e.g. Sun and Nesbitt, 1978; Wilson et al., 1995).

The values of ⁴¹⁸Nd/⁴⁰Nd of two representative samples are very consistent, ranging from 0.512652 to 0.512702 whilst ⁸⁷Sr/⁸⁶Sr shows a spread between 0.717118 and 0.718603 (Table 3). The initial εNd and initial isotopic ratios of Sr are calculated for 241Ma, the crystallization age of analyzed andesite-basalts based on the K-Ar alkali-feldspar dating (see below). The initial εNd varies between +2.08 (±0.49) and +2.88 (±0.56) whilst the initial ε⁸⁷Sr/⁸⁶Sr varies from 0.702349 (±0.002) to 0.702693 (±0.002). Deuteric mobility of Sr and Rb could have led to overestimation of the original concentrations of these elements in the magma. Strontium isotopic data is therefore considered in the sense of an orientation value only. With this in mind, the ⁴¹⁸Nd/⁴⁰Nd vs. ⁸⁷Sr/⁸⁶Sr diagram may indicate an interaction/mixing of source regions (Fig. 9A). The complexity of the source areas and their related melts that gave rise to the effusive rocks of Mt. Kuna Gora is further

### Table 2. Chemical compositions of volcanic/pyroclastic rocks from Mt. Kuna Gora

| Sample | Rock type | TsKg-1 | TsKg-1/2B | TsKg-1/3D | TsKg-3 | TsKg-4 | TsKg-7 | TsKg-10 |
|--------|-----------|--------|----------|----------|--------|--------|--------|--------|
|        |           | ab     | ab       | tu       | ab     | ab     | ab     | ab     |
| SiO₂   |           | 50.29  | 49.50    | 48.40    | 49.22  | 50.95  | 49.65  | 50.36  |
| TiO₂   |           | 0.91   | 1.46     | 0.93     | 0.97   | 1.39   | 0.99   | 1.15   |
| Al₂O₃  |           | 16.10  | 18.14    | 16.01    | 16.10  | 17.56  | 16.21  | 17.01  |
| Fe₂O₃  |           | 8.31   | 8.66     | 8.22     | 8.28   | 8.76   | 8.35   | 8.92   |
| MnO    |           | 0.04   | 0.04     | 0.09     | 0.05   | 0.03   | 0.04   | 0.03   |
| MgO    |           | 6.36   | 7.00     | 6.81     | 6.01   | 7.09   | 6.12   | 6.56   |
| CaO    |           | 2.42   | 0.79     | 2.52     | 2.18   | 1.56   | 1.68   | 0.92   |
| Na₂O   |           | 0.13   | 0.81     | 0.61     | 0.22   | 0.42   | 0.29   | 0.31   |
| K₂O    |           | 9.58   | 8.36     | 9.15     | 6.92   | 8.21   | 9.35   | 8.65   |
| P₂O₅   |           | 0.20   | 0.23     | 0.20     | 0.21   | 0.19   | 0.22   | 0.18   |
| LOI    |           | 5.40   | 5.20     | 6.90     | 7.01   | 3.84   | 7.77   | 5.52   |
| Total  |           | 99.83  | 99.82    | 99.82    | 99.87  | 100.00 | 99.67  | 99.61  |
| Mg#    |           | 61.82  | 64.05    | 63.42    | 67.42  | 64.37  | 60.91  | 59.37  |

All major elements in wt. %, trace elements in ppm. LOI = loss on ignition at 110°C. Mg# = 100*molar (MgO/(MgO+FeOtotal)). ab = andesite-basalt; tu = tuff (ignimbrite?).
adumbrated in the $\varepsilon_{\text{Nd}}$ vs. $^{147}$Sm/$^{144}$Nd diagram, plotting in the transition zone between Ocean Island Basalts (OIB), Subducted Juvenile Material (SJM), and Subducted Continental Material (SCM) (Fig. 9B). The low initial $^{143}$Nd/$^{144}$Nd and $\varepsilon_{\text{Nd}}$ values above bulk silicate earth may suggest a low degree of crustal contamination (Fig. 9A).

### K/Ar DATING

The K-Ar alkali-feldspar age of effusive and pyroclastic rocks from Mt. Kuna Gora is 241.1±5.2Ma (Table 4), which corresponds to the Middle Triassic epoch (Late Anisian-Early Ladinian, Ogg et al., 2016).

### DISCUSSION

The Middle Triassic volcanism of NW Croatia is represented by submarine flows of basaltic to rhyolitic lavas and explosive eruptions of pyroclastic material (e.g. Goričan et al., 2005; Šimunić, 1992; Slovenec et al., 2020; and references therein). Previous stratigraphic studies identified two volcanic events. The first one occurred

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**FIGURE 7.** Classification diagrams of effusive and pyroclastic rocks from Mt. Kuna Gora. A) Total Alkali Silica classification diagram (Le Bas et al., 1986). B) Nb/Y–Zr/TiO$_2$*$10^{-4}$ classification diagram (Winchester and Floyd, 1977). C) Ce/Yb–Ta/Yb discrimination diagram (Pearce, 1982).
during the Middle Anisian, when effusive rocks and tuffs formed. The tuffs are found interbedded with fine-grained clastic rocks and cherts. The second event took place in the Middle Ladinian and was characterized by massive lava flows and deposition of pyroclastic material (e.g. Šimunić, 1992; Šimunić and Šimunić, 1997; and references therein).

Published stratigraphic research does not provide the age and/or the environment of the volcanic activity during the Middle Triassic in NW Croatia. The research results presented in this paper based on mineralogical, petrological, geochemical and isotopic data allow new petrogenetic considerations about the origin and geotectonic environment of effusive and pyroclastic rocks of Kuna Gora Mt. and contribute to the understanding and reconstruction of events related to Middle Triassic volcanism.

Petrogenesis

The interstratification of pyroclastic and effusive rocks of Mt. Kuna Gora, their similar structure and analogue chemistry are in favor of contemporaneous lava flows and deposition of explosive material from pyroclastic flows. This calls for a common magma source(s), which was likely situated proximal to the sampling location, as suggested by the myriad of pristine euhedral and subhedral primary minerals.

The dominance of alkali-feldspar (~45vol.%), that crystallizes after the plagioclase and clinopyroxene, may be indicative of restrained and selective crystallization at a greater depths. The crystallization was followed by a rapid magma uplift, and quick and abundant crystallization of low-temperature felsic phases in the shallow crust. Such a scenario calls for a low magma differentiation, which is supported by low abundance of SiO₂ (<51wt.%) and uniform chemical composition of basaltic lavas and their pyroclastic (tuffaceous) manifestations.

The origin of analyzed rocks of Mt. Kuna Gora is complex. It can be inferred from the range of discrimination ratios of trace elements and the Nd isotopic data. The formation of these rocks implies either a contamination of a subduction-generated magma by lithospheric mantle melts or an enrichment of the mantle sources by subduction-related crustal melts. Low Ba/Th and Sm/La coupled with high Th/La and (La/Sm)₀ (Fig. 10) suggest an important role of subduction-related melts likely derived from crustal material. In this sense, melting of the down going slab can be assumed, while the usual fluid-saturated melting of the mantle wedge above the subducting slab is significantly subordinate. Positive values of initial εNd(t) (up to 2.88) and low values of ¹⁴⁷Sm/¹⁴⁴Nd (up to 0.143662; Table 3) of analyzed effusive and pyroclastic rocks are also in line with

| TABLE 3. Nd and Sr isotope data of volcanic rocks from Mt. Kuna Gora |
| Sample | Sm/Nd | ¹⁴⁷Sm/¹⁴⁴Nd | ¹⁴⁷Nd/¹⁴⁴Nd | εNd₀ | Rb/Sr | ¹⁰⁸Sr/⁸⁶Sr | ⁸⁷Sr/⁸⁶Sr₀ | Time (Ma) |
|---------|-------|-------------|-------------|------|-------|------------|------------|-----------|
| TaKg-12B | 0.22821 (0.11) | 0.137970 (0.007) | 0.512652 (6.1⁴⁻¹⁰) | 0.512434 (3.1⁴⁻¹⁰) | +2.08 (0.49) | 1.63636 (0.08) | 4.741336 (0.47) | 0.718603 (0.002) | 241 ± 10.4 Ma |
| TaKg-19 | 0.23763 (0.24) | 0.145961 (0.007) | 0.512702 (3.1⁴⁻¹⁰) | 0.512475 (3.1⁴⁻¹⁰) | +2.88 (0.56) | 1.65238 (0.07) | 4.207675 (0.42) | 0.717116 (10⁻¹⁰) | 241 ± 10.4 Ma |

Location number corresponds to the locations in Figure 1C. Errors in brackets for Nd and Sr isotopic ratios are given at the 2s-level. The method of calculating the errors is presented in the analytical techniques chapter.

The dominance of alkali-feldspar (~45vol.%), that crystallizes after the plagioclase and clinopyroxene, may be indicative of restrained and selective crystallization at a greater depths. The crystallization was followed by a rapid magma uplift, and quick and abundant crystallization of low-temperature felsic phases in the shallow crust. Such a scenario calls for a low magma differentiation, which is supported by low abundance of SiO₂ (<51wt.%) and uniform chemical composition of basaltic lavas and their pyroclastic (tuffaceous) manifestations.

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There is a significant input of subducted slab melts. This process likely originated from subducted juvenile material whose origin was linked to the subducted Paleotethys oceanic crust (Fig. 9B). The composition is characterized by a high content of Nd (16-21 ppm) for mantle-derived magmas in volcanic regimes. The partial melting and mixing of three source components: i) a LREE-enriched fertile arc mantle, ii) long-term LREE-enriched subducted continental material and iii) depleted or OIB-like mantle with long-term LREE-depletion (Fig. 9B). However, moderately high Th/La (0.3-0.4), Th/Yb (1.69-2.25), Th/Ta (14.4-16.2) and La/Nb (2.06-3.35) along with a slight rise in positive Pb spikes (up to 1.2), which are all susceptible to crustal contamination, do not reveal significantly elevated degrees of contamination with a crustal component. Furthermore, a high Rb/Cs ratio (38-73) indicates a moderately low sedimentary contribution (e.g., Hildreth and Moorbath, 1988). On the other hand, minor contamination by upper continental crust (Fig. 10B) may stem from: i) subduction-related crustal melts, i.e., recycled sediments, and/or ii) rapid and short-term magma uplift through tectonically weakened zones of continental crust (Hildreth and Moorbath, 1988). Finally, the positive trend of $\varepsilon_{Nd}$ vs. $^{147}$Sm/$^{144}$Nd suggests that genesis of parental magmas included melting of a mixed fertile–depleted mantle source with minor input from the continental crust. Nevertheless, significantly lower $^{147}$Sm/$^{144}$Nd in studied lavas of Mt. Kuna Gora compared with the values reported in the material from the depleted mantle calls for a small contribution from an older LREE-enriched source (Fig. 9B). Considering all the above, the formation of parental magma by hybridization of mantle-derived and crust-derived magmas, at or near the mantle-crust transition (in which the melting-assimilation-storage-homogenization MASH process occurs), is characteristic of areas above subduction zones, as well as those below long-lived intraplate volcanoes (Hildreth and Moorbath, 1988).

Various authors implemented different geochemical variables to infer the amount of partial melts extracted from a residual mantle source. It is hypothesized that this source was enriched by subduction-related processes that led to the application of a petrogenetic model based on the amounts of incompatible and immobile trace elements such as Dy and Yb (e.g., Rollinson, 1993; Thirwall et al., 1994). The Dy/Yb vs. Yb diagram (Fig. 11) thus outlines spinel and garnet peridotites as plausible mantle sources. Accordingly, basalt to andesite composition lavas of Mt. Kuna Gora might have been produced through ~8 to 12% partial melting (Fig. 11) of a shallow mantle source. In addition to partial melting, the genesis of analyzed rocks must have included fractional crystallization, which is indicated by moderate values of MgO/FeOtot (0.81-0.92) coupled with very low abundances of Ni and Cr (11-10 ppm and 26-44 ppm, respectively). Considering an early crystallization of magnetite, the process of fractional crystallization must have taken place under oxidized conditions.

In brief, it is possible to hypothesize that analyzed rocks of Mt. Kuna Gora were derived through the processes of i)
partial melting of the subcontinental lithospheric mantle, ii) subducting slab melting and iii) minor melting of a shallow asthenospheric mantle. Such “hybrid” magmas are suggested to have formed through the mixing of calc-alkaline melts that originated in a subduction-modified mantle domain while minor amounts of melts originated in a depleted sub-lithospheric or OIB-like mantle source.

**Tectonomagmatic significance**

Analyzed effusive and pyroclastic rocks of Mt. Kuna Gora, in the Hf/3-Th-Nb/16 diagram, are plotted within the field, which is unique for calc-alkaline arc-related effusive and pyroclastic rocks, thus suggesting a subduction-related environment (Fig. 12A). The same conclusion may be drawn from the clinopyroxene phase chemistry (Fig. 13). Enrichment in LILE and LREE and negative anomalies of Nb-Ta and Ti (Fig. 8), along with depletion in HFSE, are all characteristics of subduction-related magmas and suggests a strong subduction influence and retention of these elements in the slab (e.g. Arculus and Powel, 1986; Hawkesworth et al., 1993, 1997; Pearce, 1982, 1983). However, moderately high content of Zr, Hf, Ta, Nb and Th (Table 2), as well as an increasing trend of their N-MORB normalized concentrations (Fig. 8A), suggest that their source is more intercrustal than subduction-derived (Hildreth and Moorbath, 1988 and references therein). The high-K calc-alkaline character of these rocks and their characterization based on Th/Ta vs. Yb, La/Yb vs. Sc/Ni and Th/Nb vs. La/Yb clearly support the formation of Mt. Kuna Gora lavas and pyroclastics in an ensialic and mature volcanic arc setting developed in an active, Andean-type, continental margin environment (Fig. 12B-D).

**Geodynamic significance**

Current paleogeographic reconstructions of Middle Permian to Middle Triassic tectonics suggest that the western Tethys Ocean, that was a large embayment of Panthalassa, was a remnant of the Paleo-Tethyan Ocean (e.g. Berra and Angiolini, 2014 and references therein). This ocean had subducted northwards beneath the Laurussian (south European) active margin (e.g. Şengör, 1984; Stampfli and Borel, 2002, 2004; Schmid et al., 2008; Stampfli et al., 2013). According to these authors, the subduction was related to the opening of a newly formed Neotethyan Ocean to the south and the migration of Cimmeria that rifted from Gondwana toward the northeast. The opening of the Neotethys Ocean changed the tectonic constellation which lead to the closing of the Paleo-Tethys Ocean during

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**TABLE 4.** K–Ar alkali-feldspar ages of volcanic rocks from Mt. Kuna Gora

| Sample  | Location | Rock type                       | K [%] | 40Ar/39Ar (nl/g) | 40Ar/39Ar Atm [%] | Age (Ma ± 1σ) |
|---------|----------|---------------------------------|-------|------------------|------------------|---------------|
| TsKg-1  | 1        | andesite-basalt                 | 7.540 | 75.61            | 3.80             | 241.1 ± 5.2   |

Location number corresponds to the location in Figure 1C

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**FIGURE 10.** Discrimination diagrams for the effusive and pyroclastic rocks of Mt. Kuna Gora. A) Ba/Th–(La/Sm)_n diagram (after Eliot, 2004). B) Th/ La–Sm/La diagram (after Plank, 2005). Abbreviations: (N-MORB)= Normal Mid-Ocean Ridge Basalts; E-MORB= Enriched MORB; OIB= Ocean Island Basalts; PM= Primitive Mantle (Sun and McDonough, 1989); [UCC= Upper Continental Crust; LCC= Lower Continental Crust (Taylor and McLennan, 1985)]; GLOSS= Global Subduction Sediment (Plank and Langmier, 1998); DMM= Depleted MORB Mantle (Workman and Hart, 2005).
D. Slovenec and B. Šegvić

High-K calc-alkaline effusive and pyroclastic rocks from Mt. Kuna Gora, Croatia

The geodynamic and isotopic data, and the mineral composition of the studied lavas and pyroclastic rocks (Figs. 8; 12; 13) along with their close spatial contact are all consistent with a subduction-related geotectonic model for their formation. This argues for the existence of an active, ensialic mature volcanic arc developed along southern active continental margins of Laurussia. The formation of an active continental arc is related to the northward subduction of the Paleotethyan lithosphere during the Late Anisian-Early Ladinian (Slovenec et al., 2020; Fig. 14). Geochemical signatures of this effusive to explosive volcanism were likely inherited from the Paleo-Tethyan subduction slab. A high-K calc-alkaline arc-related volcanism (Fig. 12C-D) is characteristic of Andean-type active continental margins (Fig. 8). The origin of these magmas is very complex (involving mixing between several source components) and is marked by selective crystallization at maximum depths of about 45 to 49 km, followed by a rapid magma uplift and abundant crystallization of felsic mineral phases (alkali feldspar) in the upper lithosphere. That is indicative of magma generation in a base of an ensialic volcanic arc. Possible minor to moderate sedimentary input revealed by analyzed effusive and pyroclastic rocks’ geochemistry may be an indication of a large distances from the trench and consequently a greater-than-normal depth of the slab (e.g. Mazza et al., 2020).

During the Late Anisian the western Paleotethys Ocean was characterized by the uplift of a mantle dome that caused an adiabatic decompression and initial disintegration of the Adriatic-Dinaridic carbonate platform along a system of subparallel faults (e.g. Slovenec et al., 2020 and references therein). These processes enabled the proto back-arc rifting of the intra-continental lithosphere behind the peri-continental volcanic arc characterized by uncontaminated primitive (OIB-type) alkali lavas devoid of crustal contamination (e.g. Slovenec et al., 2010, 2011, and references therein). These processes enabled the proto back-arc rifting of the intra-continental lithosphere behind the peri-continental volcanic arc characterized by uncontaminated primitive (OIB-type) alkali lavas devoid of crustal contamination (e.g. Slovenec et al., 2010, 2011, and references therein). This calls for a significant rollback and retreat of the subducted sinking slab (Slovenec et al., 2020), pointing to the final subduction stages of the Paleotethys plate (Stampfli et al., 2001; Ziegler and Stampfli, 2001). Under such circumstances the peripheral portions of the upwelling primitive OIB-like mantle dome (Fig. 14) might have slightly modified the composition of parental lavas in the subduction zone. A low degree of crustal contamination may result from a attenuation of the continental crust and/or rapid magma uplift through tectonically weakened zones of the crust. This model includes the demise of active subduction of the Paleotethys plate during Early-Middle Triassic time.

Although the model of active subduction has been favored in this study, the alternative geodynamic models that presumes Middle Triassic volcanism without contemporaneous active subduction should also be considered. The model proposed by Saccani et al. (2015) for the Albanide-Hellenide segment of the Tethys and the model of Lustrino et al. (2019) for the Triassic magmatism of the Southern Alps (Italy), suggest that calc-alkaline and shoshonitic rocks were generated by partial melting of the subduction-modified heterogeneous lithospheric (subcontinental) mantle. This subcontinental mantle had

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**FIGURE 11.** Yb-Dy/Yb diagram for the effusive and pyroclastic rocks of Mt. Kuna Gora. Partial melting curves are shown for the non-modal batch melting of spinel and garnet-lherzolite sources, starting from a Primitive Mantle (PM) material (McDonough and Frey, 1989). Mineral and melt modes for spinel and garnet-lherzolite source: Ol 0.58(0.10) + Opx 0.27(0.27) + Cpx 0.12(0.50) + Gt 0.03(0.13) (Kinzler, 1997) and Ol 0.60(0.05) + Opx 0.21(0.20) + Cpx 0.08(0.30) + Gt 0.12(0.45) (Walter, 1998), respectively. Italic numbers in parentheses indicate the percentages of each mineral entering the liquid. Partition coefficients are from McKenzie and O’Nions (1991).
been contaminated and/or metasomatized during earlier Hercynian subduction events in the Late Paleozoic when local geotherms were raised due to the passive upwelling of asthenospheric mantle along the rifted margins (Saccani et al., 2015).

CONCLUSIONS

High-K calc-alkaline lavas (andesite-basalts) and associated pyroclastic products (ash-flow tuffs) of analogue mineralogical and chemical composition from Mt. Kuna Gora (NW Croatia) suggests coeval lava- and pyroclastic flows before 241.1±5.2Ma.

Petrographic data suggests the following crystallization sequence: spinel → clinopyroxene → plagioclase → alkali-feldspar (~45 vol.%) ± Fe-Ti oxides.

The matrix of the effusive rocks consist of devitrified volcanic glass and microlites of plagioclase/olivine. In the pyroclastics, the glassy matrix is altered into a mixture of
fine-grained chlorite (formed between 124.9 and 253.8°C) and white mica, further transformed into chlorite-smectite and mica-smectite during low-temperature diagenesis.

The crystallization of high-temperature mafic clinopyroxene in deeper segments of magmatic source (~1100°C) was limited and selective owing to the abrupt ascent of viscous andesite melts. However, the crystallization of low-temperature felsic mineral phase (alkali-feldspar; ~680°C) in upper lithospheric levels was rapid and abundant, resulting in poor magma differentiation.

Geochemical data as well as the isotopic composition of Sr and Nd indicate that the analyzed rocks had a complex origin, which included the contamination of a subduction-generated magma by melts of the lithospheric mantle. A lower level of crustal contamination represents the final phase of the proposed model for the formation of the studied “hybrid” magmas. A petrogenetic model for the formation of parental magmas accounts for the processes of partial melting and fractionation of subducted Paleotethys oceanic lithosphere and subcontinental lithospheric mantle. Analyzed high-K calc-alkaline rocks of Mt. Kuna Gora were derived by low degrees (8-12%) of partial melting of a shallow (spinel) mantle source region at maximal depths of ~45-49km and pressures ≤1.6GPa.

The suggested geodynamic model for the formation of the effusive and pyroclastic rocks of Mt. Kuna Gora is

![Diagram](image-url)
linked to the final phases of an active northward subduction of Paleo-Tethys ocean lithosphere during early Mid-Triassic time. The model includes the existence of an active, ensialic mature volcanic arc developed at southern active continental margins of Laurussia along the northwestern branch of the Paleo-Tethys Ocean.

**ACKNOWLEDGMENTS**

This work was supported by the Croatian Science Foundation under the project (IP-2019-04-3824). Additional support was received from the Croatian Ministry of Science, Education and Sport in the frame of the grant no. 181-195126-1141 to Da. Slovenec. We thank Boško Lugović and Hans-Peter Meyer for microprobe analyses. We extend our appreciation to Bruno Mravlja and Giovanni Zanoni for their assistance with XRD measurements. Furthermore, valuable scientific discussions with Mirko Belak and Tonči Grgasović helped to improve an early version of the manuscript. Luka Badurina is acknowledged for his assistance with Monte Carlo simulation modelling. Critical comments and constructive reviews by two anonymous reviewers, as well as the editorial handling by Michael Ort and Laura Rincón, contributed significantly to the manuscript quality.

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Manuscript received July 2020; revision accepted December 2020; published Online March 2021.